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Effect of land management practices on soil organic carbon in the mangrove ecosystem

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ABSTRACT

This study assessed the distribution of soil organic carbon among soil fractions in a mangrove ecosystem in the Ilaje Area of Ondo State, southwestern Nigeria. Soil samples were collected from cultivated, regenerated, and natural forest lands at depths of 0 to 20 cm, 20 to 40 cm, and 40 to 60 cm. Sampling was conducted at three points along the diagonal of 20 m × 20 m plots established on three transects spaced 100 m apart within each site, using a 3 cm diameter soil auger. Soil organic carbon and selected physicochemical properties were determined using standard laboratory procedures. Total organic carbon (TOC) ranged from 5.70 ± 0.52% in cultivated land at 20 to 40 cm depth to 12.37 ± 1.50% in natural forest at the same depth. TOC differed significantly ($P < 0.05$) among land management practices but showed no significant variation with soil depth. POC and mineral-associated organic carbon (MOC) were also strongly influenced by land use, with POC values ranging from 3.21 ± 0.37% in cultivated land to 6.42 ± 0.36% in natural forest at 20 to 40 cm depth. Soil pH was moderately acidic across all depths and land uses, varying from 4.24 ± 0.10 to 5.38 ± 0.06. Overall, the findings underscore the significant role of land management practices in regulating soil organic carbon dynamics and related soil properties in mangrove ecosystems.

Contribution/Originality: This study is the first to quantify soil organic carbon partitioning into particulate and mineral-associated fractions across cultivated, regenerated, and natural mangrove lands in Ilaje, Nigeria, using a depth-resolved, transect-based design, thereby linking land-use history to carbon stabilization mechanisms in a poorly studied West African mangrove system.

1. INTRODUCTION

Soil organic matter (SOM) plays a vital role in many soil properties. It has been an object of investigation in soil and environmental sciences, constituting a fundamental factor in the maintenance and sustainability of natural or managed ecosystems [1-3]. SOM refers to soil carbon in all its forms, occurring in a range of structural configurations that include both labile and stable fractions. No other changes or additions are made to the original wording [4, 5]. It originates from the partial decomposition of plant residues that enter the soil as roots, litter, crop residues, and animal manure. These inputs are first fragmented by soil fauna and then decomposed by microorganisms through successive stages of increasing complexity and structural diversity [6, 7]. During this process, much of the carbon is oxidized to carbon dioxide (CO_2), while the remaining fraction becomes stabilized and stored mainly as SOM through interactions with the soil mineral fraction. No other words are added or changed [8, 9]. Mangrove forests are forests located at the interface between land and sea in tropical and subtropical regions of the world, playing a crucial role in coastal ecosystems [10]. Mangrove plants can grow in various types of soil; therefore, their vegetation, species composition, and structure may vary considerably at global, regional, and local scales [11, 12].

The mangrove forest soils are complex, resulting from the interactions of biotic (plant and invertebrate activities) and abiotic (tides and physiography) factors, which vary greatly with distance and depth [10, 13]. The mangrove topsoil is loosely formed, consisting of sandy or clayey types. The lighter-colored topsoils are porous and facilitate water percolation and aeration during low tide. The darker-colored clayey topsoils are less well aerated [14]. Subsoils below the surface are typically waterlogged, with little aeration, which decreases with depth as the SOM content increases [15]. Soil attributes, including SOM, total organic carbon (TOC), carbon stock, clay mineralogy, salinity, iron sulfide content, redox potential, and nutrient availability, significantly influence mangrove species composition and structure [16-18]. These properties vary considerably with soil depth, making it essential to examine their distribution across different soil layers. Soils vary in their response to changes in land use and management practices [8]. However, there is limited information on such responses within mangrove forest ecosystems in Nigeria, particularly in Ilaje Local Government Area of Ondo State. This area has experienced increasing human activities and development, accompanied by shifts in land management practices, primarily driven by ongoing oil exploration. Although several studies have examined soil properties, species composition, and structural characteristics of Nigerian mangrove forests [17, 19-24], detailed research on the distribution of soil organic carbon (SOC), defined as the carbon stored in organic matter within the soil, among different soil fractions across the soil profile [25] remains scarce. This gap is notable given the importance of mangrove soils as major carbon sequestration sites. The present study, therefore, provides baseline data and offers insight into the distribution of SOC among soil fractions in mangrove forest soil profiles under different land management practices in the Ilaje area of Ondo State, Nigeria.

