The Journal of Agricultural Sciences - Sri Lanka
Vol. 21 No 1, January 2026. pp 214-224
https://doi.org/10.4038/jas.v21i1.10348

REVIEW

The Hidden World Beneath Our Feet: Unraveling the Role of Soil Pores in the Complex Mechanisms of Soil Carbon Sequestration

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Received: 28th June 2023 / Accepted: 03rd October 2025

ABSTRACT

Purpose: *This study aims to investigate how the characteristics and distribution of soil pores influence soil carbon dynamics and sequestration processes. The key hypothesis is that the size, connectivity, and spatial arrangement of soil pores regulate key biophysical processes such as microbial activity, organic matter stabilization, water retention, and gas exchange that collectively determine the capacity of soils to store carbon over the long term.*

Research Method: *Existing literature and research on soil pores, carbon dynamics, and carbon sequestration are analyzed. The interrelationships between soil pore structure, water movement, microbial activity, root penetration, carbon input, soil aggregation, and gas exchange are examined. Traditional techniques and advanced imaging methods are used to quantify and characterize soil pores.*

Findings and Values: *Soil pores play a critical role in facilitating carbon sequestration through various mechanisms. They affect water movement, microbial activity, root penetration, carbon input, soil aggregation, and gas exchange. Understanding these relationships is crucial for sustainable soil management. This research enhances existing knowledge by comprehensively examining the significance of soil pores in carbon dynamics and sequestration. It incorporates both traditional and advanced methods, providing insights for soil management and contributing to climate change mitigation efforts.*

Keywords: *Carbon sequestration, Climate change, Microbial activity, Soil organic carbon, Soil pores*

INTRODUCTION

Soil is a complex ecosystem essential for life on land, where the size, distribution, and connectivity of soil pores influence the stabilization and storage of organic carbon in aggregates and micropores that contribute to long-term climate change mitigation. The arrangement and structure of soil pores

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key soil processes such as water infiltration, retention, and movement; air exchange; root penetration; and the stabilization and sequestration of soil organic carbon. The intricate relationship between soil pores and the mechanisms involved in C sequestration is an area currently being actively researched (Kravchenko *et al.* 2015, Kravchenko & Guber 2021, Lucas *et al.* 2022). One hypothesis put forth is the protection hypothesis, which suggests that particles within the soil shield organic carbon from respiration. This shielding effect may be due to the occlusion of organic carbon within pore spaces, inaccessible to microbes and their extracellular enzymes. Additionally, factors such as advective pore-water exchange, outwelling, and methane emissions also have an impact on the sequestration of carbon in the soil (Carney *et al.* 2007). To combat climate change, sustainable practices for soil carbon sequestration and stabilization are crucial. Carbon sequestration captures and stores carbon dioxide, while stabilization prevents decomposition and promotes long-term storage in soil. A thorough understanding of these concepts is crucial for the effective management of soil carbon and the implementation of sustainable land-use practices (Banwart *et al.* 2014).

One important aspect to consider is the coexistence of mesopores and nanopores between parallel smectite particles, which has a significant impact on soil permeability (Liu *et al.* 2019). Soil organic carbon stabilization and protection are influenced by clay minerals, iron and aluminum oxides, and sequestration into macro and micropores. Biochemical stabilization also plays a role whereby microbial by-products and compounds with complex chemical structures resist decomposition, contributing to the long-term storage of carbon in soil. The distribution of microscale carbon varies depending on soil moisture, but accurately assessing this distribution within intact pore spaces remains a challenge.

Therefore, this study aims to examine the role of soil pores in carbon dynamics and sequestration, with a focus on how their physical and chemical characteristics influence the stabilization and long-term storage of soil organic carbon. The specific objective is to analyze how the size, distribution, and connectivity of soil pores contribute to soil aggregation, microbial activity, and organic matter protection. The key hypothesis is that soil pore architecture, particularly the presence of micropores, facilitates the physical and biochemical stabilization of organic carbon by limiting microbial access and enhancing organo-mineral interactions, thereby increasing the potential for long-term carbon sequestration in soils.

Physical and chemical characteristics of soil pores and their implications for Soil carbon dynamics

Soil pores, filled with air or water, are vital for soil carbon dynamics, providing a habitat for microorganisms that decompose organic matter (OM) and release CO_2 into the atmosphere (Wang *et al.* 2022). The physical and chemical characteristics of soil pores can affect the amount and stability of soil C. The size and distribution of soil pores can influence the amount of carbon stored in the soil. Larger pores allow for greater water infiltration and air exchange, which can increase microbial activity and C decomposition (Negassa *et al.* 2015). However, smaller pores can protect OM from decomposition by limiting microbial access (Meurer *et al.* 2020).

