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Research Article

Effects of Land Use and Soil Depth on Organic Carbon Fractionation in Tropical Savanna Soils of Gashaka Local Government Area, Taraba State, Nigeria

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ABSTRACT

Understanding how land use and soil depth regulate organic carbon fractionation is critical for improving carbon stabilization strategies in tropical savanna ecosystems. This study evaluated the effects of forestland, grassland, and farmland and two soil depths (0–20 and 20–50 cm) on total organic carbon (TOC), particulate organic carbon (POC), and mineral-associated organic carbon (MOC) in sandy loam soils of northeastern Nigeria. Land use significantly influenced TOC ($p = 0.0004$) and MOC ($p = 0.006$), with grassland recording the highest TOC (1.46%) and MOC (1.04%). In contrast, POC did not differ significantly among land uses ($p = 0.895$). Soil depth exerted stronger control on carbon distribution, with TOC declining from 1.62% at 0–20 cm to 1.21% at 20–50 cm ($p < 0.0001$). POC exhibited pronounced surface stratification (0.46% vs 0.38%), while MOC remained the dominant fraction at both depths, accounting for approximately 69–72% of total SOC. The findings indicate that depth exerts a greater influence on SOC variability than land use, while land use primarily regulates stabilized carbon pools. Mineral-associated fractions govern carbon persistence in these sandy loam savanna soils, highlighting the importance of management strategies that promote organo-mineral interactions for long-term carbon sequestration.

Keywords: Land use; Mineral-associated organic carbon; Particulate organic carbon; soil depth; Soil organic carbon; Tropical savanna

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INTRODUCTION

Soil organic carbon (SOC) is widely recognized as a fundamental determinant of soil productivity, structural stability, and ecosystem resilience, particularly in tropical savanna environments where high temperatures and seasonal moisture variability accelerate organic matter turnover. In such systems, the balance between carbon inputs and microbial decomposition is often delicate, making the mechanisms of carbon stabilization central to both soil sustainability and climate regulation. Beyond its agronomic importance, SOC constitutes one of the largest terrestrial carbon pools, and small changes in its storage can significantly influence atmospheric CO_2 concentrations (Lal, 2018; Paustian *et al*., 2019). Contemporary soil science increasingly emphasizes that total SOC alone provides limited insight into soil functioning. Instead, fractionation approaches that distinguish between functionally distinct carbon pools offer a more mechanistic understanding of carbon dynamics. SOC is commonly partitioned into particulate organic carbon (POC) and mineral-associated organic carbon (MOC), representing labile and relatively stable pools, respectively. POC consists mainly of partially decomposed plant residues and organic debris that are weakly protected within macro aggregates and exhibit rapid turnover rates. This fraction is highly sensitive to management disturbances and serves as an early indicator of soil quality change (Lavallee *et al*., 2020; Cotrufo *et al*., 2019). In contrast, MOC is stabilized through physical and chemical interactions with silt and clay particles via sorption, complication, and micro aggregate formation, resulting in longer residence times and greater persistence (Sokol *et al*., 2019; Liang *et al*., 2019). Increasing evidence suggests that mineral-associated fractions account for the majority of long-term carbon storage in many soils, including tropical systems. Land-use change represents one of the most significant anthropogenic drivers of SOC redistribution globally. Conversion of forestland to cultivated farmland or managed grassland alters litter inputs, below ground biomass allocation, soil disturbance regimes, and aggregate turnover processes. These changes influence not only total carbon stocks but also the relative dominance of labile versus stabilized fractions. Forest ecosystems typically promote surface carbon accumulation through continuous litter deposition and minimal mechanical disturbance. Farmland systems, particularly under conventional tillage, often exhibit reductions in POC due to aggregate disruption and enhanced decomposition (Six *et al*., 2018; Haddaway *et al*., 2017). Grassland systems may promote substantial below ground carbon inputs through dense root networks, potentially enhancing MOC formation through root-derived carbon–mineral interactions (Rocci *et al*., 2021). However, the magnitude and direction of these responses vary across soil types and climatic regimes, particularly within tropical savannas where decomposition rates are high.

