



Soil Pores: The Hidden Micropedological Indicators of Soil Health

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Soil is often perceived as a solid medium that provides physical support, water and nutrients for plant growth. In reality, soil is a highly heterogeneous and dynamic system composed of mineral particles, organic matter, aggregates, organisms and, importantly, a complex network of interconnected pore spaces. Although these pores are invisible at the field scale, they govern many of the physical, chemical and biological processes that determine soil functioning. The pore system regulates the movement and storage of water, exchange of gases, penetration and proliferation of roots, transport of nutrients and the activity of soil microorganisms. Consequently, changes in pore size, shape, distribution and connectivity can substantially alter the functional capacity of soil. This hidden architecture of soil can be examined through micropedology, which deals with the microscopic study of soil features using thin sections and microscopy. Micropedological investigations provide detailed information on soil structure, mineral composition, pore systems, organic matter distribution and biological activity. Such information is valuable for understanding soil formation, soil functioning, soil quality, water movement, nutrient cycling, root development, carbon sequestration and soil degradation. Among the various micropedological attributes, soil pores represent one of the most informative indicators of soil health, because they integrate several fundamental soil functions within a single structural framework.

Soil Pores: The Functional Space of Soil

The pore system represents the void space between and within soil particles and aggregates. These spaces are occupied by varying proportions of air and water and provide the pathways through which both abiotic and biological processes occur. The functional significance of soil pores largely depends on their size, morphology and connectivity. Smaller pores contribute substantially to water retention, whereas larger pores facilitate rapid water infiltration and drainage, gaseous exchange and root penetration. A well-developed pore network therefore requires an appropriate balance between water-storage and water-transmission pores. Beyond their hydraulic functions, pores also provide physical pathways and habitats for soil organisms. Root channels, earthworm burrows and other biologically created pores can enhance the movement of water and gases while facilitating root exploration of deeper soil layers. Thus, the pore system directly influences soil aeration, water availability, root growth, microbial activity, nutrient transport, aggregate stability and resistance to degradation.

Why Soil Pores Are Important Indicators of Soil Health

Soil health represents the capacity of soil to function as a living system capable of sustaining biological productivity, maintaining environmental quality and supporting ecosystem processes. Because many of these functions depend on soil structure and pore architecture, pore characteristics can provide valuable information about the physical and biological condition of

soil. Healthy soils generally possess a well-connected pore network with a functional distribution of micro-, meso- and macropores. Such a system promotes water infiltration, adequate water retention, aeration, root proliferation and microbial activity. In contrast, degradation of the pore system may result in reduced porosity, poor pore connectivity, compaction, restricted root growth, reduced infiltration and increased surface runoff and erosion. Therefore, soil health cannot be assessed simply by measuring the quantity of pore space. The architecture and functionality of the pore network are equally important.

Reading Soil Structure Through Micropedology

Micropedological analysis provides an opportunity to observe the spatial arrangement of soil constituents at the microscopic scale. Thin sections prepared from undisturbed soil samples can reveal the organization of aggregates, mineral components, organic materials and pore spaces. Several characteristics of the pore system can be assessed through thin-section analysis, including:

- pore-size distribution,
- pore shape and morphology,
- pore abundance,
- pore continuity,
- pore connectivity,
- biopore abundance,
- aggregate arrangement, and
- evidence of compaction and structural development.

These characteristics provide a more detailed interpretation of soil structural quality than bulk measurements alone. One particularly useful approach is two-dimensional porosity analysis, in which digital image analysis is used to quantify the number, size, shape and spatial distribution of pores visible in soil thin sections. Such measurements can provide valuable information about changes in soil microstructure resulting from land use and management.

The Diversity of Soil Pores

Soil pores are not uniform structures. Their morphology reflects their origin and the processes responsible for their formation. Micromorphological analysis commonly identifies packing pores, vughs, channels, planar pores and compound packing pores. Packing pores occur between soil aggregates, whereas vughs are generally irregular or rounded voids. Channels represent elongated continuous pores commonly associated with roots and soil fauna. Planar pores are generally associated with cracks produced by shrinkage and drying. Compound packing pores represent larger interconnected spaces associated with aggregate arrangement. The abundance and spatial distribution of these pore types provide insights into soil development, aggregation, biological activity and structural disturbance. This distinction is important because two soils with similar total porosity may have very different functional behaviour if their pore morphology and connectivity differ.

Pore Size and Connectivity: The Key to Soil Functioning

Pore size is one of the most important characteristics governing soil function. Micropores are particularly important for water retention and storage, whereas macropores facilitate rapid water transmission, drainage, aeration and root penetration. However, pore size alone does not determine functionality. Connectivity is equally important. A soil containing numerous pores that are poorly connected may restrict the movement of water and gases, whereas a smaller number of highly interconnected pores can provide effective pathways through the soil matrix. Pore shape also provides information about the processes involved in pore formation. Rounded pores may occur under compacted conditions, while elongated and irregular pores are frequently associated with biological activity. Consequently, pore number, size, shape and connectivity should ideally be interpreted together when evaluating soil structural quality.