The distribution of pore sizes can also affect the stability of soil C. Well-connected pores that allow for water movement can lead to greater C loss through leaching, while isolated pores can trap carbon and increase its stability (Xiao *et al.* 2024). The chemical properties of soil pores can also impact soil C dynamics. Soil pH regulates microbial community structure and decomposition rates: near-neutral pH (∼6–7) tends to maximize priming and breakdown of organic matter, while soils with pH $<$ 5 or $>$ 7 suppress microbial activity and slow C loss (Wang & Kuzyakov 2024). The presence of minerals and organic compounds in soil pores can also affect C stability. Minerals such as clays can protect OM from decomposition by physically binding to it, while organic compounds such as humic acids can chemically stabilize C by forming complexes with it (Fukumasu *et al.* 2022).

Soil pores and carbon sequestration

Soil pores play a crucial role in carbon sequestration. Wang *et al.* (2022) demonstrated that carbon depletion around apertures occurs in a significantly larger volume of soil than carbon enrichment around particulate organic matter (POM). Fukumasu *et al.* (2022) provides new insights into the relationships between SOC and soil pore structure in arable soil, which may lead to more accurate estimates of the effects of enhanced SOC sequestration on soil water dynamics and soil water supply to crops. According to Vashukevich *et al.* (2022), the aggregated structure of soil reduces rates of SOM decomposition and, consequently, impacts the potential for long-term C sequestration. The most promising and cost-effective environmental strategy is soil C sequestration (Umeojiakor *et al.* 2015).

By affecting the soil's physical and chemical properties and aggregate stability, the invasion of Japanese White birch (*Betula platyphylla*) had an indirect effect on soil C sequestration (Jarvis *et al.* 2020). Plant productivity and soil C sequestration may undergo substantial changes in response to increased soil pore water salinity and decreased soil water table due to drought (Hnatyshyn 2021). De Deyn *et al.* (2008) found that Teak (*Tectona grandis*) is the greatest option for maximising soil C sequestration, followed by Rubber tree (*Hevea brasiliensis*), Beechwood (*Gmelina arborea*), and Velvet tamarind (*Dialium guineense*).

Mechanisms through which soil pores affect carbon sequestration

Carbon sequestration is significantly influenced by soil porosity through multiple mechanisms.

i. Water movement and transport of organic carbon: Soil pores provide channels for the movement of water within the soil profile. This movement enables the transport of dissolved organic carbon (DOC) through the soil, facilitating its storage in deeper soil strata. Adequate pore space allows for efficient water infiltration and drainage, facilitating the movement of carbon-rich water into regions where it can be stored and stabilised (Ebrahimi & Or 2015).

ii. Microbial activity and decomposition: Soil fissures create microhabitats that support diverse microbial communities that decompose OM. In the oxygen-rich pores, microbes flourish, decomposing OM and transforming it into stable C compounds (Negassa *et al.* 2015; Santos *et al.* 2019). The presence of well-connected pores facilitates oxygen diffusion, thereby fostering aerobic microbial processes and enhancing C sequestration.

iii. Root penetration and carbon input: Soil pores allow plant roots to permeate and investigate the soil matrix. As roots develop and expand into pores, they contribute to carbon sequestration by depositing carbon derived from the roots into the soil (Eden *et al.* 2011).

iv. Carbon stabilisation and soil aggregation: Soil pores contribute to the formation of soil aggregates by providing physical space for the entrapment of organic matter, microbial by-products, and root exudates (Six *et al.* 2004; Totsche *et al.* 2018). Aggregates provide microenvironments conducive to the stabilisation and long-term storage of organic carbon (Nunan *et al.* 2023).

v. Gas exchange: Soil pores facilitate the exchange of gases between the soil and the atmosphere. Oxygen availability in capillaries is essential for aerobic microbial processes involved in carbon decomposition and stabilisation (Tang *et al.* 2019).

Understanding the complex relationship between soil porosity and carbon sequestration is essential for effective soil management and sustainable land-use practices (Ruamps *et al.* 2013; Steffens *et al.* 2017, Haruna 2019).

