

Original Research Article

Effects of Land Use Type and Soil Depth on Soil Organic and Inorganic Carbon Fractions in Ondo State, Nigeria

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Received: 04.02.2025

Accepted: 12.03.2025

Published: 15.06.2026

Journal homepage:<http://www.easpublisher.com>**Quick Response Code**

Abstract: Soil organic and inorganic carbon fractions play a critical role in soil fertility, microbial activity, and carbon sequestration. However, land use changes and soil depth variations significantly influence these carbon fractions. This study investigated the effects of different land use types and soil depth on soil organic carbon and inorganic carbon fractions in Ondo State, Nigeria. A 5 × 3 factorial experiment was laid out in a Randomized Complete Block Design (RCBD), consisting of five land-use types (oil palm plantation, cocoa plantation, mango plantation, forest land, and arable land) and three soil depth levels (0-10 cm, 10-20 cm, and 20-30 cm) was carried out at the Federal University of Technology, Akure. Soil samples were collected from the Teaching and Research Farm of the Federal College of Agriculture, Akure, Ondo State. Various carbon fractions, including microbial biomass carbon (MBC), particulate organic carbon (POC), and SOC, were analysed using standard laboratory procedures. Results indicated that forest land and oil palm plantations had the highest SOC levels, while arable land exhibited the lowest. A significant decline in SOC was observed with increasing soil depth, with the highest levels found in the top 0-10 cm layer. MBC was highest at 10-20 cm and 20-30 cm depths, suggesting favourable conditions for microbial activity in these layers. The study concludes that land use management practices that promote organic matter accumulation, such as agroforestry, are essential for enhancing soil carbon storage and microbial health. Recommendations include adopting conservation agriculture practices to mitigate the adverse effects of intensive tillage on soil quality.

Keywords: Soil organic carbon, Microbial biomass carbon, Land use, Soil depth.

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INTRODUCTION

Soil plays a crucial role in supporting agricultural productivity, regulating the Earth's climate, and maintaining environmental quality. Among its various functions, one of the most significant is carbon storage. Soil carbon exists in two primary forms: organic and inorganic. Organic carbon, mainly derived from plant and animal residues, is a key indicator of soil health, influencing microbial activity, nutrient availability, and overall soil fertility (Lal, 2004). Inorganic carbon, often in the form of carbonates, contributes to soil pH regulation and can influence soil structure and fertility (Chadwick *et al.*, 2013). The balance between organic and inorganic carbon fractions is essential in understanding soil carbon dynamics and its potential to mitigate climate change by sequestering carbon (Smith *et al.*, 2016).

In Ondo State, Nigeria, agricultural activities are a major component of the local economy, with crops such as cocoa, cassava, and maize being widely cultivated (Akinyemi *et al.*, 2019). These land-use types can significantly affect soil properties, including soil organic carbon (SOC) and soil inorganic carbon (SIC) fractions (Lal, 2010). Changes in land use, such as the transition from forested land to agricultural land, can alter the dynamics of soil carbon stocks (DeFries *et al.*, 2004). Furthermore, soil depth is a critical factor that affects the distribution and sequestration of both organic and inorganic carbon, as deeper soils generally store more carbon due to larger organic matter accumulation over time (Vogel *et al.*, 2018). However, the impact of different land-use types and soil depths on soil carbon fractions remains under-researched in the context of Ondo State, Nigeria (Ogunwole *et al.*, 2013).

In Ondo State, agricultural intensification, coupled with urbanization, has led to significant changes in land use, potentially impacting soil carbon storage and health. While organic and inorganic carbon fractions play vital roles in maintaining soil fertility and environmental stability, there is a lack of detailed understanding of how various land-use practices and soil depths influence the distribution of these carbon fractions in the region. Most existing studies on soil carbon have focused on other parts of Nigeria or have not adequately accounted for the influence of both land use type and soil depth on the carbon dynamics in the specific context of Ondo State (Akinyemi *et al.*, 2019). Without a comprehensive understanding of these interactions, there is a risk of ineffective land management strategies that fail to optimize soil carbon storage, which can further degrade soil quality, reduce agricultural productivity, and contribute to environmental concerns such as climate change and desertification (Lal, 2004; Ogle *et al.*, 2005).

