Review

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

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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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Abstract: Purpose: The study investigates soil pores' impact on carbon dynamics and sequestration processes, examining their physical and chemical characteristics and their mechanisms for carbon sequestration. **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**: 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. **Research Limitations**: This study relies on existing literature and research, which may have limitations and uncertainties. Further research is needed to address these gaps and enhance understanding. **Originality Value**: This research enhances the 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; soil organic carbon; soil pores; microbial activity

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Introduction

Soil is a complex ecosystem essential for life on land, with soil pores affecting carbon sequestration and climate change mitigation. The arrangement and structure of soil pores significantly impact these processes. The intricate relationship between soil pores and the mechanisms involved in C sequestration is an area that is currently being actively researched (Kravechenko et al., 2015; Kravechenko and Guber 2021; Lucas et al., 2022). One hypothesis that has been 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 that are 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. Soil 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. The distribution of microscale carbon varies depending on soil moisture, but accurately assessing this distribution within intact pore spaces remains a challenge. This study investigates soil pores' role in carbon dynamics and carbon sequestration processes. It explores their physical and chemical characteristics, aiming to develop effective strategies for managing soil carbon and mitigating climate change impacts.

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. However, smaller pores can protect OM from decomposition by limiting microbial access. The distribution of pore sizes can also affect the stability of soil C. Pores that are well-connected and allow for water movement can lead to greater C loss through leaching, while isolated pores can trap carbon and increase its stability.

The chemical properties of soil pores can also impact soil C dynamics. Soil pH can affect microbial activity and the decomposition of OM. Acidic soils can inhibit microbial activity and slow down C decomposition, while alkaline soils can increase microbial activity and accelerate C loss. 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.

Soil Pores and Carbon Sequestration

Soil pores serve 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) provide 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, according to analyses (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. The following is a concise summary of these mechanisms:

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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. (Santos et al., 2019; Negassa et al., 2015) The presence of well-connected pores facilitates oxygen (O_2) 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. This process increases the pool of organic carbon and its capacity for long-term storage (Eden et al., 2011).

iv. Carbon Stabilisation and Soil Aggregation: Soil pores contribute to the formation of soil aggregates, which are groupings of bound soil particles. Aggregates provide microenvironments that are conducive to the stabilisation and long-term storage of organic carbon. The porous nature of aggregates promotes the accumulation and retention of carbon in the soil by allowing the passage of water, hydrocarbons, and organic matter (Nunan et al., 2023).

v. Soil pores facilitate the exchange of gases between the soil and the atmosphere. For aerobic microbial processes involved in carbon decomposition and stabilisation, the availability of oxygen in the capillaries is essential (Tang et al., 2019). Proper aeration through well-connected apertures increases carbon sequestration by fostering favourable conditions for soil microorganisms.

Understanding the complex relationship between soil porosity and carbon sequestration is essential for effective soil management and the creation of sustainable land-use practises. Optimising pore characteristics, such as porosity, connectivity, and distribution, can assist in maximising C storage potential in soils, thereby contributing to climate change mitigation and enhanced soil health (Steffens et al., 2017; Haruna, 2019; Ruamps et al., 2013).

How Soil Pores Influence Processes like Soil Organic Matter Decomposition, Microbial Activity, and Root Growth

Soil pores significantly impact processes like SOM decomposition, microbial activity, and root development, with numerous studies investigating their mechanisms. Negassa et al. (2015) found that soil microbial community composition and carbon decomposition processes are influenced by soil pores and air/water flow status. Bouckaert et al. (2013) suggested combining X-ray micro-CT analysis with soil microbial functioning to reveal soil pore structure's influence on SOM decomposition.

The pore structure is a crucial factor in soil functioning, affecting root development and soil faunal activity. The rhizosphere priming effect, influenced by plant roots and rhizosphere activities, regulates global carbon and nitrogen cycles. This interaction is multifaceted, with pore structure being a key determinant of soil functioning (Pausch et al., 2016; Lucas et al., 2022).