Methods involved in quantifying and characterizing soil pores

Quantifying and characterizing soil pores are essential for understanding soil functions such as water and gas fluxes, chemical transport, and biota movement. Traditional techniques such as mercury intrusion porosimetry (MIP) and nitrogen adsorption isotherms (NAI) quantify porosity and pore size distribution but lack three-dimensional structural information (Sampurno *et al.* 2016).

Advanced imaging techniques including synchrotron-radiation-based X-ray computed microtomography (SR-mCT) and two-dimensional image analysis have been proposed (Udawatta *et al.* 2016; Zong *et al.* 2014; Yu *et al.* 2016). High-resolution 3D images of soil pores generated by SR-mCT enable detailed visualization and quantification of pore structure (Yu *et al.* 2016). Software tools for quantifying soil porosity from 2D images have also been proposed (Cooper *et al.* 2016). Combining SEM-EDS with SR-mCT is an effective approach for examining pore properties of soil aggregates and their interactions with cementing agents (Udawatta *et al.* 2016).

Advances in quantifying soil structure and pore characteristics

The rates of soil structure turnover can now be directly measured using a novel metric based on the contact lengths between particles and pores (Kravchenko & Guber, 2021). Determining structural characteristics important to mercury and water transport in soil has also been done using fractals and percolation theory (Passoni *et al.* 2015). For the segmentation of bio-pores in tomographic images, variational-based segmentation has been proposed. Additionally, the coordination number distribution determined from the medial axis has been utilised to investigate how soil compaction affects the physical characteristics of soil (Schlüter & Vogel, 2016).

Factors influencing soil pore dynamics

Different environmental elements, such as soil characteristics, land management practises, and climate change, have an impact on soil pore dynamics. Tillage, compaction, and irrigation are examples of land management techniques that can have an impact on soil stability and pore formation. For instance, excessive irrigation water containing sodium can cause clay dispersion, which lowers the soil's capacity to store water and its hydraulic conductivity (K) (Tas *et al.* 2022). Conversely, conservation agriculture techniques like limited tillage and cover crops can improve soil porosity, increase water penetration, and decrease soil loss (de Jonge *et al.* 2009).

The texture, structure, and OC content of the soil can all be affected by climate change, which can also have an effect on how the soil pores behave. By altering soil aggregate and pore size distributions, losing SOC, and reducing water and nutrient retention capabilities, soil degradation brought on by climate change might result in structural changes in soil (Jha *et al.* 2023). These modifications may have an impact on the soil pore networks and the activities of the soil biota.

Earthworms and fungi are important members of the soil biota shaping the soil pore networks. By tunnelling through the soil, earthworms can form macropores, which improve soil aeration, water infiltration, and nutrient availability (Milleret *et al.* 2009). On the other side, fungi have the ability to build mycelial networks that connect soil particles, forming stable aggregates and enhancing soil structure (Kohler-Milleret *et al.* 2013).

Pore formation and its effects on C sequestration are further influenced by soil characteristics such as texture, structure, and OC content. Increased SOC concentration will increase plant accessible water content and unsaturated hydraulic conductivity since soil OC content and soil porosity are positively associated, notably in the 0.2–5 and 480–720 μm diameter classes (Fukumasu *et al.* 2022). Water infiltration, runoff, and evaporation loss are all impacted by soil structure, including pore size distribution (Ghosh *et al.* 2020). According to Paz González and Vidal Vázquez (2005), soil pore dynamics and soil quality can also be impacted by soil compaction, erosion, and other physical disturbances.

Implications for soil management and climate change mitigation

For improving soil health and C sequestration, it is essential to understand soil pores alongside other critical factors such as soil texture, mineralogy, biological activity, organic matter inputs, and land management practices. For proper nutrient cycling and carbon sequestration, the soil needs to have the right balance of air and water, which is maintained by soil pores (Crawford *et al.* 2011). Enhancing C storage through manipulation and soil pore engineering has been shown to be an effective management technique for lowering greenhouse gas emissions and agriculture's role in global climate change (de Souza *et al.* 2018). It is possible to mitigate climate change through soil management (Keesstra *et al.* 2016).

According to Mangalassery *et al.* (2014), soil tillage practises have a significant impact on both the soil's physical characteristics and the balance of greenhouse gases. Nearly twice as much carbon (C) is stored in soil as particulate organic matter, which accounts for 5–15% of soil carbon (Kravchenko *et al.* 2015). Biochar made from wood can be added to compacted soils to alter their hydraulic properties, which can affect how much carbon is stored in replicated agriculture (Ahmed *et al.* 2021).