Justification

This research is important for several reasons. First, it will provide valuable insights into how different land-use types (such as arable fields, forested areas, and plantation) influence both organic and inorganic carbon stocks in soils, a crucial aspect for land management and sustainable agriculture. As land-use changes are a significant driver of soil degradation, understanding their impact on carbon fractions can help develop strategies to mitigate carbon loss and enhance carbon sequestration in soils (Bastida *et al.*, 2013; Lal, 2010).

Second, this study will highlight the role of soil depth in carbon storage, offering insights into how deeper soils, which are often less disturbed, may retain more carbon compared to shallow soils subject to more intense agricultural practices (Schulp *et al.*, 2014). Such knowledge can guide the design of land management practices that preserve deeper soil layers, which are often critical for long-term soil fertility.

Additionally, the findings of this study could contribute to the global discourse on soil carbon sequestration, especially in the context of climate change mitigation. Enhancing soil organic carbon stocks through sustainable land management practices can help sequester atmospheric CO₂, thereby contributing to the reduction of greenhouse gas concentrations in the atmosphere (Paustian *et al.*, 2016).

The research will also contribute to the broader understanding of the soil carbon cycle in West Africa, providing local and regional policymakers with data needed to develop effective land-use policies that ensure environmental sustainability and food security (Ogunwole *et al.*, 2013). Furthermore, understanding soil carbon dynamics will be vital for informing carbon credit programs, which could offer additional economic benefits for local farmers and communities.

MATERIALS AND METHODS

Study Area and Soil Collection Site

The study was conducted in Ondo State, located in the southwestern region of Nigeria, characterized by a tropical climate with two distinct seasons: a rainy season from March to October and a dry season from November to February. The research site was specifically selected within the Teaching and Research Farm of the Federal University of Technology, Akure (Latitude: 7.2872°N; Longitude: 5.1361°E). This area is representative of diverse land-use types, including agricultural fields, forested lands, and fallow plots. The soils are typical of the humid tropics, rich in organic material in natural vegetation areas, but prone to fertility loss with continuous cultivation. Soil samples were collected from these different land-use types to investigate how varying land-use practices influence soil carbon fractions at different soil depths.

Experimental Design and Soil Sampling

A 5 × 3 factorial experimental design was used, implemented in a Randomized Complete Block Design (RCBD). The design consisted of five land-use types: Oil Palm Plantation, Cocoa Plantation, Mango Plantation, Forest Land, and Arable Land, and three soil depth levels: 0–10 cm, 10–20 cm, and 20–30 cm.

Soil samples were collected from the Teaching and Research Farm of the Federal College of Agriculture, Akure, Ondo State. For each land-use type, three sample plots (5 m × 20 m) were randomly selected. A total of 30 composite soil samples were collected, with each sample consisting of nine sub-samples (three samples per depth per plot). These samples were sieved through a 2 mm mesh, with one portion stored at -20°C for microbial analysis, and the other air-dried for chemical and physical analyses.

Carbon Fraction Analysis

- Soil Microbial Respiration ($\mu\text{g CO}_2\text{-C g}^{-1}\text{ soil}$): This was determined using the alkali sorption-titration method as described by Anderson and Domsch (1990). A 10 mL solution of 0.5 M NaOH was placed in a 50 mL beaker inside a sealed plastic jar containing 100 g of soil. The evolved CO₂ was trapped in the NaOH solution, which was replaced every 7 days and titrated. At the end of each incubation week, 5 mL of 1.0 M BaCl₂ was added to precipitate carbonate (BaCO₃), and CO₂ evolution ($\mu\text{g CO}_2\text{-C g}^{-1}\text{ soil}$) was determined by titration with 0.5 M HCl, using phenolphthalein as the indicator. Two blanks (without soil) were included to account for CO₂ trapped in the absence of soil respiration.
- Microbial Biomass Carbon (MBC): MBC was measured using the substrate-induced respiration method, which is similar to the soil basal respiration procedure. However, 1 g of

glucose was added to the soil prior to incubation to stimulate microbial activity.

- Particulate Organic Carbon (POC): POC was determined following the method of Cambardella and Elliott (1992). Soil was dispersed in 5 g L⁻¹ sodium hexametaphosphate and sieved through a 53 µm mesh. The soil was then dried and ground, and the organic carbon content was determined in the resulting samples.
- Soil Organic Carbon (SOC): SOC was measured using the Walkley-Black wet oxidation method. Soil samples were reacted with 1M K₂Cr₂O₇ and concentrated H₂SO₄, and the organic carbon content was determined by titration with 0.5M FeSO₄.

