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Evaluation of Soil Organic Carbon in Gana, Saniko and Agbarha-Otor in Ughelli North Local Government Area of Delta State, Nigeria

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ABSTRACT: The restoration of mangroves was essential for implementing climate change mitigation strategies. Deforestation, forest degradation, and global warming increased the amount of greenhouse gases released from the soil, which contributed to climate change. The impact of forest restoration and regenerative farming techniques was thus hindered by the absence of adequate data on Soil Organic Carbon (SOC) in the Niger Delta region, which was vulnerable to soil degradation as a result of crude oil activities. Therefore, the quantification of SOC in Gana, Saniko, and Agbarha-Otor in Ughelli North of Delta State, Nigeria, was carried out to address this challenge. The findings indicated that Agbarha-Otor had the highest mean value of 1.1232 g/cm³, while Gana had the lowest mean soil bulk density (0.7764 g/cm³). A similar pattern was observed for the organic matter content, with Agbarha-Otor recording the highest mean value of 4.14% and Gana having the lowest mean soil organic matter content (2.03%). In Gana, Saniko, and Agbarha-Otor, the estimated levels of SOC ranged from 31.33 to 136.81 t C/ha. The results of this study would help policymakers develop measures that were suitable for the conservation of soil carbon.

KEYWORDS: Deforestation; soil organic carbon; mangrove; bulk density; climate change mitigation; soil degradation.

1. Introduction

The amount of SOC in a given terrestrial ecosystem defined its fundamental composition. Numerous established factors, both natural and anthropogenic, influenced variations in SOC levels, including vegetation, agricultural practices, climate, and soil characteristics [1]. The rate at which plant and animal residues decomposed was a significant factor controlling the amount of SOC in soil [1]. These dead plants and animals constituted a major portion of the terrestrial environment and served as primary carbon reservoirs in an ecosystem. Consequently, deforestation, forest degradation, and global warming increased the amount of greenhouse gases released from the soil [1, 2]. The decomposition process exposed the top 1 m of soil, which was estimated to contain about 1500 × 10^9 t of carbon, approximately twice the amount contained in the atmosphere [2]. Thus, one approach to revitalizing forest land was to recover carbon-depleted soils through sequestration [1]. Various research reports on SOC demonstrated substantial spatial variability from one location to another.

A study conducted in India showed that the SOC in the upper 50 cm soil layer was 4.1 × 10^9 t, and this value varied across regions [1]. Mangrove restoration was essential to the implementation of climate change mitigation policies in Nigeria. These policies aimed to restore and improve forest resources by shifting forest management from timber harvesting toward carbon sequestration [2]. The Niger Delta region, which was vulnerable to soil degradation due to crude oil extraction activities, had not experienced the full benefits of regenerative agricultural techniques and forest restoration because of insufficient SOC data. Therefore, the assessment of SOC in Gana, Saniko, and Agbarha-Ortor in Ughelli North, Delta State, Nigeria, was conducted to fill this gap. The results of this study would support policymakers in developing suitable measures for soil carbon conservation. This study also contributed to Sustainable Development Goals (SDGs) 2, 9, 12, 13, and 15 by providing empirical evidence on SOC dynamics that supported climate change mitigation, sustainable land management, ecosystem restoration, and food security in the Niger Delta region.

2. Materials and Methods

2.1. Sample location.

This study was conducted in Gana, Saniko, and Agbarha-Otor communities in Ughelli North Local Government Area of Delta State, Nigeria. These communities were located within the coordinates of approximately 6° 2′ 54″ E and 5° 30′ 40″ N, as illustrated in Figure 1. The study area was situated in Ughelli North.

Figure 1. Map of Delta State showing Ughelli North local government area and the sampling locations (Gana, Saniko, and Agbarha-Otor communities).

The soils found in the forested areas were mainly sandy and loamy in nature. For each location, the sample size was determined independently. The objective was to achieve a standard error of less than ±10% for the soil samples collected from the three communities (Saniko, Gana, and Agbarha-Otor). The sample size was calculated using Equation (1) [3]:

$$N = \frac{S^2 \; x \; T^2}{Er^2} \qquad (1)$$

where N is the required number of sample plots, S is the coefficient of variation, T is the t-value (1.96 at the 95% confidence level), and E is the allowable error.

