

Soil Organic Carbon Stock Variations Across Depth and Land use Types in the Sudano-Sahelian Zone, Gashua, Nigeria

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Abstract

This study assessed the differences in soil organic carbon (SOC) stocks across different land uses and depths in the Sudano-Sahelian area of Gashua, Yobe, Nigeria. Samples were collected from the depths of 0-15 cm and 15-30 cm under wetland, forested land, cultivated land, and grassland. Due to non-normal data (Shapiro-Wilk $p < 0.05$), Spearman's correlation analyzed SOC relationships with macronutrients, land use, and depth. Kruskal-Wallis tests assessed land use and depth effects on SOC distribution. "Wetlands and forested lands appear as the primary carbon sinks. Wetlands recorded the highest mean SOC stock of 8.45 Mg ha^{-1} at the 15-30 cm depth, followed by forested land (8.28 Mg ha^{-1}), cultivated land (6.89 Mg ha^{-1}), and grassland (5.00 Mg ha^{-1}). The soil pH is slightly acidic to neutral (6.5-7.2); the bulk density is from 1.2 to 1.3 g cm^{-3} ; nitrogen ranges from 1.8 kg ha^{-1} to 1.7 kg ha^{-1} ; phosphorus recorded 1.20 kg ha^{-1} , and potassium recorded 1.08 kg ha^{-1} . Spearman's correlation showed strong positive SOC relationships with N ($\rho=0.81$, $p<0.001$) and P ($\rho=0.81$, $p<0.001$), and a moderate positive correlation with depth ($\rho=0.66$, $p<0.01$). Kruskal-Wallis tests revealed significant depth effects ($H=5.14$, $p=0.023$) but non-significant land use differences ($H=3.71$, $p=0.16$). "These findings highlight the need to protect wetland and forested land, alongside subsurface soil management, to enhance SOC sequestration in Northern Nigeria.

Keywords: Claridae, Mormyridae, Aquaculture, By-Products, Fatty Acids, Fish Oil Extract.

Introduction

It is widely accepted that the mitigation of global warming centers on reducing emissions and improving soil organic carbon (SOC) stocks worldwide (Solomon et al., 2007). SOC played a key role as an indicator of soil quality by influencing nutrient stability, aggregation, and ecological function, where it acts as the primary universal carbon reservoir (Abegaz et al., 2020; FAO and ITPS, 2015). Additionally, natural ecosystems generally have a greater ability to increase carbon sequestration potential than human-modified settings; the detailed description of land use type in terms of agricultural land or forestland regrowth can significantly influence soil's ability to store organic carbon and total nitrogen (Bagwan et al., 2023; Onyegbule et al., 2023).

However, soil organic carbon (SOC) stock is considered the most dependable carbon storage pool of the world ecosystem, comprising ~58% of soil organic matter, and serves as the most reliable terrestrial carbon pool with critical global carbon cycle functions (Abdalla

et al., 2018; Nelson & Sommers, 1996). Agricultural productivity is enhanced through the effective change in the land-use patterns to improve the soil organic carbon (SOC), boost soil fertility, and enhance food security and terrestrial life globally. On the contrary, sustainable practices enhance sequestration, aiding the global carbon cycle and food security (FAO, 2017; Bhandari and Bam, 2013). Furthermore, understanding the mechanisms required for driving these fluctuating rates of sequestration across different land use types and soil depths is central for developing targeted strategies for monitoring and managing carbon (Yenesew et al., 2025).

Undeniably, various research studies have corroborated these findings, indicating that land-use types such as natural forests and various agricultural lands significantly enable soil chemical characteristics, including SOC, cation exchange capacity, and total nitrogen, thus emphasizing the need for further investigation of agroforestry systems' potential to store carbon and nitrogen in the forest zones (Onyegbule et al., 2023).

