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Soil Structure and Water Dynamics: Empirical Insights from Agroecological and Conventional Farming

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ABSTRACT: Agroecological farming systems (AFS) are increasingly recognized for their potential to enhance soil health and sustainability. This study compares AFS with conventional farming systems (CFS) by assessing key soil physical indicators: infiltration rate, bulk density, total porosity, and aggregate stability. Field measurements were conducted using standard methods, including the double ring infiltrometer, core sampling, and wet sieving techniques. Soil samples were collected from the 0–20 cm depth across replicated plots ($n \geq 3$ per system) in comparable agroecosystems. Results revealed that AFS significantly improved infiltration rates (43.8–47.1 mm/hour) compared to CFS (21.5–23.2 mm/hour), indicating enhanced water absorption and reduced runoff. Bulk density was lower in AFS (1.08–1.12 g/cm³), contributing to higher total porosity (57.7%–59.1%) relative to CFS (1.31–1.35 g/cm³; 48.9%–50.6% porosity). Aggregate stability was also superior under AFS (82.3%–84.7%) versus CFS (59.8%–62.5%), suggesting stronger soil structure and erosion resistance. These differences are attributed to agroecological practices such as reduced tillage, organic amendments, and minimized soil disturbance. The findings underscore the role of AFS in enhancing soil hydrological function and structural integrity, with implications for improving crop resilience, reducing erosion, and supporting climate-smart agriculture. Promoting agroecological approaches can contribute to long-term environmental stewardship and sustainable land use, especially in regions facing soil degradation and water scarcity.

Keywords: Agroecological Farming, Soil Hydrology, Aggregate Stability, Infiltration Rate, Bulk Density, Sustainable Agriculture.

INTRODUCTION

Soil hydrology and structural stability are central components in achieving agricultural sustainability. These physical soil properties influence not only water retention and aeration but also plant root development, erosion resistance, and overall productivity. A growing body of literature highlights how intensive, conventional farming practices dominated by heavy mechanization and frequent tillage have deteriorated soil functions critical to ecosystem services and food security. This chapter discusses the role of farming systems in shaping the physical condition of soil, comparing the implications of conventional and agroecological approaches in tropical and subtropical agricultural contexts.

Conventional farming systems (CFS) are characterized by repeated tillage operations and reliance on chemical inputs to enhance crop yields. However, such practices have substantial downsides for soil physical health. Frequent mechanical disturbance results in compaction, which increases bulk density and decreases total porosity. This impairs the soil's ability to hold and transmit water, leading to reduced infiltration capacity, increased surface runoff, and heightened erosion risk (Bogunović et al., 2023; Zhang et al., 2024). Furthermore, Vásquez-Velásquez (2016) observed how repeated agricultural traffic alters the moisture retention properties of the soil, limiting its buffering capacity during climatic stress events such as droughts.

Agroecological farming systems (AFS), in contrast, integrate ecological principles into farm design and management. These systems emphasize reduced tillage, crop rotations, organic amendments, and habitat diversification to promote soil health. A critical advantage of AFS lies in its ability to reverse or mitigate the damage caused by conventional systems. Reduced tillage, for example, minimizes mechanical disturbance, helping to maintain soil aggregates and increase organic matter content. As a result, soils under agroecological management often exhibit higher infiltration rates, improved porosity, and enhanced aggregate stability (Nawaz et al., 2024; Reichert et al., 2016). The formation of a stable, aerated, and porous structure supports better microbial activity and fosters greater resilience to erosion (Cooper et al., 2016).

Soil compaction, commonly associated with mechanized agriculture, has been widely studied due to its influence on water retention dynamics. Shaheb et al. (2021) noted that compacted soils resist water infiltration and fail to retain adequate moisture in the root zone. In conventional systems, this results in limited access to water during critical growth periods, ultimately reducing yields. Conversely, no-tillage systems preserve the natural pore network and allow for deeper percolation, improving the soil's capacity to store water (Ngo-Cong et al., 2021). Ramadhan & Alfaris (2023) emphasized that strategic management practices to avoid compaction directly enhance soil moisture content and, by extension, crop resilience.