Biopores: When Biological Activity Shapes Soil Structure

Among the various pore types, biopores are particularly important because they represent the physical imprint of biological activity within the soil. Roots, earthworms, termites and other soil organisms modify the soil matrix and create channels and cavities. These biologically generated pores can persist after the organisms have moved or the roots have decomposed, becoming part of the soil's long-term pore network. Biopores can improve water infiltration, drainage and aeration while providing pathways for deeper root growth and movement of soil fauna. They may also create microsites that support microbial communities and contribute to nutrient cycling. The proportion of biopores relative to total porosity can therefore provide an indication of the intensity of biological activity and the degree of structural development within a soil.

Bioporosity as an Indicator of Soil Quality

The relationship between biological activity and soil structure is clearly demonstrated through differences in bioporosity under contrasting land-use systems. A micromorphological study of Luvic Phaeozems in southeast Buenos Aires, Argentina, reported approximately 80% of total pores as biopores in natural reserve soils. Forest plantations also showed approximately 80% biopores, whereas agricultural soils contained only about 40% biological pores. This substantial difference demonstrates the influence of cultivation and soil disturbance on biological pore formation. Higher bioporosity was associated with higher organic matter, lower bulk density, lower penetration resistance, better aggregate stability and greater biological activity. These relationships indicate that bioporosity can serve as an integrated indicator of both the structural and biological condition of soil. The study also highlighted the usefulness of soil thin-section analysis for quantifying bioporosity. Among the available approaches, the point-counting method was identified as a relatively rapid and practical technique for estimating bioporosity compared with manual polygon tracing.

Agricultural Management and the Changing Pore Network

Soil pore architecture is continuously modified by both abiotic and biotic processes. Tillage, machinery traffic, wetting drying cycles and other physical processes can modify the soil structure. At the same time, root growth, earthworm activity and microbial processes continuously create and reorganize pore spaces. Agricultural management can therefore produce substantial changes in pore-size distribution, connectivity and continuity. Intensive tillage and machinery traffic may disrupt aggregates, reduce macroporosity and interrupt continuous biological channels. Conversely, management systems that minimize structural disturbance and maintain biological activity can contribute to the development and preservation of functional pore networks. The response, however, is not necessarily uniform across all soils. Soil texture, aggregation, organic matter status and management history influence how the pore system responds to agricultural practices.

Regenerating Functional Pore Space Through Soil-Health-Oriented Farming

Recent research highlighted an interesting perspective on the regeneration of soil pore architecture. Coarse and medium textured soils were reported to successfully regenerate aspects of their pore structures under pioneer management involving minimum or no tillage combined with extended plant cover, whereas fine-textured soils remained relatively resistant to management induced structural changes. One of the notable responses was the increase in intermediate storage pores ranging from 0.5 to 50 μm . These pores are important for improving plant-available water capacity and therefore have direct implications for crop water availability. Another significant structural change occurred around a pore radius of 0.3–0.5 μm . The research suggests that pores within this range can provide protected habitats for soil bacteria and contribute to organic matter stabilization by physically restricting its turnover. The study further proposed a transition from mechanically dominated pore architecture toward a more biologically influenced structure under pioneer farming systems. In this context, the soil

organic carbon-to-clay (SOC-to-clay) ratio was identified as a dominant driver of structural porosity in improved soils. This relationship highlights the close association between soil organic carbon, aggregation, pore architecture and the development of climate-resilient soils.

Conservation Agriculture and Pore Size Distribution

Conservation agriculture provides another important framework for understanding changes in soil pore architecture. Reduced soil disturbance, residue retention and increased biological activity can influence pore size distribution, pore connectivity and tortuosity. Soil pores are formed and modified by both abiotic and biotic processes. Tillage and machinery traffic can alter the larger structural pores, while roots, earthworms and microorganisms contribute to biologically generated pathways. The conservation agriculture can increase ultramicropores in the 0.1–5 μm range, which are closely associated with higher soil organic carbon. Under zero tillage, the number of pores in the 30–100 μm range was reported to decrease, while pores in the 100–500 μm range increased after four years. These findings demonstrate that changes in soil management can modify not only total porosity but also the distribution of pores among different functional classes.

A Critical Perspective: Porosity Does Not Always Respond in the Same Way

An important aspect emerging from the research presented is that the relationship between tillage and porosity is complex. Pires *et al.* (2019), reported the lowest porosity under zero tillage, while conventional tillage showed the highest porosity and pore connectivity, with reduced tillage showing intermediate values. Similarly, Mangalassery *et al.* (2014) reported porosity values of 13.6% under conventional tillage and 9.6% under zero tillage, with conventional tillage showing 46.9% greater porosity. The average pore size was reported as 0.52 mm^2 under conventional tillage compared with 0.27 mm^2 under zero tillage. Such findings emphasize an important point for soil scientists: a greater quantity of pore space does not automatically represent better soil structural quality. The functional significance of a pore system depends on pore size distribution, connectivity, continuity, stability, biological origin and the specific soil functions being evaluated. Therefore, pore characteristics must always be interpreted within the context of soil type, management system, duration of treatment and measurement methodology.