2. MATERIALS AND METHODS

This study was conducted in the mangrove forest area of Ilaje Local Government in Ondo State, Nigeria (Figure 1). Ilaje Local Government mainly occupies the Atlantic coastline of Ondo State, which lies on Latitude 5° 50′N – 6° 09′N and Longitude 4° 45′E – 5° 05′E [26].

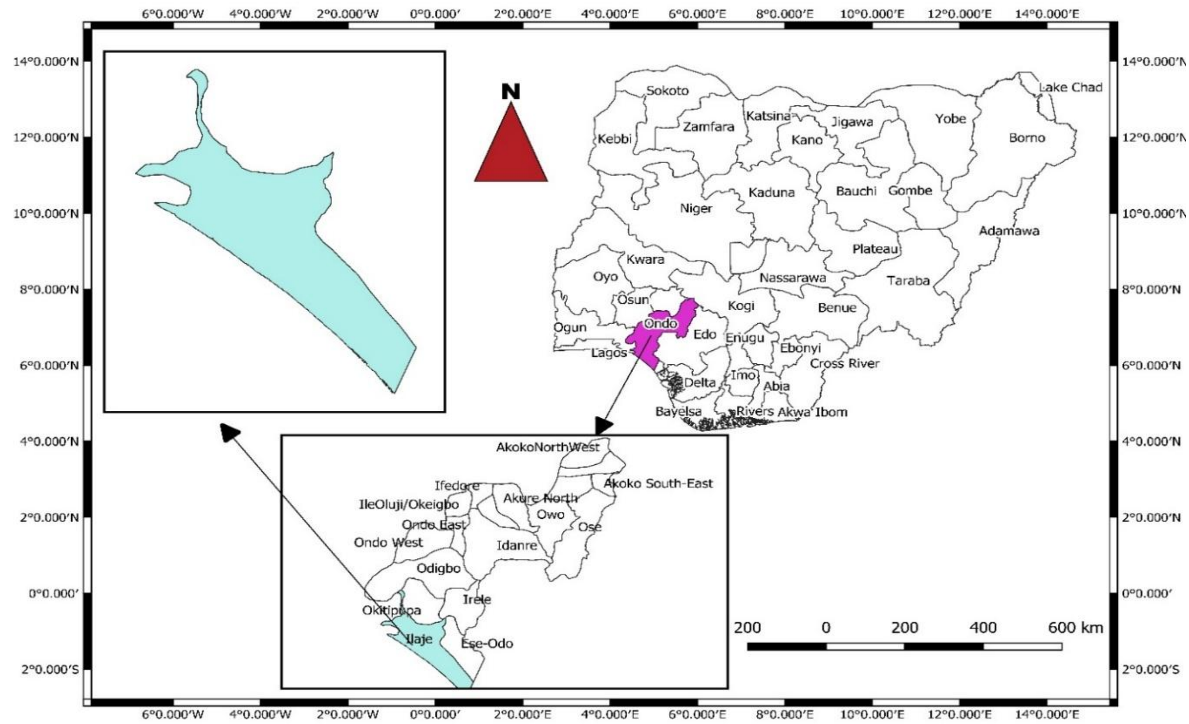

Figure 1. Map showing the study area, Ilaje LGA in Ondo State.

The study area lies within the transitional zone of the equatorial climate in southern Nigeria, characterized by both wet (April to October) and dry months (November to March). During the wet season, the average rainfall ranges between 2000 and 3000 mm, while the mean temperature is 28°C [27, 28]. There are two periods of heavy rain, in July and September, with a relatively low rainfall period in August. The soils in the Ilaje region are characterized by swampy organic and flooded organic soils, while the central part consists of decomposed and partly decomposed organic matter.