Data Analysis

Data were analyzed using Analysis of Variance (ANOVA) to assess significant differences among treatment means, with Tukey's test applied for post-hoc comparisons at a 5% significance level.

RESULTS AND DISCUSSION

Soil Organic Carbon (SOC) and Particulate Organic Carbon (POC) Fractions

The effects of different land-use types on two soil organic carbon (SOC) fractions are shown in Figure 1a. No significant differences ($P \leq 0.05$) in SOC content were observed among the land-use types. However, Forest land (FR) and Oil Palm Plantation (OP) exhibited the highest SOC levels, with values exceeding 1.2 mg kg⁻¹ soil, while Arable Land (AB) had the lowest.

In contrast, significant differences ($P \leq 0.05$) were observed in the POC content across land-use types. Forest land (FR) and Cocoa Plantation (CP) maintained significantly higher POC levels, while Arable Land (AB) recorded the lowest values. The high SOC and POC levels in FR and OP can be attributed to enhanced microbial activity and slower organic matter decomposition, which are facilitated by continuous organic material input, such as leaf litter and root biomass (Sainepo *et al.*, 2018; Welemariam *et al.*, 2021). This finding is consistent with previous research indicating that forested areas typically maintain higher SOC levels due to reduced disturbances and continuous organic inputs from vegetation (Mwakipa & Nassary, 2023; Buraka *et al.*, 2022; Abdullah *et al.*, 2022). In contrast, the lower SOC and POC levels in AB can be explained by the direct disturbances caused by agricultural practices, which disrupt soil structure and reduce its ability to store carbon (Jaconi *et al.*, 2019; Li & Hao, 2014).

Soil Depth Effects on SOC and POC

The effects of soil depth on SOC fractions are presented in Figure 1b. A significant ($P \leq 0.05$) decline in SOC content was observed with increasing soil depth,

with the highest levels recorded in the 0–10 cm layer, followed by substantial decreases in the 10–20 cm and 20–30 cm layers. A similar trend was observed for POC, although the differences across depths were not statistically significant ($P \leq 0.05$). The reduction in SOC with depth aligns with the understanding that organic material accumulates predominantly in the upper soil layer, where microbial activity is most intense due to the availability of fresh organic inputs (Malcheva *et al.*, 2022; Xu *et al.*, 2012). Conversely, deeper soil layers experience more microbial decomposition and reduced organic inputs, leading to lower SOC levels (Högberg *et al.*, 2007; Xu *et al.*, 2018). The stability of POC across soil depths may be due to its greater susceptibility to microbial degradation, meaning that although absolute concentrations are lower in deeper layers, the relative distribution of POC remains more uniform (Bobul'ská *et al.*, 2015; Xiang *et al.*, 2024).

Interaction Effects of Land Use and Soil Depth on SOC and POC

The interaction between land use and soil depth on SOC and POC is presented in Table 1. Significant differences were observed for SOC, but no significant differences were recorded for POC. The highest SOC value (1.90%) was found under Oil Palm (OP) at the 0-10 cm depth, while the lowest value (0.53%) occurred under Cocoa Plantation (CP) at 20-30 cm. The high SOC at the surface layer under OP is likely due to continuous organic matter input from fallen leaves and root residues, combined with minimal soil disturbance. Previous studies have shown that tree plantations, particularly oil palm, contribute to SOC accumulation in topsoil through the decomposition of leaf litter and root turnover (Frazão *et al.*, 2012). The low SOC at 20-30 cm depth under Cocoa Plantation suggests limited organic material input at subsoil levels, likely due to the shallow root systems of cocoa trees and lower decomposition rates at greater depths (Anikwe, 2010). In contrast, the highest POC (0.32%) was observed under CP at 0-10 cm, indicating high microbial activity and organic residue decomposition at the topsoil level, which plays a vital role in maintaining soil structure (Hergoualc'h & Verchot, 2011). The consistently low POC values (0.02%) across all depths in Arable Land (AB) underscore the detrimental effects of continuous cultivation and soil disturbance on the labile organic fraction (Haddaway *et al.*, 2017). This supports findings suggesting that intensive agricultural practices, particularly tillage, contribute to significant losses in both SOC and POC, negatively impacting soil health and fertility (Ludwig *et al.*, 2010).