Droughts and extreme precipitation events can have an impact on soil pore connectivity, which may have ambiguous effects on terrestrial carbon sequestration (Smith *et al.* 2017). By increasing soil porosity and pore size distribution, conservation agriculture can increase soil water infiltration, decrease water runoff and soil loss, and reduce evaporation loss (Ghosh *et al.* 2020). According to de Jonge *et al.* (2009), management, moisture, and the composition and complexation of solids all have an impact on the creation of soil structure and the resilience of the soil to disturbance.

According to soil type and plant type, the soil biota, which includes earthworms and mycorrhizae, has a significant impact on the physical qualities of the soil. Their independent effects can either combine or mitigate one another, differing in severity (Kohler-Milleret *et al.* 2013). In conclusion, it is essential to comprehend soil pore dynamics in order to create effective policies and methods for mitigating climate change.

Future directions and research gaps

To improve our understanding of soil pore mechanics and its connection to carbon sequestration, several knowledge gaps and potential research initiatives might be identified. These include:

i. Quantifying the role of different pore sizes and distributions: Quantifying the influence of different pore sizes and distributions on carbon sequestration is an essential area of research. Understanding the specific contributions of macro- and micro-pores and their interactions in carbon storage can yield insightful information (Meurer *et al.* 2020).

ii. Investigating the effects of soil structure and aggregation: Soil structure and aggregation play a crucial role in pore formation and stability. How soil aggregation influences carbon sequestration and the effect of management practises (e.g., tillage, organic amendments) on soil structure and pore dynamics require additional study (Meurer *et al.* 2020; Kavya *et al.* 2023).

iii. Assessing the effects of climate change on soil pore dynamics: Climate change can influence soil moisture regimes, temperature, and precipitation patterns, which can influence soil pore dynamics (Elbasiouny *et al.* 2022). It is essential to investigate how these changes influence the potential of carbon sequestration and the stability of soil pores under various climatic conditions.

Potential interdisciplinary approaches

Combining soil physics and microbial ecology can improve our understanding of the mechanisms by which soil pores interact with carbon-cycling microbial communities. Exploring these interactions can reveal how soil microbial activities are influenced by pore characteristics and how they contribute to carbon sequestration (Kaushal *et al.* 2023).

In light of the significance of soil pore dynamics in carbon sequestration, it is essential to incorporate this knowledge into land management and climate change mitigation strategies. Developing practicable guidelines and best management practises that consider soil pore characteristics can help optimise C sequestration potential in various land-use systems (Post & Kwon 2005; Elbasiouny *et al.* 2022; Kavya *et al.* 2023; Kaushal *et al.* 2023).

CONCLUSION

In soil carbon dynamics and carbon sequestration processes, soil pores are crucial. The size, distribution, and connection of soil pores, among other physical and chemical properties, have a big impact on the quantity and stability of soil carbon. Smaller pores inhibit the decomposition of organic materials while larger pores promote microbial activity and carbon decomposition. Well-connected pores help water flow and carry dissolved organic carbon, which helps the carbon to be stored in deeper soil layers. Additionally, soil pores affect microbial activity, root development, and soil aggregate production, all of which have an impact on carbon sequestration. Carbon breakdown and stabilization are also influenced by gas exchange and oxygen availability inside soil pores. Effective soil management and sustainable land-use techniques depend on an understanding of the intricate link between soil porosity and carbon sequestration. To measure and describe soil pores, a variety of methods are used, including conventional approaches and cutting-edge imaging technologies. Continuous investigation and study of soil pore dynamics will help to maximize the soil's capacity to store carbon, supporting efforts to mitigate climate change and enhance soil health.

REFERENCES

Ahmed A, Kurian J, Satyanarayana S, Raghavan V (2021) Impact of wood-derived biochar on the hydraulic characteristics of compacted soils: Its influence on simulated farmland carbon sequestration. *International Agrophysics*, 35(2), 167–177. https://doi.org/10.31545/intagr/135898.

Banwart SA, Black H, Cai Z, Gicheru P, Joosten H, Victoria RL, Pascual U (2014) The global challenge for soil carbon. In: *Soil Carbon: Science, Management and Policy for Multiple Benefits*, pp. 1–9. https://doi.org/10.1079/9781780645322.0001.