2.1. Soil Sample Collection and Sampling Procedure

Soil samples were collected from three sites representing contrasting land management practices in the study area: cultivated land, regenerated land, and natural forest land. The cultivated land comprised farmlands that had been under continuous cultivation for more than 20 years, while the regenerated land consisted of previously cultivated areas that had been left fallow for approximately 10 years. The natural forest land comprised mangrove forest areas with no record of significant anthropogenic disturbance. The selection of these land-use types was intended to capture variations in soil properties arising from long-term land management and disturbance history [29, 30]. Systematic strip sampling was employed for plot establishment within each land-use type, following standard soil and ecological sampling protocols [31, 32]. In each site, three transects were laid out at 100 m intervals. Along each transect, three sample plots measuring 20 m × 20 m were established at alternate positions, spaced 50 m apart (Figure 2). This sampling design ensured adequate spatial representation and minimized bias associated with site heterogeneity [33]. Soil core samples were collected at three depth intervals (0–20 cm, 20–40 cm, and 40–60 cm) in each plot using a soil auger with an internal diameter of 3 cm. These depth intervals are commonly used in soil organic carbon studies to assess the vertical distribution and storage of carbon under different land uses [34]. At each depth, samples were collected from three points along the diagonal of each plot and combined to obtain a representative sample for that plot and depth, as recommended for reducing within-plot variability [35, 36]. The composite soil samples were air-dried at room temperature, gently crushed, and sieved through a 2 mm mesh after removing visible roots and coarse fragments, following standard soil preparation procedures [37]. The processed samples were transported to the laboratory of the Department of Forestry and Wood Technology at the Federal University of Technology, Akure (FUTA), where total soil organic carbon was determined by dry combustion. Particulate organic carbon (POC) was quantified using physical fractionation through wet sieving, and mineral-associated organic carbon (MOC) was assessed from the silt and clay fractions following established soil organic matter fractionation procedures. Standard analyses of selected physicochemical soil properties were also conducted [38-41].

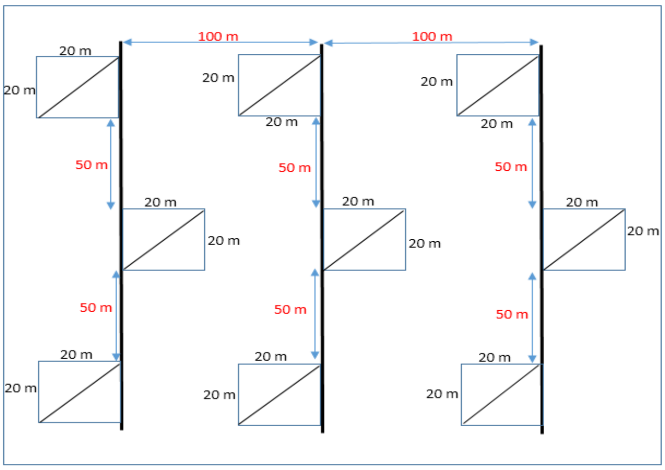

Figure 2. Plot layout and sampling technique adopted for each land use system.

2.2. Soil Particle Size Analysis

Soil particle size distribution is a relatively stable property and is commonly used for soil textural classification. In this study, particle size analysis determined the proportions of sand, silt, and clay in soil samples collected at different depths under cultivated land, regenerated land, and forest land management systems. The analysis was performed using the hydrometer method as described by Bouyoucos [42] and modified by Gee and Or [41].

For each sample, 30 g of oven-dried soil, sieved to pass through a 2 mm mesh, was weighed into a 250 ml beaker, and 100 ml of Calgon dispersing solution was added. The suspension was transferred to a dispersing cup and mechanically stirred for approximately 3 minutes to ensure adequate dispersion of soil particles. The mixture was then moved into a sedimentation cylinder and brought to volume with distilled water while the hydrometer was immersed in the suspension.

A plunger was inserted and moved vertically to thoroughly mix the suspension, followed by three slow, smooth strokes to complete the mixing process. The time at which stirring ceased was recorded. The hydrometer was carefully lowered into the suspension, and the first reading was taken after 40 seconds (R_{40s}). The temperature of the suspension was recorded simultaneously. The suspension was remixed using the plunger, and the 40-second reading was repeated until consistent values were obtained. A second hydrometer reading and temperature measurement were taken 2 hours after the final remixing (R_2h). These readings were used to calculate the percentages of sand, silt, and clay in each soil sample. The percentage fractions of the suspension were calculated as follows:

$$\%\ (\text{Silt} + \text{Clay}) = \frac{(R40_{secs} - R_a) + R_c}{W_0} \times 100 \quad (1)$$

$$\%\ \text{Clay} = \frac{(R2_{hrs} - R_b) + R_d}{W_0} \times 100 \quad (2)$$

$$\%\ \text{Silt} = \%\ (\text{Silt} + \text{Clay}) - \%\ \text{Clay} \quad (3)$$