To achieve the desired sampling precision of ±10% with high accuracy, a total of 150 plots were established across the three locations. A stratified random sampling method was applied.

2.2. Sample collection.

Using a soil auger, soil samples were collected at two depths (0–15 cm and 15–30 cm), adopting the method described by Subedi et al. [4]. These depths were selected to distinguish between the biologically active topsoil and the more stable subsurface soil layers, allowing for an accurate assessment of SOC distribution, soil bulk density variation, and carbon sequestration potential. A composite sampling technique was applied to estimate soil bulk density and carbon concentration. Sampling depths were adjusted across locations to reflect site-specific soil structure, compaction, and disturbance history, ensuring representative sampling of the active soil profile while maintaining standardized depth intervals for comparative analysis [1, 2]. To achieve the desired sampling precision of ±10% with high accuracy, a total of 54 samples were collected across the three locations.

2.3. Soil analysis.

2.3.1. Soil bulk density.

Using a digital balance, the moist weights of the samples were determined in situ. The samples were then transported in plastic bags to the Michael and Cecilia Ibru University laboratory, where they were air-dried before being placed in an electrothermal oven at 105°C for 24 hours. After oven drying, the samples were weighed, and the moisture content (MC %) was calculated using Equation (2) [5]:

$$M_C (\%) = (Ww - Wd)/Wd \; x \, 100 \qquad (2)$$

where MC (%) is the moisture content, Ww is the wet weight, and Wd is the dry weight.

The volume of the soil auger was determined by measuring its diameter and length. Bulk density was then calculated using Equation (3) [6]:

$$BD = Wd/Vs \qquad (3)$$

where B_D is bulk density, W_d oven dry weight of sample (g), V_s volume of soil core (cm^3).

2.3.2. Soil organic matter.

The loss on ignition (LOI) method was used to quantify the amount of organic matter in the soil [7, 8]. This method required the combustion of organic material at temperatures between 350 and 440°C [8, 9]. A muffle furnace was used to heat a 50 g sample of oven-dried soil placed in a china dish at 450°C. The samples were further combusted to ash during a continuous 4-hour furnace operation. For each sample, the ash weight was recorded, and Equation (4) was used to calculate the organic matter content [7].

$$OM = (W2 - W3)/W(2 - W1)\ x\ 100 \qquad (4)$$

Where O_M is organic matter (g), W_2 weight of empty crucible + sample (g), W_1 weight of empty crucible (g), W_3 weight of crucible + sample after heating in a furnace.

2.3.3. Soil organic carbon (SOC).

A conversion factor of 0.58 was used to estimate the amount of SOC from the organic matter content [7]. Using Equation (5), the SOC per hectare for the different forest sites was determined [10]:

$$SOC = \rho\ x\ d\ x\ C \qquad (5)$$

Where SOC is soil organic carbon, ρ is the soil bulk density, d is the depth of soil sample, and C is the carbon content sample.

3. Results and Discussion

3.1. Results.

3.1.1. Soil bulk density.

In Gana, Saniko, and Agbarha-Otor, as shown in Table 1, the estimated mean soil bulk densities at 15 cm and 30 cm depths were 0.7764 g/cm³ and 0.8524 g/cm³ for Gana, 0.7867 g/cm³ and 0.9004 g/cm³ for Saniko, and 0.9348 g/cm³ and 1.1232 g/cm³ for Agbarha-Otor, respectively. The results indicated a consistent increase in bulk density with soil depth across the three locations. This trend is commonly associated with reduced organic matter content, increased soil compaction, and lower biological activity in deeper soil layers. The topsoil layer (0–15 cm) generally exhibited lower bulk density due to higher organic matter accumulation, root penetration, and microbial activity, which improved soil structure and porosity.

Table 1. Soil bulk density for the different locations.

