



Soil Texture and Structure Dynamics under Continuous Monoculture Cropping Systems: A Comprehensive Analysis of Long-term Agricultural Impacts

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Abstract

Continuous monoculture cropping systems have become increasingly prevalent in modern agriculture, yet their long-term effects on soil physical properties remain inadequately understood. This study examines the dynamics of soil texture and structure under various monoculture systems over a 15-year period across multiple agricultural regions. We analyzed soil samples from continuous corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L.) cropping systems, comparing them with diversified rotation systems and natural grassland controls. Results indicate significant alterations in soil structure parameters, including bulk density increases of 12-18% in monoculture systems compared to rotational cropping. Aggregate stability decreased by 23-31% under continuous monoculture, with corn showing the most pronounced deterioration. Clay particle migration was observed in all monoculture systems, leading to subsurface clay accumulation and reduced porosity in the 15-30 cm depth interval. Soil organic matter content declined by 15-22% in monoculture systems, directly correlating with structural degradation. These findings suggest that continuous monoculture practices fundamentally alter soil physical architecture, potentially compromising long-term agricultural sustainability and ecosystem services.

Keywords: monoculture, soil structure, aggregate stability, bulk density, clay migration, soil degradation, agricultural sustainability

1. Introduction

Soil texture and structure represent fundamental physical properties that govern agricultural productivity, water infiltration, root penetration, and overall ecosystem functioning ^[1]. The increasing adoption of continuous monoculture cropping systems worldwide has raised significant concerns regarding their impact on soil physical properties and long-term sustainability ^[2]. Modern agricultural practices, driven by economic efficiency and mechanization requirements, have led to simplified cropping systems that may compromise soil health through reduced biological diversity and altered physical-chemical processes ^[3].

Soil texture, defined as the relative proportion of sand, silt, and clay particles, provides the foundation for soil physical behavior ^[4]. While texture remains relatively stable over short time periods, long-term agricultural practices can influence particle size distribution through selective erosion, clay translocation, and aggregate formation processes ^[5]. Soil structure, conversely, represents the arrangement of soil particles into aggregates and pore spaces, exhibiting greater sensitivity to management practices and serving as a critical indicator of soil health ^[6].

Continuous monoculture systems differ fundamentally from natural ecosystems and diversified agricultural systems in their impact on soil biological communities, root architecture patterns, and organic matter inputs ^[7]. These differences cascade through soil physical processes, potentially altering aggregate formation, pore size distribution, and hydraulic properties ^[8]. Previous research has documented various effects of monoculture systems on soil properties, including reduced microbial diversity ^[9], altered nutrient cycling ^[10], and increased susceptibility to erosion ^[11].

The mechanistic understanding of how continuous monoculture affects soil physical properties remains incomplete, particularly regarding long-term structural changes and their implications for agricultural sustainability^[12]. Recent studies have highlighted the role of root exudates, mycorrhizal networks, and biological aggregation processes in maintaining soil structure^[13], suggesting that monoculture systems may disrupt these natural processes through reduced plant diversity and altered rhizosphere dynamics^[14]. Furthermore, the interaction between different crop types and soil physical properties varies considerably, with root architecture, biomass production, and residue quality influencing structural development differently across species^[15]. Understanding these crop-specific effects becomes crucial for developing sustainable management strategies that minimize soil degradation while maintaining productive capacity^[16].

This study addresses critical knowledge gaps by examining long-term changes in soil texture and structure under continuous monoculture systems compared to diversified rotations and natural controls. Our objectives were to: (1) quantify changes in soil physical properties under different monoculture systems over a 15-year period, (2) identify crop-specific effects on soil structural parameters, (3) assess the relationship between soil biological activity and structural stability, and (4) evaluate implications for long-term agricultural sustainability.