The structure and porosity of soil are deeply affected by the tillage regime applied. In a comparative study, Piccoli et al. (2019) found that reduced tillage increased micropore space and carbon sequestration in just five years. Moreover, residue retention and minimized disturbance intensified biological activity, facilitating aggregate formation and moisture regulation (Reichert et al., 2016). These findings are echoed by Fouladidorhani et al. (2023), who highlighted the positive correlation between conservation tillage and improved water infiltration during erosive rainfall events.

Organic amendments further strengthen soil physical health. Long-term applications of compost, manure, or biochar lead to marked improvements in porosity, water retention, and aggregate stability (Wong et al., 2022). Organic inputs not only serve as a nutrient source but also stimulate microbial activity essential to soil structure regeneration (Wilson et al., 2020). Bogunović et al. (2023) documented that such amendments mitigate compaction and enhance soil water dynamics under high-intensity agricultural use. Furthermore, Beutler et al. (2021) emphasized how these interventions prevent structural decline and maintain long-term fertility.

Symptoms of soil degradation in conventional systems are well documented. These include crust formation, poor infiltration, low organic matter, and a weakened soil matrix prone to erosion (Bogunović et al., 2023; Zhang et al., 2024). Reduced microbial biodiversity, a hallmark of degraded soils, further impairs biogeochemical cycles and reduces the regenerative capacity of the land. According to Quinton et al. (2024), visible degradation symptoms are reliable indicators for transitioning to more sustainable land management practices. AFS, with its emphasis on ecological integration, offers a pathway to restore such soils through a combination of biological enhancement, physical protection, and reduced disturbance.

This study aims to evaluate the impact of agroecological and conventional farming practices on soil hydrology and structure by comparing bulk density, total porosity, infiltration rate, and aggregate stability in replicated field plots. By focusing on physical indicators of soil health, it addresses a critical research gap concerning the empirical performance of farming systems in relation to water and erosion management. The findings are expected to substantiate the scientific basis for scaling up agroecological practices, particularly in erosion-prone and water-deficient environments.

METHOD

Understanding soil's hydraulic and structural properties is essential for designing sustainable agricultural systems. This section outlines the study's design and the methodologies employed to assess infiltration rate, aggregate stability, bulk density, and total porosity, integrating standard protocols validated in the scientific literature.

Study Design

This study employed a comparative field-based design to evaluate agroecological (AFS) and conventional farming systems (CFS). The experimental units consisted of agricultural plots ranging from 0.25 to 1 ha, with a minimum of three replicates per system. These plots were selected to ensure consistency in soil type and climate, thereby isolating the effects of farming practices on soil physical properties.

Soil Sampling Protocol

Soil samples were extracted from the upper 0–20 cm layer using undisturbed core samplers. This depth was chosen to capture the soil zone most influenced by agricultural practices. For select indicators, additional optional sampling at 20–40 cm was conducted. The samples were immediately processed or stored under appropriate conditions to preserve their physical characteristics for laboratory analysis.

Measurement of Soil Infiltration Rate

The infiltration rate was determined using the double ring infiltrometer, a widely recognized and accurate field instrument for measuring vertical water movement into the soil. This device employs two concentric rings, with the inner ring quantifying infiltration and the outer ring acting as a buffer to limit horizontal water movement (Xu et al., 2024). Readings were taken at regular intervals until a steady infiltration rate was established. The method is known for minimizing lateral flow and providing repeatable estimates of saturated hydraulic conductivity (Al-Jburi et al., 2024).

Assessment of Aggregate Stability

Aggregate stability was evaluated using the wet-sieving method, where soil aggregates are immersed in water and subjected to mechanical agitation to simulate rainfall impact. The proportion of aggregates remaining intact after sieving is recorded, offering a quantitative estimate of structural resilience (Xu et al., 2024). Supplementary methods, such as rain simulation, were used to assess aggregate disintegration under precipitation conditions (Purwakusuma et al., 2023).

Measurement of Bulk Density and Porosity

Bulk density was measured through the core method, involving extraction of undisturbed soil cores, oven-drying, and weighing to calculate the dry mass per unit volume. Total porosity was calculated from bulk density values using the standard equation:

$$TP\ (\%) = 100 \times (1 - BD / PD),$$

where TP is total porosity, BD is the measured bulk density, and PD is the assumed particle density (2.65 g/cm^3 for mineral soils). The particle density assumption was validated through the pycnometric method in selected samples (Das & Ghosh, 2017).