Despite the global emphasis on soil organic carbon (SOC) as a means for climate mitigation, there are still persistent data gaps in SOC dynamics in this vulnerable region of the Sudano-Sahelian of Nigeria. In Gashua, Yobe State, the environment experiences rapid desertification and land-use shifts that aggravate SOC loss, yet the depth-wise dynamics remain unquantified (Onokebhagbe et al., 2025). Limited studies in the Sahelian regions highlight low SOC concentrations as a result of climate change and poor soil management, emphasizing the critical need for local assessments. Therefore, addressing this gap will inform evidence-based management in this ecologically sensitive area. This study aims to assess the differences in soil organic carbon stock distribution under different depths and land use types in the Sudano-Sahelian area of Gashua, Yobe, Nigeria.

Material and Method

Description of the Study Area

The study was conducted in Gashu'a, an area of the Bade Local Government, Yobe State, in Northeastern Nigeria. Gashua is located between latitudes 12.87°N and longitudes 11.46°E, with an altitude of 293 meters above sea level. It is situated in the Sudano-Sahel savanna ecological zone of Nigeria. The major vegetation type in the area consists of an open thorny savannah with short trees and grasses. The trees are about 5 to 10 m high (Alhassan et al., 2018).

Climate of the Study Area

The climate of the study area is characterized by high temperatures and seasonal rainfall. The minimum temperature ranges from 10 to 12°C in January, while the maximum is from 34 to 37°C in March. The minimum rainfall is from 300 to 500 mm per annum, and maximum rain is received between August and September and is unimodal, lasting mostly from June to September, while the dry season lasts from October to May (Alhassan et al. 2018).

Geology of the Study Area

The geology of Gashua is primarily characterized by the Chad Formation, which is part of the larger Chad Basin. This formation is composed mainly of unconsolidated sedimentary deposits of tertiary to quaternary age that typically include sands, silts, and clays, which have been laid down in lacustrine (lake) and fluvial (river) environments (Offodile, 1992). The soils of the study area are typically neutral to slightly alkaline with significant limitation and a very low content of organic matter. The dominant soil type in the area is sandy loam (Sani, 2018).

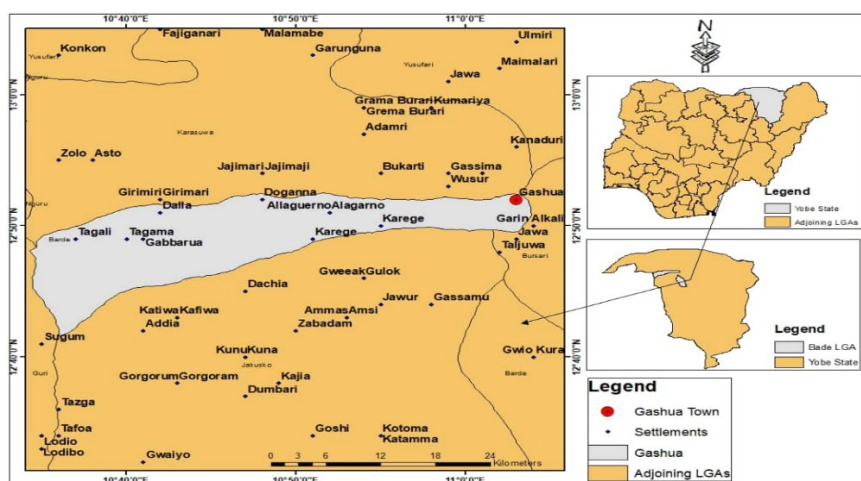


Figure 1. Map of the Study Area.

Soil Samples Collection

The soil samples were collected at random using an auger from four distinct land uses (grassland, cultivated land, forested land, and cultivated land) at two depth intervals: 0–15 cm and 15–30 cm. was obtained from two depths, with five replicates per location to make 40 individual samples. These samples were homogenized and composited (n=8) for analysis.