$$\%\ \text{Sand} = 100 - [\%\ (\text{Silt} + \text{Clay})] \quad (4)$$

2.3. Soil Particle Size Fractionation into Particulate and Mineral Associated Fractions

Soil particle physical fractionation was conducted using the method developed by Cambardella and Elliott [38]. A 50g sample of AA ≥ 2mm soil was weighed and transferred into a 250ml sample bottle, with 105ml of distilled water added to form a suspension. The suspension was washed through a 53µm sieve to separate the coarse fraction. Soil retained on the 53µm sieve was considered particulate SOM, while that passing through was regarded as mineral-associated SOM. The particulate (≥53µm) and mineral-associated (<53µm) soil organic matter fractions were dried in an oven at 100 °C and analyzed for organic carbon following standard laboratory procedures.

2.4. pH, Organic Carbon, and Nitrogen Determination

Soil pH was determined using a 1:1 (w/v) soil to distilled water ratio and a calibrated pH meter (i.e., one calibrated with a standard buffer solution). At the same time, SOC concentrations in the soil samples were determined in the bulk soil (≥53µm) and (<53µm) soil fractions as TOC, POC, and mineral-associated organic carbon (MOC), respectively, following the Walkley-Black wet oxidation method as described by Shang et al. [43] using potassium dichromate ($K_2Cr_2O_7$) and concentrated H_2SO_4. The sample-reagent mixture was gently boiled at 170 °C for thirty (30) minutes to ensure complete oxidation of the organic carbon, while the excess $K_2Cr_2O_7$ was titrated with ferrous ammonium sulfate to determine the amount of organic carbon (C) in the sample. The total nitrogen (N) concentration in the digest was then determined using the semi-micro Kjeldahl method described by Nelson and Sommers [39].

2.5. Data Analysis

The soil data generated was collated using Excel spreadsheet software and analyzed with SPSS version 23. The data obtained were then used to compare SOC distribution among the selected plots and at different soil depths using analysis of variance (ANOVA) and Duncan's New Multiple Range tests for means separation.

3. RESULTS

3.1. Effect of Land Management Practices on Soil Particle Size in Mangrove Ecosystems

The particle size distribution of soils under different land management practices is summarized in Table 1. In cultivated lands, sand content did not differ significantly ($P > 0.05$) between 20–40 cm and 40–60 cm depths. However, sand content at these depths was significantly lower ($P < 0.05$) than at 0–20 cm. Silt content averaged 19.03 ± 6.73%, with the highest at 0–20 cm (27.20 ± 2.65%), followed by 20–40 cm (16.20 ± 4.36%), and the lowest at 40–60 cm (13.70 ± 0.50%). Clay content in cultivated soils averaged 2.85 ± 2.92% and showed a depth-related trend similar to that of silt.

In regenerated lands, the mean sand content was 67.23 ± 6.79%, with the highest proportion observed at 20–40 cm (71.12 ± 9.54%). The clay content averaged 7.68 ± 4.02% but exhibited a distinct depth pattern compared to sand and silt. The highest clay content was recorded at 0–20 cm (10.01 ± 4.73%), followed by 40–60 cm (6.68 ± 2.65%), and the lowest at 20–40 cm (6.35 ± 4.80%). No significant differences ($P > 0.05$) were detected in sand, silt, or clay content across soil depths in regenerated areas.

In natural forest soils, the sand content averaged 74.23 ± 6.33%, with the maximum proportion observed at depths of 40–60 cm (79.12 ± 5.29%). Clay content increased with soil depth, indicating a trend of accumulation in deeper layers.

These results indicate that land management practices influence the vertical distribution of soil particles in mangrove ecosystems, with cultivated lands showing more pronounced depth-dependent variation in sand, silt, and clay fractions than regenerated and natural forest soils.

Table 1. Particle size distribution of mangrove soils in Ilaje LGA of Ondo State under the selected land management practices.