Accuracy and Limitations

While the double ring infiltrometer is effective for field conditions, infiltration readings may vary based on soil moisture, compaction, and organic matter content. Calibration with tension infiltrometers may be necessary in extreme conditions (Girei et al., 2019). Similarly, porosity estimations are sensitive to accurate bulk density values and require careful core sampling.

This integrated methodology ensures a robust and comprehensive evaluation of the effects of farming systems on soil hydrology and structure.

RESULT AND DISCUSSION

This section presents the empirical findings on soil hydrology and structure in agroecological (AFS) and conventional (CFS) systems, using field-measured indicators: infiltration rate, bulk density, porosity, and aggregate stability. Each subsection interprets the data in relation to prior research.

Infiltration Rate

The AFS plots demonstrated markedly higher infiltration rates than CFS plots. The double ring infiltrometer recorded rates between 43.8 and 47.1 mm/hour in AFS, versus 21.5 to 23.2 mm/hour in CFS. These differences reflect the enhanced permeability of agroecological soils due to reduced compaction and improved structure (Blanco-Canqui & Ruis, 2020). Infiltration rates in conventional systems align with previous studies showing reduced rates of 2–10 mm/hour due to machinery-induced compaction and limited soil aggregation. Organic matter further contributes to higher permeability in AFS, promoting pore connectivity and water movement (Wang et al., 2022).

Reduced infiltration in CFS leads to surface runoff, diminished water availability, and erosion (Sun et al., 2020). Land management intensity directly impacts these patterns; frequent tillage in CFS inhibits infiltration, whereas conservation practices in AFS improve infiltration up to 50% more.

Table 1: Soil Infiltration Rate (mm/hour)

Plot ID	Farming System	Infiltration Rate (mm/hour)
A1	AFS	45.2
A2	AFS	43.8
A3	AFS	47.1
C1	CFS	21.5
C2	CFS	23.2
C3	CFS	22.8

Bulk Density & Porosity

AFS soils exhibited lower bulk densities (1.08–1.12 g/cm³) and higher total porosity (57.7%–59.1%), while CFS soils had higher bulk densities (1.31–1.35 g/cm³) and lower porosity (48.9%–50.6%). These results align with findings that agroecological practices reduce compaction, maintaining favorable bulk densities for root development and microbial activity (Reichert et al., 2016).

Optimal bulk density for plant growth ranges between 1.1 and 1.4 g/cm³ in sandy soils and 0.9 to 1.3 g/cm³ in clay soils. Porosity facilitates gas exchange and water flow, both critical to root zone dynamics. Enhanced porosity under AFS is attributed to reduced tillage and organic input, which foster aggregate formation and pore space development.

Table 2: Bulk Density and Porosity

Plot ID	Farming System	Bulk Density (g/cm³)	Total Porosity (%)
A1	AFS	1.12	57.7
A2	AFS	1.10	58.5
A3	AFS	1.08	59.1
C1	CFS	1.32	50.2
C2	CFS	1.35	48.9
C3	CFS	1.31	50.6

Aggregate Stability

AFS plots achieved aggregate stability between 82.3% and 84.7%, compared to 59.8%–62.5% in CFS. Organic matter and microbial activity are key drivers of this difference. Stable aggregates are sustained by microbial byproducts such as glomalin and polysaccharides (Yang et al., 2024). CFS plots, with reduced biological input and more disturbance, showed lower resilience to disintegration.

Soils under no-till and organic management typically exhibit aggregate stability above 60% (Blanco-Canqui & Ruis, 2020). Disintegration from erosion is strongly linked to aggregate collapse, decreasing water retention and increasing nutrient loss (Yang et al., 2024). The higher stability in AFS demonstrates its capacity to maintain soil health and prevent structural breakdown during heavy rainfall (Sun et al., 2020).

Table 3: Aggregate Stability (%)

Plot ID	Farming System	Aggregate Stability (%)
A1	AFS	82.3
A2	AFS	84.7
A3	AFS	83.1
C1	CFS	61.4
C2	CFS	59.8
C3	CFS	62.5

These findings empirically support the superiority of agroecological systems in improving soil hydrological function and structural resilience.