Soil depth further regulates carbon fractionation patterns. Surface horizons typically contain higher concentrations of labile carbon due to direct organic inputs from litter and root exudes. In contrast, subsurface layers are often characterized by reduced total carbon content but a greater relative contribution of mineral-associated fractions, reflecting long-term stabilization mechanisms (Rumpel & Kögel-Knabner, 2018; Poeplau *et al*., 2018). Vertical stratification ratios have therefore been used as indicators of management impacts and soil structural integrity. Nevertheless, depth-dependent carbon responses are strongly influenced by land use. For example, tillage may homogenize carbon distribution and reduce stratification, whereas forest and undisturbed grassland systems often maintain pronounced surface enrichment. Understanding how land use and soil depth interact to influence carbon fractionation is therefore essential for elucidating stabilization pathways.

Although substantial progress has been made in temperate regions, empirical evidence from West African savanna ecosystems remains comparatively limited. Many studies conducted in Nigerian savanna landscapes have focused primarily on total organic carbon or general soil fertility indicators without explicitly distinguishing between particulate and mineral-associated fractions. Moreover, few investigations adopt factorial experimental designs that explicitly test the interaction between land use and soil depth. Such interaction effects are critical, as they reveal whether land-use impacts are consistent throughout the soil profile or concentrated within specific horizons.

The tropical savanna soils of northeastern Nigeria, characterized largely by sandy loam textures and moderate mineral activity, present a unique context for examining carbon stabilization mechanisms. Sandy-dominated soils typically exhibit lower inherent physical protection of organic matter compared to finer-textured soils, making organo-mineral associations particularly important for long-term carbon persistence. Evaluating how contrasting land uses influence both labile and stabilized fractions across soil depths can therefore provide mechanistic insight into carbon resilience under changing land management regimes.

This study investigates the interactive effects of land use (forestland, grassland, and farmland) and soil depth on organic carbon fractionation in tropical sandy loam soils of Gashaka, northeastern Nigeria. Specifically, the objectives are to: (i) quantify variations in total organic carbon (TOC), particulate organic carbon (POC), and mineral-associated organic carbon (MOC) across land-use systems; (ii) assess depth-dependent distribution patterns of these fractions; and (iii) determine whether significant land use by depth interactions govern carbon stabilization dynamics. By integrating fractionation analysis with factorial statistical evaluation, this study advances understanding of carbon stabilization processes in savanna ecosystems and contributes evidence relevant to sustainable land management and climate mitigation strategies in tropical regions.

MATERIALS AND METHODS

Study Area

The study was conducted in Gashaka Local Government Area, Taraba State, northeastern Nigeria (6°51′–8°00′N and 10°56′–11°57′E) (Figure 1). The area lies within the tropical savanna agro-ecological zone and experiences a distinct wet and dry seasonal climate. Mean annual rainfall ranges between 1,200 and 1,800 mm, occurring predominantly between April and October, while mean annual temperature varies from 24°C to 32°C. Relative humidity is typically higher during the wet season and declines markedly during the dry Harmattan period Cotrufo *et al*., 2019; Lavallee *et al*., 2020).

The dominant soils in the study area are sandy loam in texture, developed over basement complex parent materials. These soils are moderately drained and characterized by relatively low clay content, making organo-mineral interactions particularly important for carbon stabilization. Vegetation varies across land uses and includes natural forest stands, perennial grasses, and cultivated cropland Cotrufo *et al*., 2019; Lavallee *et al*., 2020).

Land Use Types and Experimental Design

Three different land-use systems were selected: Forestland (FL) – minimally disturbed natural vegetation with continuous litter deposition. Grassland (GL) – perennial grass-dominated system with limited mechanical disturbance. Farmland (FA) – cultivated land subjected to periodic tillage and crop residue removal (Figure 2).

A factorial sampling design was adopted to evaluate the interactive effects of land use and soil depth. Within each land-use type, representative sampling locations were established based on uniform topography and management history. Soil samples were collected from two depth intervals: 0–20 cm (surface layer) and 20–50 cm (subsurface layer). A total of 40 soil samples were obtained at each depth within each of the three land-use types. This resulted in 80 samples per land-use system and an overall total of 240 soil samples across the study area.