Land use type	Depth	Sand content (%)	Silt content (%)	Clay content (%)	Soil texture
Cultivated land	0-20 cm	66.79 ± 5.51^{b}	27.20 ± 2.65^{a}	6.01 ± 3.06^{a}	Loamy Sand
	20-40 cm	82.45 ± 4.73^{a}	16.20 ± 4.36^{b}	1.35 ± 0.58^{b}	
	40-60 cm	85.12 ± 1.00^{a}	13.70 ± 0.50^{b}	1.18 ± 1.32^{b}	
	Average	78.12 ± 9.33^{i}	19.03 ± 6.73^{j}	2.85 ± 2.92^{j}	
Regenerated land	0-20 cm	64.79 ± 7.64^{a}	25.20 ± 3.00^{a}	10.01 ± 4.73^{a}	Sandy Loam
	20-40 cm	71.12 ± 9.54^{a}	22.53 ± 5.20^{a}	6.35 ± 4.80^{a}	
	40-60 cm	65.79 ± 0.58^{a}	27.53 ± 2.08^{a}	6.68 ± 2.65^{a}	
	Average	67.23 ± 6.79^{j}	25.09 ± 3.85^{i}	7.68 ± 4.02^{i}	
Natural forest	0-20 cm	69.12 ± 7.00^{b}	22.53 ± 3.21^{a}	8.35 ± 7.23^{a}	Sandy Loam
	20-40 cm	74.45 ± 2.89^{a}	20.20 ± 2.29^{a}	5.35 ± 3.33^{a}	
	40-60 cm	79.12 ± 5.29^{a}	18.20 ± 2.65^{a}	2.68 ± 2.65^{a}	
	Average	74.23 ± 6.33^{i}	20.31 ± 3.03^{j}	5.46 ± 4.86^{ij}	

Note: Values are means ± standard error. Means with different superscript letters (a, b) within the same column indicate significant differences among land-use types, while means with different superscript letters (i, j) within the same row indicate significant differences among soil depths, based on Duncan's New Multiple Range Test at $P < 0.05$.

3.2. Effect of Land Management Practices on Soil TOC in Mangrove Ecosystem

Table 2 presents the total soil organic carbon (SOC) content of mangrove soils across various land management practices studied. The natural forest exhibited the highest average TOC at 11.04 ± 2.06%, with the peak TOC of 12.37 ± 1.50% recorded at the 20–40 cm soil depth. No significant differences ($P > 0.05$) were observed among the TOC values at the three examined soil depths within the natural forest.

Regenerated land exhibited an average TOC of 9.62 ± 1.74%, reaching a maximum of 10.18 ± 2.59% at 20–40 cm depth. Similar to natural forest, TOC did not significantly differ across soil depths in regenerated areas ($P > 0.05$). Cultivated land showed the lowest average TOC at 6.20 ± 1.62%, with the highest mean of 6.73 ± 2.93% at 40–60 cm depth. No significant variation was detected among soil depths in cultivated land ($P > 0.05$).

Comparisons across land management practices indicated no significant difference in TOC between natural forest and regenerated land (P > 0.05). In contrast, TOC in cultivated land was significantly lower than in both natural forest and regenerated areas (P < 0.05).

Table 2. TOC content of mangrove soils in Ilaje LGA of Ondo State under the selected land management practices.

Land use type	Depth	Organic carbon content (%)
Cultivated land	0-20 cm	6.16 ± 0.89^{a}
	20-40 cm	5.70 ± 0.52^{a}
	40-60 cm	6.73 ± 2.93^{a}
	Average	$\mathbf{6.20\pm1.62^{j}}$
Regenerated land	0-20 cm	9.57 ± 1.71^{a}
	20-40 cm	10.18 ± 2.59^{a}
	40-60 cm	9.11 ± 1.29^{a}
	Average	$\mathbf{9.62\pm1.74^{i}}$
Natural forest	0-20 cm	10.57 ± 2.34^{a}
	20-40 cm	12.37 ± 1.50^{a}
	40-60 cm	10.17 ± 2.28^{a}
	Average	$\mathbf{11.04\pm2.06^{i}}$

Note: Values are means ± standard error. Means with different superscript letters (a, b) within the same column indicate significant differences among land-use types, while means with different superscript letters (i, j) within the same row indicate significant differences among soil depths, based on Duncan's New Multiple Range Test at $P < 0.05$.

3.3. Effect of Land Management Practices on Particulate and Mineral-Associated SOC Content in Mangrove Ecosystem

The POC and MOC content of mangrove soils in Ilaje LGA, Ondo State, under selected land management practices are summarized in Table 3.

Table 3. Particulate and mineral-associated SOC content of mangrove soils in Ilaje LGA, Ondo State, under selected land management practices.