Microbial Biomass Carbon (MBC)

The effects of land use and soil depth on microbial biomass carbon (MBC) are shown in Table 2. No significant differences ($P \leq 0.05$) in MBC were observed among land-use types across all sampling days, except for day 4. High MBC values in Forest land, Mango plantations, and Oil Palm plantations suggest that

undisturbed ecosystems and tree-based cropping systems favor microbial biomass. In contrast, Arable land (AB) exhibited lower MBC values, particularly on day 4 (1.64%), indicating that agricultural disturbances are more detrimental to microbial communities. This observation aligns with previous studies highlighting the sensitivity of microbial communities to agricultural practices, which often result in lower MBC in cultivated soils (Muraškieñė *et al.*, 2023; Agbeshie *et al.*, 2020).

Significant differences ($P \leq 0.05$) in MBC were observed across soil depths on all days. MBC was consistently higher at the 10–20 cm and 20–30 cm depths compared to the 0–10 cm layer. The highest MBC values were recorded at the 10–20 cm and 20–30 cm depths on day 3 (2.02%). The lowest MBC values were found at the 0–10 cm depth on day 7 (1.48%). The higher MBC in deeper soil layers contrasts with the general expectation that microbial biomass is highest in surface soils due to organic matter input. This may be attributed to factors such as reduced microbial competition and predation in deeper soil layers, allowing microbial populations to thrive (Lepcha & Devi, 2020). Additionally, deeper layers retain moisture more effectively, providing a stable environment that supports microbial activity (Shange *et al.*, 2012).

Interaction Effects of Land Use and Soil Depth on MBC

The interaction effects of land use and soil depth on microbial biomass carbon (MBC) are summarized in Table 3. Significant differences ($P \leq 0.05$) were observed in MBC across land-use types and soil depths. The 10–20 cm soil depth generally had the highest MBC, particularly under Forest land and Mango plantations, with Forest land recording the highest MBC values of 2.20% and 2.11% on days 2 and 7, respectively. Forest ecosystems provide an optimal environment for microbial communities, with rich organic matter and stable moisture conditions. The presence of diverse vegetation types supports microbial biomass by providing a variety of organic substrates through litter fall and root exudates (Eisenhauer *et al.*, 2017; Ni *et al.*, 2022). Additionally, seasonal variations in moisture and temperature can influence microbial biomass, with wet conditions generally promoting higher microbial activity (Araújo *et al.*, 2013; Patel, 2010). In contrast, the lower MBC in the 0–10 cm depth can be attributed to the exposure of surface soils to environmental fluctuations, including temperature extremes and moisture loss.

Soil Respiration

The main effects of land use and soil depth on soil respiration are shown in Table 4. No significant differences ($P \leq 0.05$) in soil respiration were observed across land-use types. However, Forest land (FR) consistently exhibited the highest soil respiration rates, with values ranging from 1.72 to 1.94. This finding supports the notion that forest ecosystems typically support higher microbial activity and organic matter decomposition due to greater litter inputs and more stable soil environments compared to agricultural systems (Smith *et al.*, 2021; Sheng *et al.*, 2010). Cocoa Plantation (CP) and Mango Plantation (MP) also showed relatively high respiration rates, particularly on days 1 and 3, likely due to organic matter inputs from the crops themselves. Conversely, Arable land (AB) consistently recorded the lowest respiration rates, particularly on days 5 and 6, reflecting the impacts of tillage and reduced organic matter availability that characterize conventional agricultural practices (Couto *et al.*, 2016; Chen *et al.*, 2010).

Significant differences ($P \leq 0.05$) in soil respiration were observed across soil depths. The 0–10 cm depth had the lowest respiration rates, with values consistently below 1.60 across all days, likely due to lower organic matter accumulation and microbial activity in the topsoil. This trend is exacerbated by agricultural practices that disturb the soil (Mazzetto *et al.*, 2016). In contrast, the deeper soil layers (10–20 cm and 20–30 cm) exhibited significantly higher respiration rates, with means above 2.00 for the 10–20 cm depth. This suggests that deeper layers retain more moisture and organic matter, providing a more favorable environment for microbial activity (Aini *et al.*, 2020).