Bouckaert L, Van Loo D, Ameloot N, Buchan D, Van Hoorebeke L, Sleutel S (2013) Compatibility of X-ray micro-computed tomography with soil biological experiments. *Soil Biology and Biochemistry*, 56, 10–12. https://doi.org/10.1016/j.soilbio.2012.02.002.

Carney K, Hungate B, Drake B, Megonigal J (2007) Altered soil microbial community at elevated CO_2 leads to loss of soil carbon. *Proceedings of the National Academy of Sciences USA*, 104, 4990–4995. https://doi.org/10.1073/pnas.0610045104.

Charoenjit K, Zuddas P, Allemand P (2013) Estimation of natural carbon sequestration in eastern Thailand: Preliminary results. *Procedia Earth and Planetary Science*, 7, 139–142. https://doi.org/10.1016/j.proeps.2013.03.187.

Chen X, Santos IR, Hu D, Zhan L, Zhang Y, Zhao Z, Hu S, Li L (2022) Pore-water exchange flushes blue carbon from intertidal saltmarsh sediments into the sea. *Limnology and Oceanography Letters*, 7(4), 312–320. https://doi.org/10.1002/lol2.10236.

Colombi T, Walder F, Büchi L, Sommer M, Liu K, Six J, van der Heijden MGA, Charles R, Keller T (2019) On-farm study reveals positive relationship between gas transport capacity and organic carbon content in arable soil. *Soil*, 5, 91–105. https://doi.org/10.5194/soil-5-91-2019.

Cooper M, Boschi RS, Silva VBD, Silva LFSD (2016) Software for micromorphometric characterization of soil pores obtained from 2-D image analysis. *Scientia Agricola*, 73(4), 388–393. https://doi.org/10.1590/0103-9016-2015-0053.

Crawford JW, Deacon L, Grinev D, Harris JA, Ritz K, Singh BK, Young I (2012) Microbial diversity affects self-organization of the soil–microbe system with consequences for function. *Journal of the Royal Society Interface*, 9(71), 1302–1310. https://doi.org/10.1098/rsif.2011.0679.

De Deyn GB, Cornelissen JHC, Bardgett RD (2008) Plant functional traits and soil carbon sequestration in contrasting biomes. *Ecology Letters*, 11(5), 516–531. https://doi.org/10.1111/j.1461-0248.2008.01164.x.

de Jonge LW, Moldrup P, Schjønning P (2009) Soil infrastructure, interfaces and translocation processes in inner space ("soil-it-is"): Towards a roadmap. *Hydrology and Earth System Sciences*, 13, 1485–1502. https://doi.org/10.5194/hess-13-1485-2009.

de Souza LC, Fernandes C, Moitinho MR, da Silva Bicalho E, La Scala N (2018) Soil carbon dioxide emission associated with soil porosity after sugarcane field reform. *Mitigation and Adaptation Strategies for Global Change*, 24(1), 113–127. https://doi.org/10.1007/s11027-018-9800-5.

Ebrahimi A, Or D (2015) Hydration and diffusion processes shape microbial community organization and function in model soil aggregates. *Water Resources Research*, 51(12), 9804–9827. https://doi.org/10.1002/2015wr017565.

Eden M, Schjønning P, Moldrup P, De Jonge LW (2011) Compaction and rotovation effects on soil pore characteristics of a loamy sand soil with contrasting organic matter content. *Soil Use and Management*, 27(3), 340–349. https://doi.org/10.1111/j.1475-2743.2011.00344.x.

Elbasiouny H, El-Ramady H, Elbehiry F, Rajput VD, Minkina T, Mandzhieva S (2022) Plant nutrition under climate change and soil carbon sequestration. *Sustainability*, 14(2), 914. https://doi.org/10.3390/su14020914.

Fukumasu J, Jarvis N, Koestel J, Kätterer T, Larsbo M (2022) Relations between soil organic carbon content and the pore size distribution for an arable topsoil with large variations in soil properties. *European Journal of Soil Science*, 73(1). https://doi.org/10.1111/ejss.13212.

Ghosh T, Maity PP, Das TK, Krishnan P, Bhatia A, Bhattacharya P, Sharma DK (2020) Variation of porosity, pore size distribution and soil physical properties under conservation agriculture. *The Indian Journal of Agricultural Sciences*, 90(11), 2051–2058. https://doi.org/10.56093/ijas.v90i11.108558.