	Land use type	Depth	Organic carbon content (%)
Particulate	Cultivated land	0-20 cm	4.35 ± 1.56^{a}
		20-40 cm	3.21 ± 0.37^{a}
		40-60 cm	3.45 ± 2.29^{a}
		Average	$\mathbf{3.67\pm1.49^{j}}$
	Regenerated land	0-20 cm	5.21 ± 0.38^{a}
		20-40 cm	4.98 ± 1.85^{a}
		40-60 cm	4.62 ± 0.81^{a}
		Average	$\mathbf{4.93\pm1.06^{ij}}$
	Natural forest	0-20 cm	5.11 ± 1.48^{a}
		20-40 cm	6.42 ± 0.36^{a}
		40-60 cm	5.51 ± 1.36^{a}
		Average	$\mathbf{5.68\pm1.17^{i}}$
Mineral associated	Cultivated land	0-20 cm	1.81 ± 1.02^{a}
		20-40 cm	2.49 ± 0.49^{a}
		40-60 cm	3.28 ± 1.22^{a}
		Average	$\mathbf{2.52\pm1.05^{j}}$
	Regenerated land	0-20 cm	4.37 ± 1.44^{a}
		20-40 cm	5.20 ± 0.75^{a}
		40-60 cm	4.49 ± 0.61^{a}
		Average	$\mathbf{4.69\pm0.95^{i}}$
	Natural forest	0-20 cm	5.46 ± 0.87^{a}
		20-40 cm	5.95 ± 1.28^{a}
		40-60 cm	4.66 ± 1.74^{a}
		Average	$\mathbf{5.35\pm1.29^{i}}$

Note: Values are means ± standard error. Means with different superscript letters (a, b) within the same column indicate significant differences among land-use types, while means with different superscript letters (i, j) within the same row indicate significant differences among soil depths, based on Duncan's New Multiple Range Test at $P < 0.05$.

For POC, the natural forest exhibited the highest average value (5.68 ± 1.17%), with the maximum observed at a soil depth of 20–40 cm (6.42 ± 0.36%). No significant differences ($P > 0.05$) were detected among the three soil depths within the natural forest. The regenerated land followed closely, with an average POC of 4.93 ± 1.06%, reaching a peak of 5.21 ± 0.38% at a depth of 0–20 cm, again showing no significant variation across depths ($P > 0.05$). The cultivated land had the lowest average POC (3.67 ± 1.49%), with the highest value at 0–20 cm (4.35 ± 1.56%), followed by 40–60 cm (3.45 ± 2.29%), while 20–40 cm depth had the lowest POC (3.21 ± 0.37%). Although no significant differences were observed within regenerated and natural forest lands or within cultivated land across depths, a significant difference ($P < 0.05$) was observed between the POC of natural forest and cultivated lands.

Regarding MOC, a similar trend was observed. The natural forest had the highest average MOC (5.35 ± 1.29%), with the maximum value at 20–40 cm (5.95 ± 1.28%). There were no significant differences across soil depths ($P > 0.05$). The regenerated land had an average MOC of 4.69 ± 0.95%, with the highest value at 20–40 cm (5.20 ± 0.75%). The cultivated land recorded the lowest average MOC (2.52 ± 1.05%), with the peak at 40–60 cm (3.28 ± 1.22%).

These results indicate that natural and regenerated forests maintain higher POC and MOC levels compared to cultivated lands, highlighting the impact of land use on soil carbon sequestration in mangrove ecosystems.

3.4. Effect of Land Management Practice on Soil Total Nitrogen Content (TN) in Mangrove Ecosystem

The total nitrogen (TN) content of mangrove soils across different land-use types and soil depths is presented in Table 4. The natural forest exhibited the highest average soil TN content (0.21 ± 0.02%), with the maximum value observed at 0–20 cm depth (0.22 ± 0.02%), followed by 20–40 cm (0.21 ± 0.04%), and the lowest at 40–60 cm (0.20 ± 0.02%). Differences in TN content among the three soil depths of the natural forest were not statistically significant ($P > 0.05$).

Regenerated land showed an average TN content of 0.20 ± 0.02%, with the highest TN observed at 40–60 cm (0.21 ± 0.00%), followed by 20–40 cm (0.20 ± 0.02%), and the lowest at 0–20 cm (0.19 ± 0.02%). Similar to the natural forest, no significant differences in TN content were detected among soil depths within the regenerated land ($P > 0.05$).