The findings of this study provide compelling evidence of the advantages agroecological farming systems (AFS) offer in enhancing soil hydrological and structural properties compared to conventional farming systems (CFS). This discussion explores the mechanisms underlying these improvements, their implications for crop resilience, insights from long-term comparative studies, and the broader ecological benefits.

Agroecological systems demonstrate better soil hydrology primarily through practices that enhance soil structure and organic matter content. Organic inputs such as compost and green manure improve porosity and aggregate formation, increasing infiltration rates and moisture retention capacity (Francioli et al., 2016; Janke et al., 2024). Furthermore, these systems support microbial diversity, which plays a critical role in stabilizing soil aggregates through biological exudates that bind particles together (Kundel et al., 2020). Reduced tillage in AFS preserves existing soil architecture, maintaining water pathways and further enhancing infiltration (Reichert et al., 2016). These mechanisms explain the higher infiltration and improved hydrological function observed in the AFS plots.

Improved physical soil conditions also support greater crop resilience. Enhanced porosity and hydraulic conductivity facilitate water movement and aeration in the root zone, allowing for more effective nutrient uptake and root development (Kaur, 2023). These characteristics are essential during stress periods such as drought, when plants rely on deeper soil moisture and efficient gas exchange. Organic matter enriches nutrient-holding capacity and fosters microbial activity, thereby supporting root vigor and increasing the availability of essential elements during critical growth stages (Fadiji et al., 2020; Nayana et al., 2023).

Insights from long-term studies further reinforce these findings. Research comparing organic and conventional systems over extended periods consistently reports higher organic carbon content, reduced compaction, and increased aggregate stability in AFS (Chies et al., 2022, p. 20). Agroecological systems also exhibit greater microbial diversity, which contributes to sustained improvements in soil fertility and structure (Kundel et al., 2020; Reichert et al., 2016). By contrast, CFS typically show a decline in soil quality due to repeated tillage and chemical inputs, often resulting in decreased organic matter and heightened susceptibility to erosion (Yzquierdo et al., 2023).

Beyond productivity, improved soil structure in AFS delivers substantial ecological benefits. Healthy, structured soils provide habitats for diverse soil organisms, supporting essential ecosystem services such as nutrient cycling and pest suppression (Francioli et al., 2016). Well-structured soils reduce surface runoff and prevent sedimentation in nearby water bodies, helping to maintain aquatic ecosystem health (Yageta et al., 2019). Additionally, stable aggregates contribute to carbon sequestration, thereby aiding in climate change mitigation through long-term storage of organic carbon (Shapkota & Kafle, 2021).

Altogether, these findings highlight that agroecological farming not only improves immediate soil function but also fosters resilience and sustainability across environmental scales. The synergy between structural integrity, biological activity, and hydrological function underpins a holistic model for soil health management one that is vital for food security and ecological stewardship in the face of global change.

CONCLUSION

This study provides clear evidence that agroecological farming systems significantly enhance soil hydrological and structural properties compared to conventional systems. Across three key indicators infiltration rate, bulk density and porosity, and aggregate stability AFS consistently outperformed CFS. These improvements are attributed to practices such as reduced tillage, organic amendments, and minimal soil disturbance, which collectively promote soil integrity and water functionality.

Higher infiltration rates observed in AFS suggest a more effective water absorption capacity, reducing surface runoff and improving moisture availability. The lower bulk density and higher porosity reflect better soil aeration and root penetration, crucial for plant health and nutrient uptake. Enhanced aggregate stability in AFS further indicates stronger resistance to erosion and greater structural resilience.

Beyond physical advantages, the benefits of agroecological practices extend to ecological and agronomic domains. These include improved microbial activity, increased carbon sequestration, better nutrient cycling, and enhanced biodiversity. Collectively, these outcomes support greater resilience of farming systems under climatic stress and contribute to long-term environmental sustainability.

The study's main contribution lies in empirically validating the superior performance of agroecological systems in supporting soil health. It underscores the importance of adopting sustainable soil management practices not only for yield enhancement but also for broader ecological integrity. Future research should explore the integration of agroecological practices with region-specific innovations to optimize soil-water-plant interactions in diverse agroecosystems.

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