2. Materials and Methods

2.1 Study Sites and Experimental Design

The study was conducted across four agricultural research stations in the Midwestern United States, representing diverse soil types and climatic conditions. Sites were selected to encompass major soil orders including Mollisols, Alfisols, and Inceptisols, with clay content ranging from 18% to 42%. Long-term experiments were established in 2008, with continuous monitoring through 2023.

Each site employed a randomized complete block design with four replications. Treatment plots measured 20 × 30 meters to accommodate large-scale agricultural equipment and minimize edge effects. Six primary treatments were implemented: (1) continuous corn monoculture, (2) continuous wheat monoculture, (3) continuous soybean monoculture, (4) corn-soybean rotation, (5) corn-wheat-soybean rotation, and (6) natural grassland control.

2.2 Soil Sampling and Laboratory Analysis

Soil samples were collected annually at three depth intervals: 0-15 cm, 15-30 cm, and 30-45 cm. Sampling followed a systematic grid pattern within each plot, with 12 sample points per plot to ensure representative coverage. Undisturbed soil cores were obtained using a hydraulic soil sampler for structural analysis, while disturbed samples were collected for textural and chemical analyses.

Particle size distribution was determined using the hydrometer method following sodium hexametaphosphate dispersion^[17]. Soil structure parameters included bulk density measurement using the core method, aggregate stability determination through wet sieving^[18], and pore size distribution analysis using mercury intrusion porosimetry. Soil organic matter content was quantified through loss-on-ignition at 450°C for 4 hours^[19].

2.3 Biological Activity Assessment

Microbial biomass carbon was determined using the chloroform fumigation-extraction method^[20]. Enzyme activities, including β -glucosidase, phosphatase, and urease, were measured using standard fluorometric assays^[21]. Mycorrhizal colonization was assessed through root sampling and microscopic examination following trypan blue staining^[22].

2.4 Statistical Analysis

Data were analyzed using mixed-effects models with treatment as fixed effects and site, year, and block as random effects. Temporal trends were evaluated using regression analysis, while treatment comparisons employed Tukey's HSD test at $\alpha = 0.05$. Principal component analysis was used to identify relationships among soil physical, chemical, and biological parameters.

3. Results

3.1 Changes in Soil Texture

Long-term monoculture cropping resulted in measurable changes in soil particle size distribution across all study sites (Table 1). Clay content in the surface horizon (0-15 cm) decreased by 8-15% under continuous monoculture systems compared to initial measurements, with corresponding increases in the subsurface layers (15-30 cm). This pattern suggests active clay translocation processes under monoculture management.

Table 1: Changes in soil particle size distribution (%) after 15 years of different cropping systems

Treatment	Sand (0-15 cm)	Silt (0-15 cm)	Clay (0-15 cm)	Clay (15-30 cm)
Continuous Corn	48.2 ± 2.1 ^a	38.4 ± 1.8 ^b	13.4 ± 1.2 ^c	19.8 ± 1.5 ^a
Continuous Wheat	46.8 ± 1.9 ^a	39.8 ± 2.2 ^b	13.4 ± 1.4 ^c	18.9 ± 1.3 ^{ab}
Continuous Soybean	47.5 ± 2.3 ^a	38.9 ± 1.7 ^b	13.6 ± 1.1 ^c	18.2 ± 1.4 ^b
Corn-Soybean Rotation	45.2 ± 1.8 ^b	39.2 ± 1.9 ^b	15.6 ± 1.3 ^b	17.1 ± 1.2 ^c
Diversified Rotation	44.1 ± 1.6 ^b	40.1 ± 2.1 ^a	15.8 ± 1.1 ^b	16.8 ± 1.1 ^c
Grassland Control	43.8 ± 1.4 ^b	41.2 ± 1.8 ^a	17.0 ± 1.2 ^a	16.2 ± 0.9 ^c

Different letters within columns indicate significant differences ($P < 0.05$)

The most pronounced textural changes occurred under continuous corn cultivation, where clay migration was most extensive. Silt content remained relatively stable across treatments, while sand content increased in monoculture systems due to the relative loss of finer particles. These changes were most evident in the surface 15 cm, where intensive tillage and reduced organic matter inputs facilitated particle redistribution.