Haruna S (2019) Influence of winter wheat on soil thermal properties of a Paleudalf. *International Agrophysics*, 33(3), 389–395. https://doi.org/10.31545/intagr/110850.

Helweg A (1975) Degradation of ^{14}C-maleic hydrazide in soil as influenced by adsorption on activated carbon. *Weed Research*, 15(2), 129–133. https://doi.org/10.1111/j.1365-3180.1975.tb01110.x.

Hnatyshyn M (2021) Economics of soil carbon and its specifics in Ukraine. *Scientific Bulletin of Mukachevo State University Series "Economics"*, 9(4). https://doi.org/10.52566/msu-econ.9(4).2022.9-15.

Jarvis N, Coucheney E, Chenu C, Herrmann A, Keller T, Kätterer T, Meurer K (2020) Modelling dynamic interactions between soil structure and soil organic matter. https://doi.org/10.5194/egusphere-egu2020-3613.

Jha A, Bonetti S, Smith AP, Souza R, Calabrese S (2023) Linking soil structure, hydraulic properties, and organic carbon dynamics: A holistic framework to study the impact of climate change and land management. *Journal of Geophysical Research: Biogeosciences*, 128, e2023JG007389. https://doi.org/10.1029/2023JG007389.

Kaushal S, Sharma N, Singh I, Singh H (2023) Soil carbon sequestration: A step towards sustainability. *International Journal of Plant and Soil Science*, 35(11), 160–171. https://doi.org/10.9734/ijpss/2023/v35i112957.

Kavya SR, Rani B, Banu MRF, Jabin PPN (2023) Carbon sequestration and stabilisation mechanisms in the agricultural soils: A review. *International Journal of Plant and Soil Science*, 35(13), 79–94. https://doi.org/10.9734/ijpss/2023/v35i132991.

Keesstra SD, Bouma J, Wallinga J, Tittonell P, Smith P, Cerdà A, Montanarella L, Quinton J, Pachepsky Y, van der Putten WH, Bardgett RD, Moolenaar S, Mol G, Fresco LO (2016) Forum paper: The significance of soils and soil science towards realization of the UN sustainable development goals (SDGs). *Soil*. https://doi.org/10.5194/soil-2015-88.

Kohler-Milleret R, Le Bayon RC, Chenu C, Gobat JM, Boivin P (2013) Impact of two root systems, earthworms and mycorrhizae on the physical properties of an unstable silt loam Luvisol and plant production. *Plant and Soil*, 370(1–2), 251–265. https://doi.org/10.1007/s11104-013-1621-4.

Kolaric LM, Popovic V, Paunovic J, Zivanovic L, Ikanovic J, Sikora V (2015) Sugar beet yield and quality in the agroecological conditions of Central Banat, Serbia. *Agriculture and Forestry*, 61(4). https://doi.org/10.17707/agricultforest.61.4.03.

Kravchenko AN, Negassa WC, Guber AK, Rivers ML (2015) Protection of soil carbon within macro-aggregates depends on intra-aggregate pore characteristics. *Scientific Reports*, 5(1). https://doi.org/10.1038/srep16261.

Kravchenko A, Guber A (2021) Imaging soil structure to measure soil functions and soil health with X-ray computed micro-tomography. In: *Advances in Measuring Soil Health*, pp. 111–138. https://doi.org/10.19103/as.2020.0079.11.

Liu G, Song L, Gao M, Wang X, Li C, Liu B, Chen W (2019) Ion current rectification in high-salt environment from mesoporous TiO_2 microplug in situ grown at the tip of a micropipette induced by space-confined evaporation. *Analytical Chemistry*, 91(24), 15377–15381. https://doi.org/10.1021/acs.analchem.9b04424.

Lucas M, Nguyen LTT, Guber A, Kravchenko AN (2022) Cover crop influence on pore size distribution and biopore dynamics: Enumerating root and soil faunal effects. *Frontiers in Plant Science*, 13. https://doi.org/10.3389/fpls.2022.928569.

Mangalassery S, Sjögersten S, Sparkes DL, Sturrock CJ, Craigon J, Mooney SJ (2014) To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? *Scientific Reports*, 4(1). https://doi.org/10.1038/srep04586.

Meurer KHE, Chenu C, Coucheney E, Herrmann AM, Keller T, Kätterer T, Nimblad Svensson D, Jarvis N (2020) Modelling dynamic interactions between soil structure and the storage and turnover of soil organic matter. *Biogeosciences*, 17(20), 5025–5042. https://doi.org/10.5194/bg-17-5025-2020.