Interaction Effects of Land Use and Soil Depth on Soil Respiration

The interaction between land use and soil depth on soil respiration is presented in Table 5. The highest interaction effect was observed in the 10–20 cm depth for Forest Plantation, which recorded the highest respiration rate of 2.54 on Day 6. This indicates that forest plantations at this depth support high microbial activity, benefiting from organic matter accumulation that enhances respiration rates. In contrast, the lowest interaction effect on soil respiration was observed in the 0–10 cm depth for Arable land (AB), which recorded the lowest respiration rates across multiple days, particularly on Day 5 with a value of 1.33. This low respiration rate can be attributed to the effects of tillage and soil disturbance typical of agricultural practices, which reduce organic matter and microbial activity in the topsoil (Hergoualc'h *et al.*, 2017).

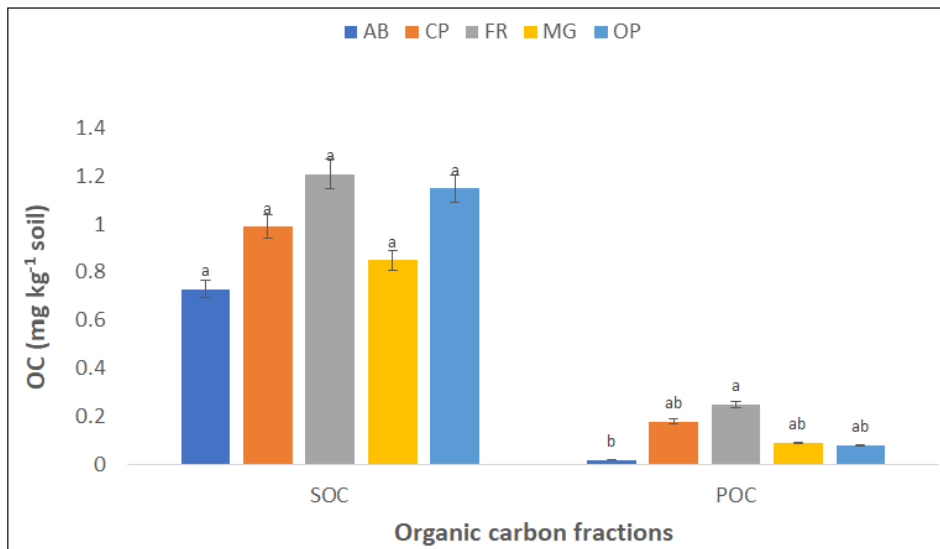


Figure 1a: Effects of Land use on two soil organic carbon fractions

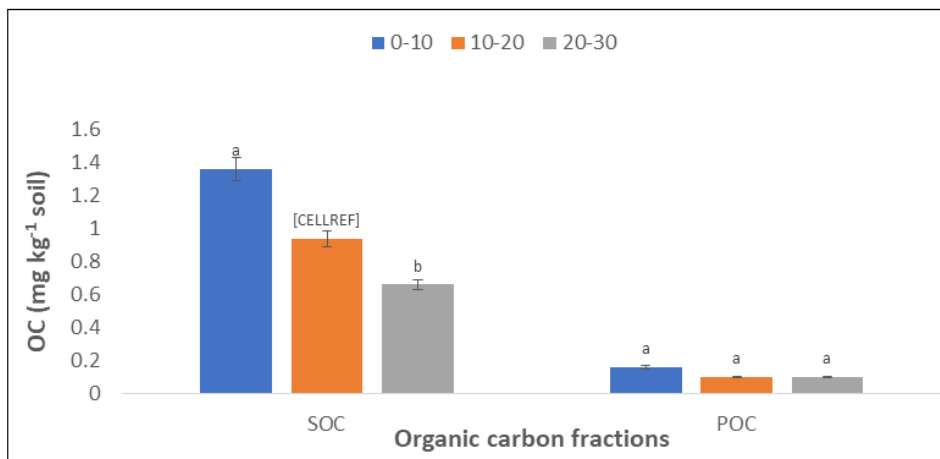


Figure 1b: Effects of Soil depth on two soil organic carbon fractions

Table 1: Interaction between depth and Land use on Soil Organic Carbon (SOC) and Particulate organic carbon (POC) among land use

Soil depth (cm)	Land use	SOC (%)	POC (%)
0-10	AB	0.80ab	0.02a
	CP	1.79ab	0.32a
	FR	1.22ab	0.27a
	MG	1.09ab	0.13a
	OP	1.90a	0.08a
10-20	AB	0.71ab	0.02a
	CP	0.65ab	0.08a
	FR	1.60ab	0.30a
	MG	0.82ab	0.04a
	OP	0.93ab	0.07a
20-30	AB	0.68ab	0.02a
	CP	0.53b	0.12a
	FR	0.82ab	0.20a
	MG	0.63ab	0.11a
	OP	0.63ab	0.07a