Laboratory Analysis

All analyses followed SSSA standardized procedures (Sparks et al., 1996; Page et al., 1982), including Walkley-Black SOC, Olsen-P, alkaline permanganate N, and flame photometry for exchangeable cations. The particle size analysis was determined using the hydrometer method described by Piper (2002) using sodium hexametaphosphate as a dispersing agent. In this method, the amount of silt and clay in the soil suspension was determined by measuring the depth as a function of time using the hydrometer method. The bulk density of soil is determined by the use of a graduated measuring cylinder (Black 1965). The pH was determined in a 1:25 soil water suspension using a digital pH meter (Jackson, 2014). Available nitrogen was determined by the use of the alkaline potassium permanganate method as given by Subbiah and Ashija (1956) as modified by Sahrawat (1982) to include

nitrate and nitrite fractions through Devarda's alloy addition for a more wide-ranging assessment in tropical soils. Soil Organic Carbon (SOC) was analyzed via the Walkley-Black wet oxidation method (1934), as refined by Nelson and Summers (1982) and used by Hamza and Shehu (2025). Available phosphorus was determined with the help of the colorimetric method of Olsen (1954). as adapted by Kuo (1996) with ascorbic acid reduction to minimize interferences and enhance stability using a two-step process, i.e., extraction of phosphorus from soil by sodium bicarbonate. Following extraction from the soil, phosphorus in the extract measures the reaction of phosphorus with ammonium molybdate in an acid medium to form molybdophosphoric acid for 24 hours. The available potassium was determined by a flame photometer; the extraction principle followed the Toth and Prince (1949) procedure.

Statistical Data Analysis

Dual statistical tools were employed to evaluate the factors influencing soil organic carbon (SOC) distribution across land use types and soil depths in the study area. The interrelationship between SOC stock and soil chemical properties was first explored using Spearman's correlation due to its robustness with non-normally distributed data. Subsequently, the Kruskal-Wallis test was applied to assess the significance of land use types and soil depth on SOC distribution using the R statistical software package. Non-normal data (Shapiro-Wilk $p < 0.05$) tests confirmed the data were not normally distributed (Conover, 1999). Thus, Spearman's correlation was used to analyze associations between SOC stock and land use types across soil depths.

Results and Discussion

Result:

Table 1: Physicochemical properties of the study area

Land use types	Depth	pH	SO C	S O M	N	P	K	N a	C E C	EC	Bulk density	Particle Density	A W C	SOC Stock
Grass land	1	7.01	0.35	0.603	192.12	17.71	0.29	1.13	8.83	0.024	1.38	2.792	22.81	4.707
	2	7.42	0.12	0.206	212.01	19.01	0.86	0.87	5.22	0.019	1.39	2.792	24.11	5.004
Cultivated Land	1	7.03	0.22	0.379	192.12	16.91	1.23	1.28	7.51	0.031	1.35	2.786	23.33	4.455
	2	7.61	0.17	0.293	220.01	20.11	1.89	1.11	4.31	0.046	1.35	2.786	26.22	6.885

Land use types	Depth	pH	SO C	S O M	N	P	K	N a	C E C	EC	Bulk density	Particle Density	A W C	SOC Stock
Forested land	1	7.11	0.33	0.568	198.12	17.09	1.58	1.19	6.82	0.034	1.19	2.798	23.82	5.891
	2	7.06	0.23	0.396	226.2	21.11	1.98	1.17	4.56	0.038	1.21	2.798	25.64	8.281
Wetland	1	6.92	0.29	0.499	192.12	18.08	0.54	1.14	5.15	0.061	1.23	2.757	25.56	5.351
	2	7.25	0.22	0.379	216.23	21.01	1.12	0.77	5.22	0.112	1.28	2.757	28.24	8.448
Mean	1.50	7.17	0.24	0.41	206.11	18.87	1.18	1.08	5.95	0.04	0.08	2.78	24.96	6.12
Std	0.53	0.23	0.07	0.13	14.06	1.69	0.61	0.17	1.59	0.02	0.02	0.01	1.79	1.57
SE	0.18	0.08	0.02	0.04	4.97	0.59	0.21	0.06	0.56	0.01	1.23	0.01	0.63	0.55