Soil Pores and Carbon Dynamics

The pore system also plays an important role in soil carbon dynamics. The spatial arrangement and size of pores influence microbial habitats, movement of enzymes and substrates, accessibility of organic matter and the physical protection of carbon within aggregates. Bouckaert *et al.* (2013), as reported positive relationships between larger pore necks particularly 150–250, 250–350 and >350 μm and slow-pool carbon mineralization, whereas very small pore necks below 9.44 μm were associated with reduced microbial activity and enzyme movement. Rabbi *et al.* (2016) reported that micro-aggregates had 54% lower porosity but contained 64% more occluded particulate organic carbon (oPOC). This illustrates the important role of aggregate structure and pore environment in carbon protection. Similarly, Quigley *et al.* (2018) reported that pores between 40 and 90 μm promoted rapid decomposition of newly added carbon, whereas pores smaller than 40 μm enhanced carbon protection and stabilization. These observations demonstrate that the soil pore system is closely connected with the soil carbon cycle and that pore architecture can influence both carbon turnover and carbon stabilization.

From Two Dimensions to Three: X-ray μCT

Traditional micromorphological analysis provides a detailed two-dimensional view of soil structure. However, soil pores are inherently three-dimensional structures, and their functionality depends strongly on their spatial connectivity. This is where X-ray micro-computed tomography (μCT) has become an important modern technique. X-ray μCT is a non-destructive imaging approach that enables visualization and characterization of soil pore architecture in three dimensions.

The technique can be applied to investigate soil hydraulic properties, pore-network geometry, seed soil contact and root architecture. The major advantage of μ CT is that it allows researchers to move beyond measurements of individual pore characteristics and investigate the three-dimensional organization of the entire pore network. This technological development is particularly valuable because a pore that appears disconnected in a two-dimensional section may actually be connected through another plane. Three-dimensional imaging therefore provides a more comprehensive understanding of pore continuity, connectivity and tortuosity.

Integrating Micropedology with Modern Soil Assessment

The development of digital image analysis and X-ray μ CT has considerably expanded the scope of micropedological investigations. Traditional thin-section microscopy remains valuable for identifying soil fabrics, aggregates, pore types and biological features. Digital image analysis allows these features to be quantified more systematically, while μ CT provides a three-dimensional perspective of pore architecture. Together, these techniques provide an increasingly powerful approach for relating soil structure to soil function. Such integration is particularly relevant for evaluating changes associated with conservation agriculture, organic amendments, compaction, land-use change, carbon management and soil restoration.

Toward Pore-Centred Soil Health Management

The study of soil pores provides an important conceptual shift in the assessment of soil health. Rather than considering soil only as a reservoir of nutrients and organic carbon, it can be viewed as a dynamic physical-biological network in which the arrangement of solid particles and pore spaces determines how resources move and how organisms interact. From a soil-management perspective, the objective should not simply be to maximize total porosity. Instead, the emphasis should be on maintaining a functionally balanced pore system containing appropriate proportions of storage and transmission pores with adequate connectivity. Practices that maintain soil cover, reduce unnecessary structural disturbance, promote root activity and enhance organic matter inputs can contribute to the development of biologically active and structurally stable pore networks. This is particularly important under changing climatic conditions, where efficient water infiltration, water storage, aeration and root exploration can contribute to the resilience of agricultural soils.

The Future: Soil Health Written in Microscopic Architecture

The future of soil-health assessment is likely to involve increasing integration of conventional soil physical measurements with micromorphological and advanced imaging techniques. Measurements such as bulk density, aggregate stability, infiltration and water retention provide valuable information at the field scale. Micropedology complements these measurements by explaining why those functional differences occur at the structural level. The pore system provides a link between soil structure and several critical processes—including water movement, aeration, root development, microbial activity, nutrient transport and carbon dynamics. Therefore, understanding soil pores is not merely an exercise in describing microscopic morphology. It is a means of understanding the mechanisms through which soil performs its ecological and agricultural functions.

Conclusion

Among the diverse micropedological features of soil, soil pores represent a powerful and integrative indicator of soil health. Their size, shape, distribution, connectivity and biological origin influence the movement of water and gases, root development, microbial activity, nutrient cycling and carbon dynamics. Biopores provide evidence of biological activity and structural development, while pore-size distribution and connectivity provide insights into the hydraulic and aeration characteristics of soil. Modern approaches such as digital image analysis and X-ray μ CT are further expanding our ability to characterize this hidden architecture at increasingly precise spatial scales. At the same time, research demonstrates that pore responses to agricultural management are complex and strongly dependent on soil type, management history and the specific pore characteristics being measured. Ultimately, soil health is not

determined only by what the soil contains, but also by how those components are organized in space. The invisible network of pores beneath our feet is therefore much more than empty space. It is the functional architecture through which soil stores water, exchanges gases, supports roots, shelters microorganisms and regulates carbon dynamics. To understand the health of soil, looking not only at the soil itself but also at the spaces within it.

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