Milleret R, Le Bayon RC, Lamy F, Gobat JM, Boivin P (2009) Impact of roots, mycorrhizas and earthworms on soil physical properties as assessed by shrinkage analysis. *Journal of Hydrology*, 373(3–4), 499–507. https://doi.org/10.1016/j.jhydrol.2009.05.013.

Negassa WC, Guber AK, Kravchenko AN, Marsh TL, Hildebrandt B, Rivers ML (2015) Properties of soil pore space regulate pathways of plant residue decomposition and community structure of associated bacteria. *PLOS ONE*, 10(4), e0123999. https://doi.org/10.1371/journal.pone.0123999.

Nunan N, Schmidt H, Chenu C, Pouteau V, Raynaud X (2023) Heterogeneity and C dynamics in soil. https://doi.org/10.5194/egusphere-egu23-13193.

Olanrewaju S, Akinro E, Oladipupo O (2014) Fungi colonization of the rhizoplane of okra (*Hibiscus esculentus*) plant. *IOSR Journal of Environmental Science, Toxicology and Food Technology*, 8(2), 18–22. https://doi.org/10.9790/2402-08221822.

Passoni S, Pires LF, Heck R, Rosa JA (2015) Three-dimensional characterization of soil macroporosity by X-ray microtomography. *Revista Brasileira de Ciência do Solo*, 39(2), 448–457. https://doi.org/10.1590/01000683rbcs20140360.

Pausch J, Loeppmann S, Kühnel A, Forbush K, Kuzyakov Y, Cheng W (2016) Rhizosphere priming of barley with and without root hairs. *Soil Biology and Biochemistry*, 100, 74–82. https://doi.org/10.1016/j.soilbio.2016.05.009.

Paz González A, Vidal Vázquez E (2005) Compaction and erosion: Effects on soil ecology and soil quality. In: *Silvopastoralism and Sustainable Land Management*, Proceedings of an International Congress, Lugo, Spain, pp. 223–230. https://doi.org/10.1079/9781845930011.0223.

Post W, Kwon K (2005) Soil carbon sequestration and land-use change: Processes and potential. *Carbon Dioxide Information Analysis Center (CDIAC) Datasets*. https://doi.org/10.3334/cdiac/tcm.009.

Rath M, Guseva K, Kaiser C (2023) Effect of pore network architecture on the efficiency of microbial soil organic matter decomposition. https://doi.org/10.5194/egusphere-egu23-12021.

Ruamps LS, Nunan N, Pouteau V, Leloup J, Raynaud X, Roy V, Chenu C (2013) Regulation of soil organic C mineralisation at the pore scale. *FEMS Microbiology Ecology*, 86(1), 26–35. https://doi.org/10.1111/1574-6941.12078.

Sampurno J, Azwar A, Latief FDE, Srigutomo W (2016) Multifractal characterization of pore size distributions of peat soil. *Journal of Mathematical and Fundamental Sciences*, 48(2), 106–114. https://doi.org/10.5614/j.math.fund.sci.2016.48.2.2.

Santos IR, Maher DT, Larkin R, Webb JR, Sanders CJ (2019) Carbon outwelling and outgassing vs. burial in an estuarine tidal creek surrounded by mangrove and saltmarsh wetlands. *Limnology and Oceanography*, 64(3), 996–1013. https://doi.org/10.1002/lno.11090.

Schenck zu Schweinsberg-Mickan M, Jörgensen RG, Müller T (2012) Rhizodeposition: Its contribution to microbial growth and carbon and nitrogen turnover within the rhizosphere. *Journal of Plant Nutrition and Soil Science*, 175(5), 750–760. https://doi.org/10.1002/jpln.201100300.

Schlüter S, Vogel HJ (2016) Analysis of soil structure turnover with garnet particles and X-ray microtomography. *PLOS ONE*, 11(7), e0159948. https://doi.org/10.1371/journal.pone.0159948.

Shobha Rathod BG, Somasundaram E (2017) Effect of organic rice to weed management practices on yield parameters and microbial population grown under lowland condition. *International Journal of Current Microbiology and Applied Sciences*, 6(7), 2154–2162. https://doi.org/10.20546/ijcmas.2017.607.314.

Šimanský V, Kováčik P (2014) Carbon sequestration and its dynamics in water-stable aggregates. *Agriculture (Pol'nohospodárstvo)*, 60(1), 1–9. https://doi.org/10.2478/agri-2014-0001.