Table. 2. Spearman's Rank Order Correlation Among Soil Properties

Variable	pH	SOC Stock	N	P	K	Depth
pH	1.00					
SOC Stock	0.45	1.00				
N	0.71**	0.81***	1.00			
P	0.43	0.81***	0.85***	1.00		
K	0.48	0.52*	0.73	0.36	1.00	
Depth	0.76***	0.66	0.89***	0.87***	0.44	1.00

Table. 3. Kruskal-Wallis Test Results for Soil Organic Carbon

Parameters	Test statistic	df	p-value	Results
Land use (4)	H = 3.71	3	0.16	NS
Depth (2)	H = 5.14	1	0.023	SN

The table shows that the Kruskal-Wallis tests confirmed significant SOC decline with depth, $H(1) = 5.14$, $p = 0.02$, but non-significant land use differences, $H(3) = 3.71$, $p = 0.16$. Note:

Composite samples (n = 8). Land use categories: forested land, wetland, cultivated land, and grassland. Depths: 0-15 cm vs. 15-30 cm. $p < .05$. NS = non-significant, SN = significant

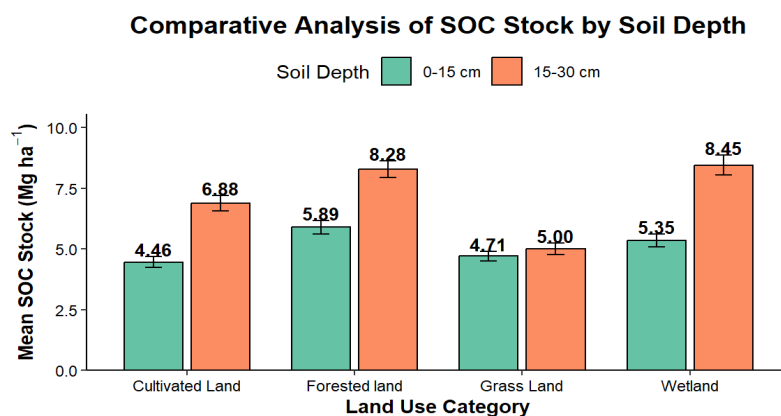


Figure 2: difference in mean value of the soil organic carbon stock across the different land use types with depth.