Means followed by the same letter in the same column are not significantly different from each other by Tukey’s HSD at 5% level of probability. Keys: OP = Oil palm plantation, CP = Cocoa plantation, MG = Mango plantation, FR= Forest land, AB = Arable land

Table 2: Main effect of land use and soil depth on the distribution of microbial biomass carbon (%)

Land use	Days						
	1	2	3	4	5	6	7
AB	1.80a	1.64a	1.89a	1.64b	1.67a	1.64a	1.58a
CP	1.82a	1.73a	1.90a	1.74ab	1.70a	1.66a	1.75a
FR	1.87a	1.85a	1.97a	1.77a	1.71a	1.68a	1.69a
MP	1.80a	1.76a	1.99a	1.73ab	1.67a	1.70a	1.71a
OP	1.87a	1.78a	1.93a	1.74ab	1.74a	1.56a	1.61a
Soil depth (cm)							
0-10	1.62b	1.67a	1.77b	1.70a	1.55b	1.52b	1.48b
10-20	1.95a	1.86a	2.02a	1.74a	1.79a	1.69a	1.71a
20-30	1.94a	1.73a	2.02a	1.73a	1.76a	1.74a	1.82a

Means followed by the same letter in the same column are not significantly different from each other by Tukey's HSD at 5% level of probability. Keys: OP = Oil palm plantation, CP = Cocoa plantation, MG = Mango plantation, FR= Forest land, AB = Arable land

Table 3: Interaction between depth and land use on microbial biomass carbon (%)

Soil depth (cm)	Land use	Days						
		1	2	3	4	5	6	7
0-10	AB	1.58a	1.73ab	1.77a	1.56a	1.53a	1.49a	1.44bc
	CP	1.56a	1.44b	1.76a	1.70a	1.50a	1.59a	1.31c
	FR	1.59a	1.58ab	1.81a	1.80a	1.56a	1.52a	1.51bc
	MP	1.63a	1.74ab	1.76a	1.70a	1.56a	1.56a	1.67abc
	OP	1.72a	1.83ab	1.76a	1.74a	1.60a	1.43a	1.48bc
10-20	AB	1.94a	1.80ab	1.90a	1.69a	1.80a	1.73a	1.78ab
	CP	1.94a	1.78ab	1.98a	1.76a	1.79a	1.67a	1.70abc
	FR	2.09a	2.20a	2.11a	1.74a	1.80a	1.77a	2.11a
	MP	1.83a	1.78ab	2.06a	1.82a	1.69a	1.63a	1.84ab
	OP	1.93a	1.72ab	2.07a	1.69a	1.89a	1.64a	1.67abc
20-30	AB	1.89a	1.67ab	2.00a	1.67a	1.78a	1.89a	1.58bc
	CP	1.96a	1.69ab	1.97a	1.76a	1.74a	1.72a	1.66bc
	FR	1.94a	1.78ab	2.06a	1.78a	1.78a	1.76a	1.72abc
	MP	1.94a	1.74ab	2.11a	1.66a	1.78a	1.74a	1.81ab
	OP	1.96a	1.78ab	1.98a	1.78a	1.74a	1.61a	1.78ab

Means followed by the same letter in the same column are not significantly different from each other by Tukey's HSD at 5% level of probability. Keys: OP = Oil palm plantation, CP = Cocoa plantation, MG = Mango plantation, FR= Forest land, AB = Arable land

Table 4: Main effect of land use and soil depth on soil respiration

Land use	Days						
	1	2	3	4	5	6	7
AB	1.84a	1.64a	1.68a	1.62a	1.46a	1.50b	1.59a
CP	1.91a	1.63a	1.74a	1.67a	1.59a	1.61b	1.60a
FR	1.94a	1.76a	1.80a	1.72a	1.63a	1.96a	1.89a
MP	1.93a	1.61a	1.76a	1.66a	1.59a	1.79ab	1.67a
OP	1.85a	1.70a	1.75a	1.66a	1.56a	1.66ab	1.74a
Soil depth (cm)							
0-10	1.53b	1.59a	1.48b	1.48b	1.40b	1.41b	1.40b
10-20	2.10a	1.72a	1.91a	1.77a	1.66a	1.76a	1.89a
20-30	2.05a	1.69a	1.91a	1.74a	1.63a	1.94a	1.81a