The design therefore consisted of 3 land uses by 2 depths, enabling statistical evaluation of man and interaction effects.

Soil Sampling Procedure

At each land-use site, multiple composite samples were collected using a stainless-steel auger to minimize contamination. Surface litter was carefully removed prior to sampling. For each depth interval. A total of 40 soil samples were collected at each depth within each of the three land-use types. This resulted in 80 samples per land-use system and an overall total of 240 soil samples across the study area. Soil cores were collected from randomly distributed points within each plot and homogenized to obtain representative composite samples.

Samples were air-dried under laboratory conditions, gently crushed, and passed through a 2 mm sieve prior to analysis. Subsamples for carbon fractionation were further processed according to the requirements of the fractionation procedure.

Determination of Total Organic Carbon (TOC)

Total organic carbon (TOC) was determined using the Walkley–Black wet oxidation procedure as described by **Donald L. Sparks (2016)**. The method involves oxidation of soil organic matter with potassium dichromate ($K_2Cr_2O_7$) in the presence of concentrated sulfuric acid (H_2SO_4), followed by back-titration of the excess dichromate with standardized ferrous ammonium sulfate. This procedure estimates the oxidizable fraction of soil organic carbon and is widely adopted in tropical soil studies due to its analytical reliability and suitability for routine laboratory analysis. Results were expressed as percentage organic carbon (%C) on an oven-dry weight basis.