The cultivated land had the lowest average TN content (0.19 ± 0.02%), following a slightly different pattern. The highest TN content was recorded at 20–40 cm (0.20 ± 0.02%), followed by 0–20 cm (0.19 ± 0.02%), and the lowest at 40–60 cm (0.18 ± 0.00%), with no significant differences among soil depths ($P > 0.05$).

Comparisons across land-use types revealed no significant difference ($P > 0.05$) in average TN content between regenerated and cultivated lands. However, the TN content of soils from both regenerated and cultivated lands was significantly lower than that of the natural forest ($P < 0.05$), highlighting land management's impact on soil nitrogen.

Table 4. Soil total nitrogen content in mangrove soils of Ilaje LGA, Ondo State, under selected land management practices

Land use type	Depth	Soil total nitrogen (%)
Cultivated land	0-20 cm	0.19 ± 0.02^{a}
	20-40 cm	0.20 ± 0.02^{a}
	40-60 cm	0.18 ± 0.00^{a}
	Average	$\mathbf{0.19 \pm 0.02^{j}}$
Regenerated land	0-20 cm	0.19 ± 0.02^{a}
	20-40 cm	0.20 ± 0.02^{a}
	40-60 cm	0.21 ± 0.00^{a}
	Average	$\mathbf{0.20 \pm 0.02^{ij}}$
Natural forest	0-20 cm	0.22 ± 0.02^{a}
	20-40 cm	0.21 ± 0.04^{a}
	40-60 cm	0.20 ± 0.02^{a}
	Average	$\mathbf{0.21 \pm 0.02^{i}}$

Note: Values are means ± standard error. Means with different superscript letters (a, b) within the same column indicate significant differences among land-use types, while means with different superscript letters (i, j) within the same row indicate significant differences among soil depths, based on Duncan's New Multiple Range Test at $P < 0.05$.

3.5. Effect of Land Management Practice on Soil pH in Mangrove Ecosystem

The pH values of mangrove soils in Ilaje LGA, Ondo State, under various land management practices are shown in Table 5. Cultivated land had the highest average soil pH of 4.93 ± 0.49, with a maximum of 5.38 ± 0.06 at 0–20 cm depth. The pH at 20–40 cm and 40–60 cm depths was lower, at 4.83 ± 0.59 and 4.59 ± 0.34, respectively. These differences across depths were not statistically significant (P > 0.05).

Regenerated land exhibited an average soil pH of 4.79 ± 0.51, with the highest value of 5.11 ± 0.59 at 40–60 cm depth. Similar to cultivated land, no significant pH differences were observed across soil depths (P > 0.05). Conversely, natural forest land had the lowest average soil pH of 4.36 ± 0.33, showing a pattern comparable to cultivated land.

Comparisons among land-use types showed no significant differences in soil pH between regenerated and natural forests or between regenerated and cultivated land (P > 0.05). However, soil pH in natural forests was significantly lower than in cultivated land (P < 0.05).

Table 5. Soil pH levels of mangrove soils in Ilaje LGA, Ondo State, under specific land management practices.

Land use type	Depth	pH
Cultivated land	0-20 cm	5.38±0.06^{a}
	20-40 cm	4.83±0.59^{a}
	40-60 cm	4.59±0.34^{a}
	Average	**4.93±0.49^{i}**
Regenerated land	0-20 cm	4.38±0.42^{a}
	20-40 cm	4.88±0.31^{a}
	40-60 cm	5.11±0.59^{a}
	Average	**4.79±0.51^{ij}**
Natural forest	0-20 cm	4.55±0.57^{a}
	20-40 cm	4.28±0.03^{a}
	40-60 cm	4.24±0.10^{a}
	Average	**4.36±0.33^{j}**

Note: Values are means ± standard error. Means with different superscript letters (a, b) within the same column indicate significant differences among land-use types, while means with different superscript letters (i, j) within the same row indicate significant differences among soil depths, based on Duncan's New Multiple Range Test at $P < 0.05$.