The rhizosphere priming effect, influenced by plant roots and rhizosphere activities, plays a crucial role in regulating global carbon and nitrogen cycles (Pausch et al., 2016). The architecture of soil pore networks significantly impacts microbial processes, including the decomposition of soil organic matter (Rath et al., 2023). Rhizodeposition accelerates SOM decomposition and N immobilization, even in plant growth competition (Schenck zu SchweinsbergMickan et al., 2012). Organic matter releases nutrients, enhances soil physicochemical properties, and boosts microbial population (Shobha Rathod & Somasundaram, 2017). Soil with high organic matter content has higher microbial activity, leading to faster decomposition. Root exudates, such as volatile and dissolved exudates, influence microbial growth in the soil surrounding roots, with most activities associated with roots or newly decomposing organic matter (Helweg, 1975; Olanrewaju et al., 2014).

The soil pore space's architecture and uneven substrate distribution significantly impact microbial processes. Rath et al. (2023) found that pore network architecture and properties like average node degree, shortest path length, and clustering coefficient affect microbial OM decomposition efficacy. The structure of soil pores also affects nutrient solubility, microbial activity, and root development. Kolaric et al. (2015) found that soil characteristics affect not only nutrient solubility but also microbial activity and root development. Soil pores significantly impact processes like SOM decomposition, microbial activity, and root development. Further research is needed to fully understand their role in these processes.

The Interactions Between Soil Pore Structure, Water Movement, and Gas Exchange in Relation to Carbon Sequestration

Carbon sequestration is influenced by soil pore structure, water transport, and gas exchange. Studies have explored the relationship between these interactions and carbon sequestration. Santos et al. (2019) estimated soil, pore water, and surface-water C fluxes in an Australian estuarine tidal creek to determine if advective pore-water exchange releases carbon. Chen et al. (2022) found that pore-water exchange and outwelling are crucial components of salt marsh C budgets and should be considered for carbon sequestration and climate change mitigation strategies.

Fukumasu et al. (2022) found a close relationship between SOC content and pore size distribution in arable soil. They discovered a close relationship between the pore size distribution and the SOC content. Charoenjit et al. (2013) estimated C sequestered during soil-water interaction using a hydrological model incorporating alkalinity and topography variations. Imansk and Kováik (2014) found that soil management practices significantly influence carbon sequestration and dynamics in water-stable aggregates. These findings highlight the importance of understanding the relationship between SOC content and pore size distribution in arable soil.

Soil structure and physical properties play a crucial role in C sequestration, particularly at the agricultural level. Colombi et al. (2018) found that soil structure and physical properties are understudied. Yoo et al. (2006) suggested refining functions for calculating the least limiting water range (LLWR) and understanding interactions between management, pore structure, and SOC mineralization could help predict tillage practices' impact on SOC sequestration.

Methods Involved in Quantifying and Characterizing Soil Pores.

Soil pores are crucial for understanding soil functions and health. Quantifying and characterizing these pores is essential for understanding processes like water and gas fluxes, chemical transport, and biota movement. Traditional techniques like mercury intrusion porosimetry (MIP) and nitrogen adsorption isotherms (NAI) can quantify porosity and pore size distribution, but they have limitations in providing information on the three-dimensional (3D) structure of soil pores (Sampurno et al., 2016). Advanced imaging methods have been proposed for pore analysis, but these methods have limitations in providing information on the three-dimensional (3D) structure of soil pores.

For the assessment and characterisation of soil porosity, cutting-edge imaging techniques including synchrotron-radiation-based X-ray computed microtomography (SR-mCT) and 2-D image analysis have been proposed (Zong et al., 2014; Yu et al., 2016; Gantzer et al., 2006). High-resolution 3D pictures of soil pores are produced by X-ray computed microtomography using synchrotron radiation, enabling the visualisation and quantification of soil pore structure (Yu et al., 2016). A software programme has also been suggested for quantifying and characterising soil porosity using information obtained from 2-D photographs (Cooper et al., 2016). An effective tool for measuring the pore properties of soil aggregates and examining interactions between the pore structure and cementing agents within the aggregates is the combination of scanning electron microscopy (SEM)-EDS and SR-mCT techniques (Gantzer et al., 2006).

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,

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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 that shape 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 m 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. 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 the 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 carbon sequestration potential 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; 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.

Conflicts of Interest: There is no conflict of interest to disclose in this study.

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