Six J, Conant RT, Paul EA, Paustian K (2004) Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, 241(2), 155–176. https://doi.org/10.1023/A:1016125726789.

Smith AP, Bond-Lamberty B, Benscoter BW, Tfaily MM, Hinkle CR, Liu C, Bailey VL (2017) Shifts in pore connectivity from precipitation versus groundwater rewetting increases soil carbon loss after drought. *Nature Communications*, 8(1). https://doi.org/10.1038/s41467-017-01320-x.

Steffens M, Rogge DM, Mueller CW, Höschen C, Lugmeier J, Kölbl A, Kögel-Knabner I (2017) Identification of distinct functional microstructural domains controlling C storage in soil. *Environmental Science and Technology*, 51(21), 12182–12189. https://doi.org/10.1021/acs.est.7b03715.

Tang H, Liu Y, Li X, Muhammad A, Huang G (2019) Carbon sequestration of cropland and paddy soils in China: Potential, driving factors, and mechanisms. *Greenhouse Gases: Science and Technology*, 9(5), 872–885. https://doi.org/10.1002/ghg.1901.

Tas I, Yildirim YE, Gokalp Z (2022) The effect of excessive sodium-containing irrigation waters on soil infiltration rate. *Current Trends in Natural Sciences*, 11(22), 19–28. https://doi.org/10.47068/ctns.2022.v11i22.002.

Totsche KU, Amelung W, Gerzabek MH, Guggenberger G, Klumpp E, Knief C, Kögel-Knabner I (2018) Microaggregates in soils. *Journal of Plant Nutrition and Soil Science*, 181(1), 104–136. https://doi.org/10.1002/jpln.201600451.

Udawatta RP, Gantzer CJ, Anderson SH, Assouline S (2016) Synchrotron microtomographic quantification of geometrical soil pore characteristics affected by compaction. *Soil*, 2, 211–220. https://doi.org/10.5194/soil-2-211-2016.

Umeojiakor AO, Egbuche CT, Ubeakwe RE, Nwaihu EC (2015) Effect of selected tree species on maximizing soil organic carbon sequestration in Imo State, Nigeria. *Agriculture, Forestry and Fisheries*, 4(3), 40. https://doi.org/10.11648/j.aff.s.2015040301.17.

Vashukevich NV, Gusev AS, Varnina VA, Chulkov VA, Fedorov AN (2022) Agroecological monitoring of soils in the educational and experimental farm of the Ural State Agrarian University. *IOP Conference Series: Earth and Environmental Science*, 1043(1), 012020. https://doi.org/10.1088/1755-1315/1043/1/012020.

Wang H, Dai Z, Trettin CC, Krauss KW, Noe GB, Burton AJ, Stagg CL, Ward EJ (2022) Modeling impacts of drought-induced salinity intrusion on carbon dynamics in tidal freshwater forested wetlands. *Ecological Applications*, 32(8). https://doi.org/10.1002/eap.2700.

Wang C, Kuzyakov Y (2024) Soil organic matter priming: The pH effects. *Global Change Biology*, 30(6), e17349. https://doi.org/10.1111/gcb.17349.

Xiao Y, Zhou M, Liu X, Zhang X, Xiao L, Liu J, Cruse RM (2024) Pore connectivity and anisotropy affect carbon mineralization via extracellular enzymes in >2 mm aggregates under conservation tillage of Mollisols. *Soil and Tillage Research*, 106253. https://doi.org/10.1016/j.still.2024.106253.

Yoo G, Nissen TM, Wander MM (2006) Use of physical properties to predict the effects of tillage practices on organic matter dynamics in three Illinois soils. *Journal of Environmental Quality*, 35(4), 1576–1583. https://doi.org/10.2134/jeq2005.0225.

Yu X, Fu Y, Lu S (2016) Characterization of the pore structure and cementing substances of soil aggregates by a combination of synchrotron radiation X-ray micro-computed tomography and scanning electron microscopy. *European Journal of Soil Science*, 68(1), 66–79. https://doi.org/10.1111/ejss.12399.

Zong Y, Yu X, Zhu M, Lu S (2014) Characterizing soil pore structure using nitrogen adsorption, mercury intrusion porosimetry, and synchrotron-radiation-based X-ray computed microtomography techniques. *Journal of Soils and Sediments*, 15(2), 302–312. https://doi.org/10.1007/s11368-014-0995-0.