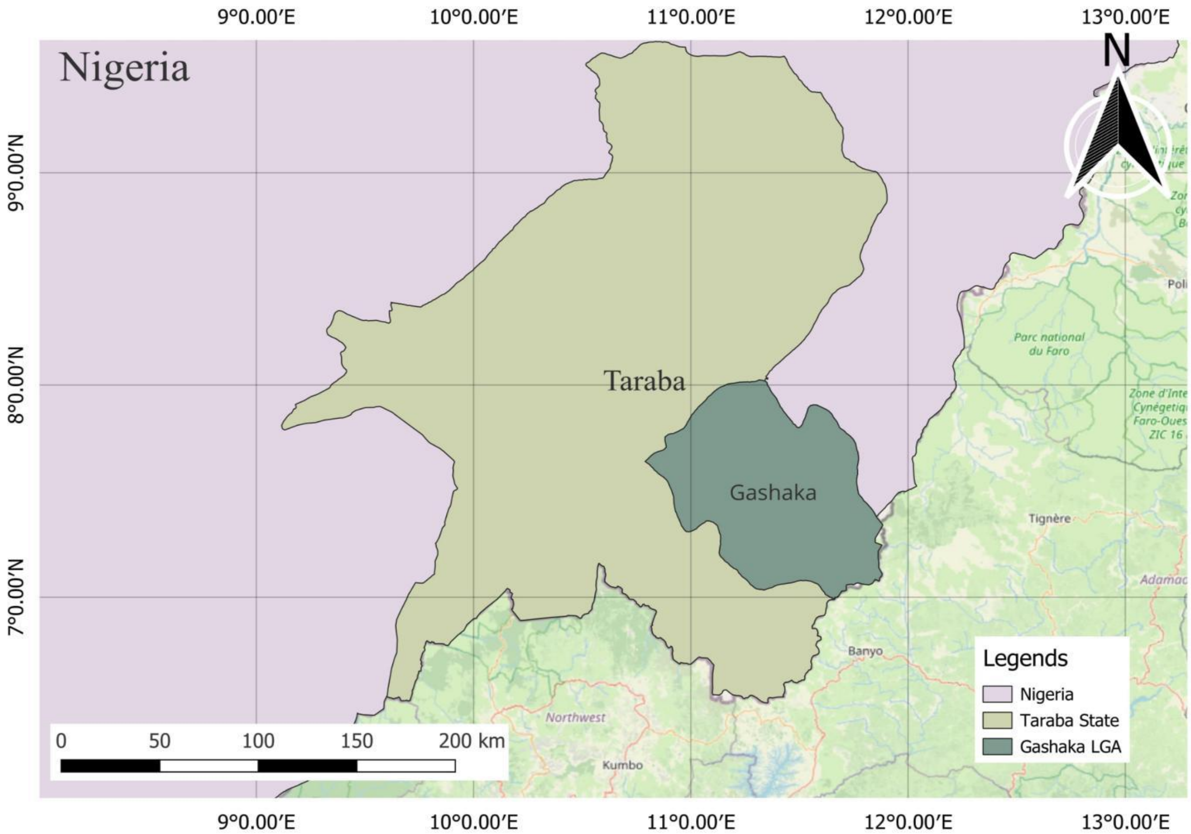

Figure 1: Map of Taraba State Showing Gashaka Local Government Area

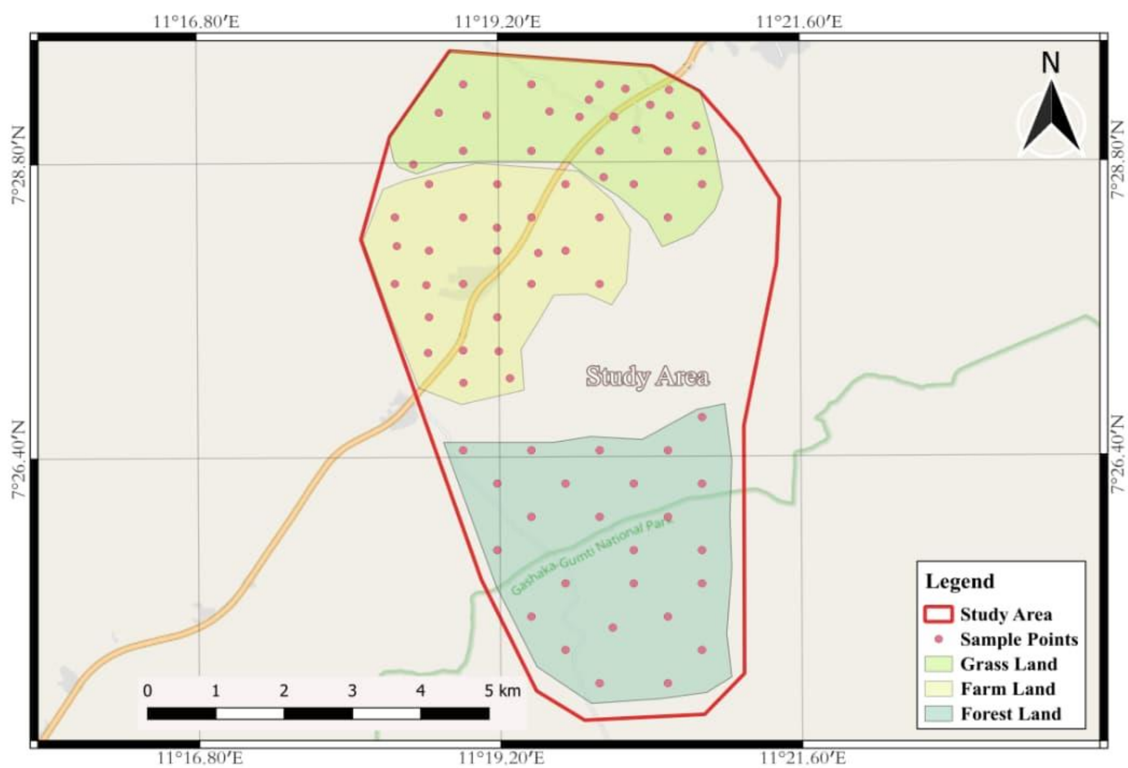

Figure 2: Map of the Study Area Showing Sampling Points

Soil Organic Carbon (SOC)

Soil organic carbon (SOC) was fractionated into particulate organic carbon (POC) and mineral-associated organic carbon (MOC) using a size-based physical fractionation procedure following the protocol described by Six et al. (2018) and further applied in recent tropical soil carbon studies. The method separates labile, coarse particulate organic matter (>53 µm), representing POC, from the finer mineral-associated fraction (<53 µm), representing MOC, through dispersion and wet sieving. This approach enables differentiation between relatively unstable, fast-cycling carbon pools and more stabilized carbon associated with silt and clay particles. The fractionated carbon contents were subsequently quantified and expressed on a dry weight basis.