3.2 Soil Structure Deterioration

Continuous monoculture cropping significantly impacted soil structural properties across all measured parameters (Figure 1). Bulk density increased progressively over the 15-year study period, with monoculture systems showing 12-18% higher values compared to diversified rotations by year 15. The most severe compaction occurred under continuous corn, reaching $1.52 \pm 0.08 \text{ g cm}^{-3}$ compared to $1.28 \pm 0.06 \text{ g cm}^{-3}$

in grassland controls.

Aggregate stability, measured as the percentage of water-stable aggregates >0.25 mm, declined substantially under monoculture management. Continuous corn showed the

greatest reduction (31% decrease), followed by wheat (27% decrease) and soybean (23% decrease). In contrast, diversified rotation systems maintained aggregate stability values within 10% of initial measurements.

Table 2: Soil structural parameters after 15 years of different cropping systems

Treatment	Bulk Density (g cm ⁻³)	Water-Stable Aggregates (%)	Total Porosity (%)	Macroporosity (%)
Continuous Corn	1.52 ± 0.08 ^a	42.3 ± 3.2 ^c	42.6 ± 2.8 ^c	8.2 ± 1.1 ^c
Continuous Wheat	1.48 ± 0.07 ^{ab}	45.8 ± 2.9 ^c	44.1 ± 2.5 ^c	9.1 ± 1.3 ^c
Continuous Soybean	1.45 ± 0.06 ^b	48.2 ± 3.1 ^c	45.3 ± 2.7 ^c	9.8 ± 1.2 ^c
Corn-Soybean Rotation	1.38 ± 0.05 ^c	58.4 ± 2.8 ^b	47.9 ± 2.1 ^b	12.4 ± 1.4 ^b
Diversified Rotation	1.35 ± 0.04 ^c	61.2 ± 2.6 ^b	49.1 ± 1.9 ^b	13.2 ± 1.3 ^b
Grassland Control	1.28 ± 0.06 ^d	68.7 ± 2.4 ^a	51.7 ± 1.8 ^a	15.8 ± 1.1 ^a

Different letters within columns indicate significant differences ($P < 0.05$)

Pore size distribution analysis revealed significant alterations in soil architecture under monoculture systems. Total porosity decreased by 15-20% in monoculture treatments, with macroporosity (pores >50 µm) showing the most dramatic reductions. This change in pore architecture has important implications for water infiltration, gas exchange, and root penetration.

3.3 Organic Matter Dynamics

Soil organic matter content declined substantially under continuous monoculture cropping, with decreases ranging from 15% in soybean systems to 22% in corn systems over the 15-year period (Figure 2). This decline was most pronounced in the surface horizon, where organic matter inputs are typically highest. The relationship between organic matter loss and structural degradation was highly significant ($r = 0.78$, $P < 0.001$), indicating the critical role of organic matter in maintaining soil structure.

3.4 Biological Activity Indicators

Microbial biomass carbon decreased by 25-35% under monoculture systems compared to diversified rotations and grassland controls. Enzyme activities showed similar patterns, with β -glucosidase activity declining by 28-42% in monoculture treatments. Mycorrhizal colonization rates were significantly lower in monoculture systems, particularly under continuous corn (18% colonization vs. 45% in grassland).

4. Discussion

4.1 Mechanisms of Textural Change

The observed changes in soil particle size distribution under continuous monoculture cropping reflect complex processes of clay translocation and selective particle movement²³. The decrease in surface clay content coupled with subsurface accumulation suggests enhanced clay migration through the soil profile, likely facilitated by reduced organic matter content and altered pore structure²⁴. This process is particularly pronounced under continuous corn cultivation, where intensive tillage and high residue removal rates create conditions conducive to clay dispersion and transport²⁵.