Variation of SOC Stock by Land Use

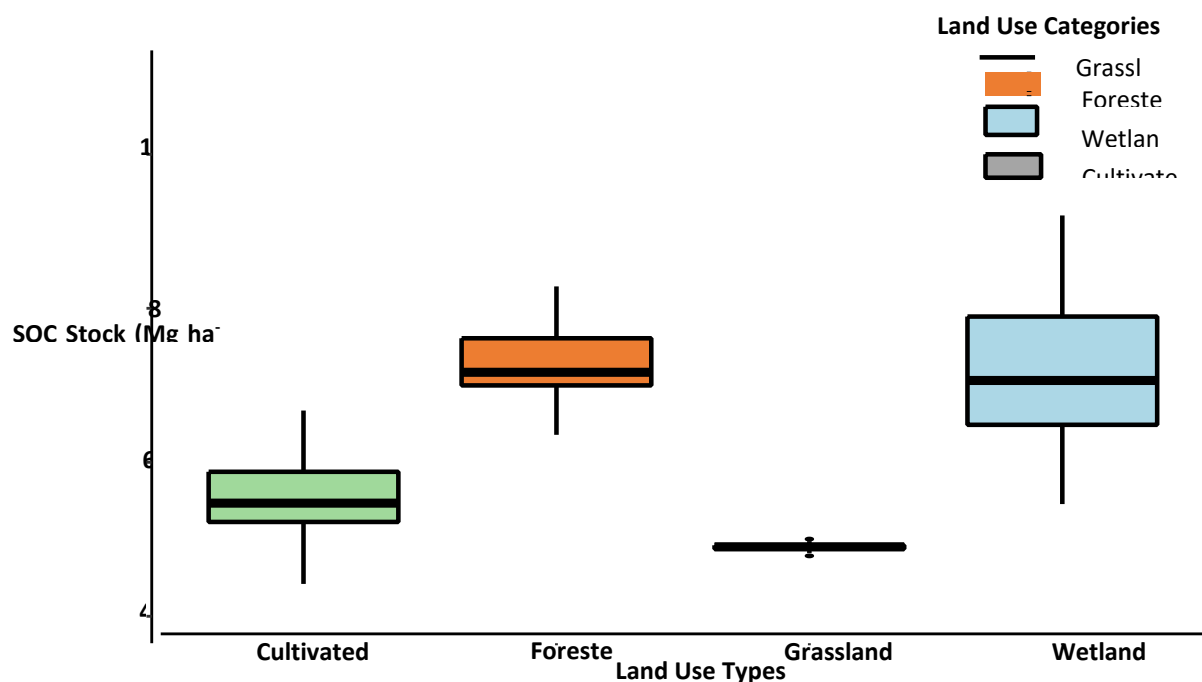


Figure 3. Variations in SOC stock across different land-use types.

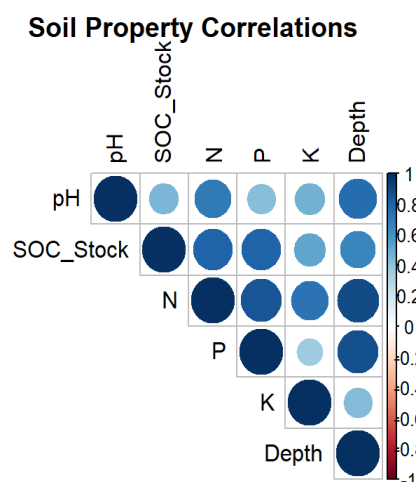


Figure 4. Correlation Plot (Soil Property Correlations).

Discussion

Statistical Evaluation of Soil Organic Carbon Stock Across Land Use Types and Depth

Figure 2 (bar chart) shows that wetland soils have higher SOC stocks at the surface (0-15 cm: 5.35 Mg ha⁻¹) than at the subsurface (15-30 cm: 8.45 Mg ha⁻¹). This implies that even with lower inputs, wetland conditions in deeper marsh layers improve carbon preservation. While Figure 2 shows the mean, Figure 3 (boxplot) shows significant spatial heterogeneity (wide interquartile range) within wetland soils. In Figure 4, the soil organic carbon (SOC) stock and nitrogen ($\rho = 0.68$, $p < 0.01$) and phosphorus ($\rho = 0.52$, $p < 0.05$) showed strong positive associations according to Spearman correlation analysis, suggesting that nutrient enrichment goes hand in hand with SOC accumulation. On the other hand, in line with surface organic matter stratification, SOC stock had a negative correlation with both soil depth ($\rho = -0.71$, $p < 0.01$) and potassium ($\rho = -0.45$, $p < 0.05$), which may be due to surface litter stratification (Jobbágy & Jackson, 2000). However, as a result of non-normal distributions and a limited sample size ($N = 8$), Kruskal-Wallis tests showed significant depth stratification ($H = 5.14$, $df = 1$, $p = 0.023$) but non-significant land use differences ($H = 3.71$, $df = 3$, $p = 0.156$).

pH, Soil Organic Carbon (SOC), And Soil Organic Matter (SOM):

From Table 1, the pH range is between 6.92 (wetland at depth 1) and 7.61 (cultivated land at depth). The pH is slightly more alkaline in cultivated lands than in grassland and forested land. Wetland soils showed a lower pH. Similar findings were reported by Jiang et al. (2006), where they reported cultivated lands to have slightly higher pH values due to liming and fertilizer applications, while wetlands had lower pH due to waterlogging and organic matter decomposition. The SOC varies from 0.12% (grassland depth 2) to 0.35% (grassland depth 1). SOM follows a similar trend. Forested and grassland areas tend to have higher SOC and SOM than cultivated lands. Wetlands, with moderate SOM, indicate the role of waterlogged conditions in preserving organic material. Similar trends were observed by Lal

(2019), who noted that forest soils typically have higher SOC stocks due to leaf litter and less disturbance, while cultivated lands experience depletion due to tillage and reduced organic matter inputs.