Particulate organic carbon (POC)

Particulate organic carbon (POC) was isolated using a size-based physical fractionation procedure as described by Six et al. (2018). Briefly, soil samples were dispersed in a sodium hexametaphosphate solution to disrupt soil aggregates, followed by wet sieving through a 53 µm mesh. The material retained on the sieve (>53 µm fraction) was carefully collected, oven-dried, and analyzed for carbon content. This fraction predominantly represents partially decomposed plant residues and labile organic materials associated with macroaggregates, reflecting the relatively active and fast-cycling pool of soil organic carbon.

Mineral-associated organic carbon (MOC)

The fraction passing through the 53 µm sieve (<53 µm fraction) was operationally defined as mineral-associated organic carbon (MOC) following the physical fractionation framework described by Lavallee et al. (2020). Carbon content in this fine fraction was determined and expressed as MOC.MOC= TOC - POC

This fraction represents organic carbon stabilized through organo–mineral interactions with silt and clay particles, as well as protection within microaggregates. Mineral-associated carbon is generally considered the more stable and long-residence-time pool of soil organic matter, particularly in tropical soils where rapid turnover of labile fractions occurs.

Carbon Stratification Ratio

To evaluate vertical carbon distribution, a stratification ratio (SR) was calculated as:

$$SR = = \frac{C0-20}{C20-50}$$

where C0–20C_{0–20}C0–20 represents the carbon concentration at 0–20 cm depth and C20–50C_{20–50}C20–50 represents the carbon concentration at 20–50 cm depth.

The variables C0–20C_{0–20}C0–20 and C20–50C_{20–50}C20–50 represent carbon concentrations in the surface and subsurface depths, respectively. Higher SR values indicate stronger surface enrichment of organic carbon and are commonly associated with reduced soil disturbance, improved aggregation, and enhanced soil quality under conservation or forest land-use systems (Franzluebbers, 2021; Blanco-Canqui, 2020).

Data Analysis

Data were tested for normality and homogeneity of variance prior to analysis. A two-way analysis of variance (ANOVA) was conducted to examine: Main effects of land use (L). Main effects of soil depth (D) and Land use by depth interaction (L × D).

Where significant differences were detected ($p < 0.05$), means were separated using Tukey's Honest Significant Difference (HSD) test.

All statistical analyses were performed using SAS 9.4 statistical software version

Data Interpretation Background

The interpretation of results was guided by current soil carbon stabilization theory, distinguishing between: Labile carbon responsiveness (POC sensitivity to disturbance), Mineral-associated stabilization mechanisms (MOC persistence), and Vertical redistribution under land-use change.

Significant interaction effects were interpreted as evidence that land-use impacts vary with soil depth, indicating mechanistic differences in carbon protection processes across the soil profile.

RESULTS AND DISCUSSION

Land-Use Influence on Soil Chemical Properties and Carbon Fractions

Table 1. Shows soil pH and electrical conductivity differed statistically among land uses ($p < 0.0007$), the magnitude of variation was minimal. Soil pH ranged only from 6.28 in grassland to 6.35 in forestland, indicating moderately acidic conditions across all systems. This narrow range suggests that inherent

soil properties and parent material exert stronger control over soil reaction than current land management practices. Similarly, EC values (0.72–0.82 dS m^{-1}) remained within non-saline limits, implying that land-use conversion has not induced salinity-related chemical shifts in the study area. In contrast, organic carbon fractions responded more distinctly to land-use differences. Total organic carbon (TOC) was significantly higher in grassland (1.46%) compared to forestland (1.38%) and farmland (1.41%). The superiority of grassland is particularly notable because savanna grass systems often promote substantial belowground biomass production. Continuous root turnover and rhizodeposition can enhance microbial processing and facilitate the formation of mineral-associated carbon pools (Cotrufo *et al*., 2019; Lavallee *et al*., 2020).