Means followed by the same letter in the same column are not significantly different from each other by Tukey's HSD at 5% level of probability. Keys: OP = Oil palm plantation, CP = Cocoa plantation, MG = Mango plantation, FR= Forest land, AB = Arable land

Table 5: Interaction between depth and land use on soil respiration

Soil depth (cm)	Land use	Days						
		1	2	3	4	5	6	7
0-10	AB	1.56bc	1.52a	1.49cd	1.47b	1.33ab	1.37c	1.39cd
	CP	1.60bc	1.53a	1.50cd	1.44b	1.39b	1.54bc	1.37d
	FR	1.51c	1.68a	1.42d	1.56ab	1.56ab	1.47c	1.47bcd
	MP	1.50c	1.53a	1.46d	1.50b	1.42ab	1.32c	1.39cd
	OP	1.50c	1.56a	1.52bcd	1.44b	1.32b	1.36c	1.39cd
10-20	AB	2.17a	1.78a	1.87ab	1.91a	1.50ab	1.96abc	2.17a
	CP	2.09a	1.67a	1.91a	1.71ab	1.66ab	1.58bc	1.78abcd
	FR	2.28a	1.86a	2.00a	1.62ab	1.68ab	2.54a	2.11a
	MP	1.92ab	1.63a	1.92a	1.82ab	1.61ab	1.81bc	1.86abcd
	OP	2.06a	1.80a	1.83abc	1.78ab	1.72ab	1.56bc	2.04abc
20-30	AB	2.11a	1.69a	1.89a	1.78ab	1.50ab	1.90abc	1.59abcd
	CP	2.04a	1.69a	1.82abc	1.71ab	1.78a	1.71bc	1.66abcd
	FR	2.11a	1.72a	1.78abcd	1.83ab	1.67ab	1.71bc	1.72abcd
	MP	2.00a	1.67a	1.91a	1.64ab	1.74ab	2.14ab	1.78abcd
	OP	2.00a	1.70a	1.88ab	1.76ab	1.63ab	1.58bc	1.78abcd

Means followed by the same letter in the same column are not significantly different from each other by Tukey’s HSD at 5% level of probability. Keys: OP = Oil palm plantation, CP = Cocoa plantation, MG = Mango plantation, FR= Forest land, AB = Arable land

CONCLUSION

This study examined the effects of land-use types and soil depth on soil organic carbon (SOC) fractions, microbial biomass carbon (MBC), and soil respiration. The results demonstrate that land use significantly affects SOC and particulate organic carbon (POC) levels, with forest land (FR) and oil palm plantations (OP) maintaining the highest SOC levels due to continuous organic inputs and minimal disturbances. In contrast, arable land (AB) showed the lowest SOC and POC values, highlighting the adverse effects of intensive agricultural practices on soil carbon storage.

Soil depth also played a critical role in carbon distribution, with SOC declining significantly with increasing depth. The highest SOC levels were recorded in the 0–10 cm layer, while deeper layers (10–30 cm) exhibited substantially lower carbon content. Conversely, microbial biomass carbon (MBC) was highest in the 10–20 cm and 20–30 cm layers, likely due to reduced competition and more stable moisture conditions in these deeper layers.

Soil respiration was influenced by both land use and depth, with forest land (FR) exhibiting the highest respiration rates, reinforcing the role of undisturbed ecosystems in sustaining microbial activity. The lowest respiration rates were observed in arable land (AB), particularly at the 0–10 cm depth, which further underscores the negative impact of tillage and soil disturbances on microbial processes.

To enhance soil organic carbon storage and microbial activity, land-use systems that promote organic matter accumulation—such as forest plantations and perennial tree-based cropping systems like oil palm and cocoa plantations—should be prioritized.

Additionally, considering the higher microbial biomass carbon in deeper soil layers (10–20 cm), targeted soil management practices should be implemented to optimize microbial activity and maintain soil fertility, especially in these deeper zones.

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Cite This Article: Ekikereabasi, J, Adejoro, S. A, Adeyemo, A. J, Olu-Ogbera, O. A, Ewulo, B. S (2026). Effects of Land Use Type and Soil Depth on Soil Organic and Inorganic Carbon Fractions in Ondo State, Nigeria. *East African Scholars J Agri Life Sci*, 9(6), 121-129.