Nitrogen (N), Phosphorus (P), and Potassium (K)

Nitrogen concentrations showed 192.12 mg/kg (grassland, depth 1) and 226.2 mg/kg (forested land, depth 2). Forested land and wetland soils give a higher nitrogen value than cultivated land and grassland; likely it may be as a result of organic matter inputs and slower decomposition in these environments. A study by Bationo and Kihara (2016) reported higher nitrogen levels in forested soils and wetlands than in agricultural soils, which resulted in nitrogen lost due to leaching and crop removal. The result on phosphorus ranges from 16.91 mg/kg (cultivated land, depth 1) to 21.11 mg/kg (forested land, depth 2). Forested and wetland soils have higher phosphorus content, while cultivated lands show a notable increase with depth. The results align consistently with those of Singh and Ryan (2016), who found higher phosphorus concentrations in forested soils due to organic matter turnover, whereas cultivated soils showed phosphorus depletion due to crop uptake unless replenished by fertilizers. The potassium ranges between 0.29 mg/kg (grassland, depth 1) and 1.98 mg/kg (forested land, depth 2). Higher potassium levels are observed in forested and cultivated lands, while grassland shows the lowest values. This observation agrees with findings from Marschner (2017), who reported that potassium levels in forest soils are often higher due to the recycling of nutrients through leaf litter, while grasslands may have lower levels depending on plant uptake and soil type.

Cation Exchange Capacity (CEC), and Electrical Conductivity (EC)

The results on the CEC recorded 4.31 cmol/kg (cultivated land, depth 2) and 8.83 cmol/kg (grassland, depth 1). Grassland soils show the highest CEC, while cultivated soils have lower values. The higher CEC in grassland soils is in line with the findings of Brady and Weil (2016), who reported that soils with higher organic matter, such as those in grasslands, generally exhibit higher CEC values, enabling them to retain more nutrients. The EC results range between 0.019 dS/m (grassland, depth 2) and 0.112 dS/m (wetland, depth 2). Wetland soils have a higher EC, indicating a higher level of dissolved salts, potentially due to waterlogging or mineralization processes. Similar results were observed by Schlesinger (2017), who reported that wetland soils tend to accumulate salts due to poor drainage and evaporation, which increases electrical conductivity.

Bulk Density & Particle Density:

Bulk density shows a record from 1.19 g/cm³ (forested land, depth 1) to 1.39 g/cm³ (grassland, depth 2). Particle density remains relatively constant across all land uses. Higher bulk density in grasslands and cultivated lands suggests compaction, likely due to agricultural activities and grazing pressure. Sims and Sharpley (2016) also reported that bulk density tends to be higher in soils subjected to continuous grazing or tillage, which can lead to soil compaction, reducing porosity and water infiltration.

SOC Stock and Available Water Capacity (AWC):

Soil Organic Carbon stock (SOC) is 4.455 Mg/ha (cultivated land, depth 1) to 8.448 Mg/ha (wetland, depth 2). Wetland and forested soils show higher SOC stocks compared to grassland and cultivated soils. Lal (2019) also reported higher SOC stocks in wetland and forested soils compared to cultivated soils, largely due to the accumulation of organic matter and reduced decomposition rates under wet and undisturbed conditions. The AWC varies from 22.81% (grassland, depth 1) to 28.24% (wetland, depth 2). Wetlands have the highest AWC, indicating better moisture retention, while grassland soils show the lowest AWC. The high record of AWC in wetlands as found in our study is supported by Post and Kwon (2017), who also found that waterlogged conditions in wetland soils tend to increase their ability to retain water, while soils with lower organic matter content, like grasslands, have reduced water-holding capacity.