This interpretation is reinforced by the mineral-associated organic carbon (MOC) values. Grassland recorded the highest MOC concentration (1.04%), significantly exceeding forestland (0.96%) and farmland (0.98%). Since mineral-associated carbon represents the more persistent and stabilized pool of soil organic matter, this finding suggests that grassland in the study area may provide more favorable conditions for long-term carbon stabilization. Interestingly, particulate organic carbon (POC) did not differ significantly among land uses (0.42–0.43%). Because POC typically represents the labile, disturbance-sensitive fraction, one might expect cultivated farmland to exhibit lower values. The absence of significant variation may indicate moderate management intensity, similar residue returns patterns, or rapid turnover that minimizes detectable differences at the time of sampling.

Across all land uses, MOC accounted for approximately 69–71% of total SOC, underscoring the dominance of mineral stabilization mechanisms in these sandy loam soils. In coarse-textured savanna soils, where aggregate protection is often limited, organo-mineral interactions become the principal pathway for carbon persistence.

Table 1: Effects of Land Use on Soil pH, EC and Organic Matter Fraction of the Study area

Soil Depth	San (%)	Silt (%)	Clay (%)	Textural Classes	pH (1:2)	EC (dS/m)	TOC (%)	POC (%)	MOC (%)	OM (%)
Forest Land	68	22	10	Sandy loam	6.35[a]	0.72[a]	1.38[b]	0.42[a]	0.96[b]	2.37[b]
Farm Land	71	19	10	Sandy loam	6.30[a]	0.82[a]	1.41[b]	0.43[a]	0.98[b]	2.42[b]
Grass Land	69	20	11	Sandy loam	6.28[a]	0.77[a]	1.46[a]	0.42[a]	1.04[a]	2.52[a]
P of F					<0.07	<0.07	0.0004	0.895	0.006	0.007
LSD					0.22	0.14	0.04	0.04	0.05	0.07

Means with same letters in the same column are not significantly different at 5 % probability level

Source: Fields data, 2024.

Key: EC: Electrical conductivity, TOC: Total organic carbon, POC: Particulate organic carbon, MOC: Minerals organic carbon, OM: Organic Matter

Depth-Dependent Distribution of Carbon Fractions

Soil depth (Table 2) exerted a far stronger influence on carbon fractions than land use. Surface soils (0–20 cm) contained substantially higher TOC (1.62%) compared with the 20–50 cm layer (1.21%), representing a marked decline with depth. This vertical gradient reflects the concentration of plant residues, microbial activity, and root exudes near the soil surface. The depth effect was even more pronounced for POC. Surface POC (0.46%) declined to 0.38% in the subsurface horizon, indicating strong stratification of labile carbon. Such enrichment of particulate carbon in upper horizons is widely attributed to fresh organic inputs and limited downward movement of coarse organic fragments (Lavallee *et al*., 2020).

Mineral-associated organic carbon also declined with depth (1.16% to 0.83%), but remained the dominant fraction at both depths. When expressed proportionally, MOC constituted approximately 71.6% of TOC in the surface layer and 68.6% in the subsurface. This persistence confirms that mineral associations provide structural protection across the soil profile, even as total carbon availability decreases with depth (Cotrufo *et al*., 2019; Sani *et al*., 2019). Organic matter content mirrored TOC trends, decreasing from 2.79% at 0–20 cm to 2.08% at 20–50 cm. The consistent decline across all fractions confirms that vertical carbon distribution in the study area is primarily governed by surface-driven biological inputs rather than uniform profile accumulation.

Table 2: Effects of Soil Depth on pH, EC and Organic Matter Fractions of the Study area

Soil Depth	pH (1:2)	EC (dS/m)	TOC (%)	POC (%)	MOC (%)	OM (%)
0-20	6.28[a]	0.77[a]	1.62[a]	0.46[a]	1.16[a]	2.79[a]
20-50	6.35[a]	0.77[a]	1.21[b]	0.38[b]	0.83[b]	2.08[b]
P of F	<0.08	0.031	<0.0001	<0.0001	<0.0001	<0.0001
LSD	0.18	0.11	0.03	0.03	0.04	0.06

Means with same letters in the same column are not significantly different at 5 % probability level

Source: Fields data 2024.