4. DISCUSSION

Land management practices significantly influence the total organic carbon (TOC) content in mangrove soils within the study area. Throughout all soil depths, TOC levels were lowest in cultivated lands compared to regenerated and natural forests. The higher TOC in regenerated and natural forests is due to their increased silt and clay content, which are rich in organic matter. These finer particles facilitate the formation of organo-mineral complexes with metal ions and hydrous oxides, stabilizing organic matter and creating cohesive mud layers. Conversely, cultivated soils contain more sand and less silt and clay, resulting in lower TOC levels [10, 44]. This finding aligns with previous studies indicating that clay particles strongly bind organic carbon, which reduces carbon loss [45-47]. Similarly, Tue et al. [48] and Nengi-Benwari et al. [49] highlighted that high clay content in mangrove sediments enhances carbon sequestration, while other studies have linked the stable fraction of soil organic matter directly to silt and clay content. Analysis of soil depth showed that the 20–40 cm layer had the highest total organic carbon (TOC) in most land uses, with upper layers (0–20 cm and 20–40 cm) generally richer in TOC than the 40–60 cm layer. An exception was cultivated land, where TOC peaked at 40–60 cm, surpassing levels in upper layers. This pattern likely results from human activities like logging and farming, which remove organic matter from surface layers and promote oxidation of labile carbon, leaving more stabilized carbon in deeper horizons [50].

Land use significantly influences soil organic carbon (SOC) fractions. Cultivated soils show reductions in both particulate and mineral-associated SOC across all depths, indicating that continuous cultivation accelerates labile SOC depletion and reduces organic matter inputs. Soil carbon storage depends heavily on litter input, vegetation residues, and their decomposition rates, all affected by land management practices [45]. The labile particulate fraction consistently makes up a larger share of total SOC than the mineral-associated fraction across land uses. Regenerated and natural forests exhibit higher SOC levels in both fractions compared to cultivated land, highlighting their superior capacity for organic matter accumulation and storage. These findings differ from observations in other ecosystems. Bayer et al. [1] reported lower particulate SOC relative to mineral-associated SOC in Brazilian soils, while Jamala and Oke [35] found the mineral-associated fraction dominated in the Southern Guinea Savanna of Nigeria due to climatic conditions favoring rapid decomposition of labile matter. Mineral-associated SOC, which is the recalcitrant and stabilized fraction, was highest in natural forests, followed by regenerated lands, with cultivated lands showing significantly lower levels. Across all land uses, mineral-associated SOC tended to increase with depth, peaking at 20–40 cm in regenerated and natural forests, but at 40–60 cm in cultivated land. Factors such as higher clay and silt content, microaggregation of soil particles, and low oxygen conditions in mangrove sediments likely contribute to organic carbon stabilization in undisturbed soils [10, 35, 51-53].

Cultivated soils also exhibited lower total nitrogen, likely due to leaching, mineralization, and removal during harvest, compounded by tillage that exposes organic matter to oxidation. Similar trends have been reported by Malo et al. [54] in other ecosystems as well. Soil pH across various depths and land uses ranged from moderately acidic (4.24–5.38). Mangrove soil acidity results from sulfide oxidation, litter decomposition, and organic acid formation, processes affected by tidal currents and root activity, influencing soil chemistry and plant growth in these environments [55-58]. The slightly higher pH observed in cultivated soils may result from reduced litter input and organic matter, reflecting lower plant cover and higher human disturbance compared to undisturbed forests [59-61].

5. CONCLUSION

Mangroves are among the most productive terrestrial ecosystems, playing a vital role in terrestrial and marine carbon cycling. Their high primary productivity and long-term carbon storage in waterlogged soils make mangrove forests significant carbon reservoirs, essential for global carbon balance and climate regulation.

The interaction between anthropogenic and climatic factors influences the structure and function of mangrove ecosystems. Human activities such as land-use change, coastal development, pollution, and deforestation increasingly degrade these environments and diminish their carbon storage capacity. Concurrently, climate stressors like sea-level rise, altered precipitation patterns, and more frequent extreme weather events affect mangrove hydrology, sediment dynamics, and nutrient availability, further impacting ecosystem health and resilience.

Results from this study demonstrate that land management practices significantly influence soil organic carbon stocks and related soil physicochemical properties in mangrove ecosystems. Variations in management intensity and disturbance levels lead to measurable changes in soil characteristics, emphasizing the sensitivity of mangrove soils to human activities. These findings underscore the importance of implementing sustainable land management strategies to preserve soil quality, maintain carbon stocks, and support the long-term resilience of mangrove environments.

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