Correlation of Soil Chemical Properties with Organic Carbon Stock with Land Use and Depth

Dual statistical tools assessed factors affecting soil organic carbon (SOC) distribution by land use and soil depth. Spearman's correlation analyzed SOC stock versus soil chemical properties, given non-normal data (Shapiro-Wilk tests, $p < 0.05$). The Kruskal-Wallis test then evaluated land use and depth effects on SOC ($H = 3.71$, $p < 0.02$ for land use; $H = 5.14$, $p < 0.16$ for depth). Spearman correlation analysis (Table 4) revealed significant positive associations between SOC stock and macronutrients, particularly nitrogen ($r = 0.805$) and phosphorus ($r = 0.810$). Furthermore, soil depth exhibited strong positive correlations with N ($r = 0.894$) and P ($r = 0.873$). The non-parametric Kruskal-Wallis tests on composite SOC data ($n=8$) revealed non-significant differences across four land uses ($H = 3.71$, $df = 3$, $p = 0.16$), but significant depth stratification ($0-15 > 15-30$ cm; $H = 5.14$, $df = 1$, $p = 0.02$). Wetland ($0.26 \pm 0.05\%$) and forest ($0.28 \pm 0.07\%$) showed the highest SOC but were not statistically distinct from grassland or cultivated land. The positive relationship between depth and pH ($r = 0.764$) suggests a vertical gradient in soil alkalinity that corresponds with increased organic matter accumulation.

The distribution of SOC stocks in Gashua reflects the unique environmental constraints of the Sahelian zone. As shown in the bar chart, the higher accumulation in wetlands (8.45 Mg ha⁻¹) and forested lands (8.28 Mg ha⁻¹) at the 15-30 cm depth aligns with Hamza and Shehu (2025), who found that natural vegetation and moisture-heavy land uses are critical for carbon preservation in Northern Nigeria.

Furthermore, the positive correlation between depth and SOC stock observed in this study suggests that subsurface layers provide a cooler, steadier environment for organic matter, protecting it from the rapid oxidation typical of Sahelian surface soils, a process substantiated by Hengl et al. (2020). The high variance within the wetland category (Figure 3) further emphasizes the spatial sensitivity of these 'blue carbon' reservoirs in arid

landscapes. Research has shown consistently that SOC content is prevalently higher at the surface depth with a gradual decline in the deeper horizons, a trend corroborated by Lorenz and Lal (2018) and observed in similar African landscapes by Abegaz et al. (2020).

Conclusion

The study assessed the differences in soil organic carbon (SOC) stocks across depths and land-use types in the Sudano-Sahelian zone of Gashua, Nigeria. The findings observed that each land use type demonstrated a unique way through which organic carbon is stored in the soil, with the wetland and forested land recording the highest carbon capacity, followed by cultivated land and grassland.

The findings from this research point to the fact that there is a significant difference in soil organic carbon as we go vertically into the soil, where a subsurface depth of 15-30 cm served as the primary reservoir, especially in the wetland soils (8.45 Mg ha^{-1}). This positive relationship with depth ($\rho = 0.71$, $p = 0.047$) showed that deeper soil depths are more resilient to the activities of temperatures and oxidation reactions in the Sahelian environment. Furthermore, the strong correlations between SOC, total nitrogen ($\rho = 0.81$), and phosphorus ($\rho = 0.81$) agreed that organic matter dynamics are always linked to soil quality and nutrient availability.

Significant SOC stratification by depth was verified by Kruskal-Wallis tests ($H = 5.14$, $df = 1$, $p = 0.02$); however, due to limited replication ($N = 8$), land use differences were not significant ($H = 3.71$, $df = 3$, $p = 0.16$) for smaller samples that may not be normal, nonparametric methods that agreed with (Conover, 1999).

Limitation

The study's relatively small sample size ($n=8$ across land use-depth combinations) hindered parametric tests like ANOVA and reduced statistical power for finding sensitive variations, despite the thorough analysis carried out in the research. Land use effects' non-significant Kruskal-Wallis results ($H=3.71$, $p=0.16$) can be the product of Type II mistakes rather than actual biological equivalency. To confirm these trends, future studies should use a larger sample size ($n \geq 30$ per treatment) and take soil series and microclimatic differences into account. According to our results, improving SOC and guaranteeing sustainable agricultural output in Northern Nigeria may depend heavily on subsurface soil preservation and planned land-use management.

Conflict of Interest

The authors declare no potential conflicts or competing interests.

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