The preferential loss of clay particles from surface horizons has significant implications for soil fertility and water retention capacity²⁶. Clay particles serve as important sites for nutrient retention and water storage, and their redistribution may contribute to reduced surface soil quality over time²⁷. Furthermore, the accumulation of clay in subsurface layers can create restrictive layers that impede root penetration and water movement²⁸.

4.2 Structural Degradation Mechanisms

The deterioration of soil structure under continuous monoculture reflects the combined effects of reduced biological activity, altered organic matter inputs, and mechanical disturbance²⁹. The significant increase in bulk density observed across all monoculture systems indicates progressive soil compaction, likely resulting from repeated traffic patterns and reduced soil biological activity³⁰.

The decline in aggregate stability represents a particularly concerning trend, as stable aggregates are essential for maintaining soil porosity, preventing erosion, and facilitating root growth. The relationship between organic matter content and aggregate stability observed in this study confirms the critical role of organic binding agents in soil structure formation. Under monoculture systems, reduced plant diversity limits the variety of root exudates and organic compounds that contribute to aggregate formation and stabilization.

4.3 Crop-Specific Effects

The differential impacts of various monoculture crops on soil physical properties reflect differences in root architecture, biomass production, and residue quality. Continuous corn showed the most severe structural degradation, likely due to its extensive root system that requires high soil porosity and its tendency toward complete residue removal in many management systems. The relatively shallow root system of wheat may contribute to surface compaction, while soybean's nitrogen fixation capability may partially offset structural degradation through enhanced biological activity.

These crop-specific differences have important implications for management strategies, suggesting that the choice of monoculture crop significantly influences the rate and extent of soil degradation. Understanding these differences can inform decisions about crop selection and rotation frequency to minimize negative impacts on soil physical properties.

4.4 Long-term Sustainability Implications

The progressive degradation of soil physical properties under continuous monoculture cropping raises serious concerns about long-term agricultural sustainability. The observed changes in texture and structure are likely to reduce soil's capacity to support plant growth, retain water, and resist erosion. Furthermore, these changes may be partially irreversible over management-relevant timescales, particularly for textural alterations resulting from clay migration.

The relationship between soil physical degradation and biological activity decline creates a positive feedback loop

that may accelerate soil deterioration over time. Reduced biological activity limits the production of organic binding agents necessary for aggregate stability, while structural degradation creates conditions less favorable for soil organisms.

5. Conclusion

This comprehensive 15-year study demonstrates that continuous monoculture cropping systems significantly alter soil texture and structure compared to diversified agricultural systems and natural controls. Key findings include substantial increases in bulk density (12-18%), decreases in aggregate stability (23-31%), and redistribution of clay particles from surface to subsurface horizons. These changes are accompanied by significant reductions in soil organic matter content (15-22%) and biological activity indicators. The magnitude and consistency of these changes across different soil types and climatic conditions suggest that structural degradation is an inherent characteristic of continuous monoculture systems rather than a site-specific phenomenon. The strong relationships observed between organic matter decline, reduced biological activity, and structural deterioration indicate that these processes are interconnected and mutually reinforcing.

Among the monoculture crops examined, continuous corn cultivation resulted in the most severe structural degradation, followed by wheat and soybean systems. However, all monoculture treatments showed significant negative impacts compared to diversified rotation systems, highlighting the importance of crop diversity in maintaining soil physical properties.

These findings have important implications for agricultural sustainability and soil conservation strategies. The progressive nature of soil physical degradation under monoculture systems suggests that intervention through diversified rotations, cover cropping, or other management practices may be necessary to prevent long-term soil deterioration. Future research should focus on developing management strategies that can maintain agricultural productivity while preserving soil physical integrity.

The results of this study emphasize the critical importance of considering soil physical properties in agricultural sustainability assessments and policy development. As global food security concerns drive intensification of agricultural production, understanding and mitigating the long-term impacts of monoculture systems on soil resources becomes increasingly important for maintaining productive agricultural landscapes.

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