Note: EC: Electrical conductivity, TOC: Total organic carbon, POC: Particulate organic carbon, MOC: Minerals organic carbon, OM: Organic Matter

Integrative Perspective on Land Use and Depth

The present findings demonstrate that soil depth exerted the strongest control on SOC concentration, reflecting the progressive decline in organic inputs, microbial biomass, and bioturbation with increasing depth. This vertical pattern is consistent with recent syntheses emphasizing that depth-dependent carbon distribution is largely regulated by root density gradients and mineral surface reactivity rather than surface management alone (Lal, 2018; Lavallee et al., 2020). Across all land-use systems, SOC declined from 0–20 cm to 20–50 cm, confirming that surface enrichment is primarily driven by concentrated biological activity and organic matter deposition in the upper soil layer.

Although total SOC showed modest variation among land uses, carbon fractions revealed clearer mechanistic differences. The relatively stable POC values across forest, grassland, and farmland suggest that labile carbon inputs are rapidly cycled in these sandy loam soils. However, the strong stratification of POC with depth indicates that vertical gradients in root turnover and decomposition dynamics exert greater control than horizontal land-use contrasts. In coarse-textured tropical soils, particulate carbon is often transient and highly responsive to short-term inputs, limiting pronounced land-use separation unless disturbance intensity is extreme (Blanco-Canqui, 2020).

In contrast, mineral-associated organic carbon (MOC) displayed significant land-use sensitivity, with grassland consistently outperforming forest and farmland. This result is particularly noteworthy, as forest systems are frequently assumed to accumulate greater carbon stocks due to aboveground litter deposition. However, emerging evidence indicates that root-derived carbon contributes more efficiently to long-term stabilization than surface litter inputs because it is preferentially incorporated into mineral fractions and protected within microaggregates (Lavallee et al., 2020; Cotrufo et al., 2019). The dense fibrous root systems typical of grassland vegetation provide continuous belowground carbon inputs through rhizodeposition and fine-root turnover, enhancing microbial processing and facilitating the formation of organo–mineral complexes.

Furthermore, grassland systems in tropical savanna environments often experience minimal mechanical disturbance compared with cultivated farmland. Reduced disturbance promotes aggregate stability and protects mineral-associated carbon from rapid mineralization. Even when compared with forestland, grasslands may achieve more efficient carbon stabilization in sandy loam soils where litter decomposition is rapid and mineral surface interactions ultimately determine persistence. In such soils, stabilization capacity is strongly linked to silt and clay fractions and their ability to adsorb microbial by-products (Lal, 2018; Lavallee et al., 2020). Thus, the superior MOC observed under grassland likely reflects enhanced microbial transformation of root-derived substrates into mineral-bound forms rather than simply greater total carbon input.

These findings suggest that in the sandy loam soils of the study area, carbon persistence is predominantly mineral-mediated rather than litter-driven. While forest systems contribute visible surface residues, grassland appears more effective at converting organic inputs into stable mineral-associated pools with longer residence times. The results therefore reinforce contemporary conceptual models that distinguish between particulate and mineral-associated carbon as functionally distinct pools responding differently to management (Lavallee et al., 2020).

Generally, the study highlights that sustainable carbon management in tropical savanna ecosystems should prioritize land-use systems that maintain continuous root activity and minimize disruptive disturbance. Grassland, through sustained belowground inputs and enhanced stabilization efficiency, demonstrated a comparative advantage in promoting long-term SOC persistence. These findings provide important implications for soil quality improvement and climate mitigation strategies in sandy-textured tropical landscapes.

CONCLUSION

This study demonstrates that soil depth exerts a stronger control on organic carbon distribution than land use in the sandy loam soils of the tropical savanna ecosystem studied. Total organic carbon and its fractions declined significantly with depth, reflecting the concentration of biological inputs and carbon turnover in surface horizons. While particulate organic carbon showed limited sensitivity to land use differences, mineral-associated organic carbon varied significantly among systems and constituted the dominant proportion of total SOC across all treatments. Grassland exhibited comparatively higher stabilized carbon, suggesting enhanced mineral-associated carbon formation under continuous root inputs. The consistent dominance of mineral-associated fractions highlights the central role of organo-mineral interactions in governing carbon persistence in these soils. These findings indicate that management strategies aimed at long-term carbon sequestration in savanna environments should prioritize practices that promote root-derived inputs and protect mineral-associated carbon pools.

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