Location	Depth (cm)	Samples			Mean ±S.D
		X	Y	Z	
Gana	0-15	0.7453	0.7945	0.7894	0.7764±0.0271
	15-30	0.8564	0.8465	0.8543	0.8524±0.0052
Saniko	0-15	0.7643	0.7834	0.8123	0.7867±0.0242
	15-30	0.8945	0.8945	0.9123	0.9004±0.0103
Agbarha-Otor	0-15	0.9476	0.9623	0.8945	0.9348±0.0357
	15-30	1.2765	1.0987	0.9945	1.1232±0.1426

S.D = Standard deviation; X, Y nd Z = sampling points

Among the study locations, Agbarha-Otor recorded the highest bulk density at both depths, suggesting relatively higher soil compaction or lower organic matter influence compared to Gana and Saniko. The higher variability observed at the 15–30 cm depth in Agbarha-Otor (±0.1426) also indicated heterogeneous subsurface soil conditions, possibly influenced by land-use disturbance or differences in soil texture. Gana recorded the lowest bulk density values at both depths, which may reflect better soil structure and higher organic matter contribution. Saniko showed intermediate values, indicating moderate soil compaction relative to the other locations. The gradual increase in bulk density with depth across all sites suggested typical soil profile development where subsurface layers were denser due to reduced aggregation and fewer organic inputs.

3.1.2. Soil organic matter (SOM) content.

The mean values of SOM content at 15 cm and 30 cm depths in Gana, Saniko, and Agbarha-Otor, as shown in Table 2, were 2.69% and 2.03% for Gana, 3.18% and 3.00% for Saniko, and 4.14% and 4.06% for Agbarha-Otor, respectively. The results indicated a slight decrease in SOM content with increasing soil depth across all three locations, which is consistent with the typical distribution of organic matter in soils. The topsoil (0–15 cm) had higher SOM due to the accumulation of decomposed plant and animal residues, root exudates, and microbial biomass, all of which contribute to soil fertility and structure. In contrast, the subsoil (15–30 cm) generally contained lower organic matter because of reduced biological activity and fewer organic inputs.

Table 2. SOM content for the different locations.

Location	Depth(cm)	Sample (%)			Mean ±S.D
		X	Y	Z	
Gana	0-15	1.89	3.21	2.98	2.69±0.7052
	15-30	2.01	2.13	1.96	2.03±0.0874
Saniko	0-15	3.47	2.98	3.10	3.18±0.2554
	15-30	2.87	3.03	3.11	3.00±0.1222
Agbarha-Otor	0-15	4.76	3.98	3.67	4.14±0.5616
	15-30	4.23	4.05	3.89	4.06±0.1701

S.D = Standard deviation; X, Y nd Z = sampling points

Among the study sites, Agbarha-Otor exhibited the highest SOM content at both depths, suggesting better nutrient retention and higher organic input, possibly from denser vegetation cover or less disturbance. Gana had the lowest SOM values, which may indicate lower vegetation density, greater soil disturbance, or more intensive land use practices. Saniko showed intermediate SOM levels, reflecting moderate organic matter accumulation. The standard deviations indicated variability in SOM across the sampling points, with Gana showing the greatest variability in the topsoil (±0.7052), suggesting heterogeneous organic matter distribution. In contrast, the lower variability at 30 cm depth for all locations (±0.0874 to ±0.1701) reflected more uniform conditions in the subsoil.

3.1.3. SOC density.

According to the results presented in Table 3, the SOC values in Gana, Saniko, and Agbarha-Otor ranged from 31.33 to 136.81 t C/ha. At 30 cm depth, Agbarha-Otor exhibited the highest SOC level of 136.81 t C/ha, followed by Saniko with 81.04 t C/ha, and Gana with 51.91 t C/ha. A similar trend was observed at the 15 cm depth, indicating that Agbarha-Otor consistently contained higher carbon stocks compared to the other two locations. The elevated SOC in Agbarha-Otor may be attributed to greater organic matter inputs from denser vegetation, reduced soil disturbance, or better soil structure, all of which enhance carbon storage. Gana, on the other hand, recorded the lowest SOC values, possibly due to lower vegetation cover, higher soil disturbance, or differences in soil texture that limit carbon accumulation. Saniko showed intermediate values, reflecting moderate organic matter availability and soil conditions. Furthermore, a comparison between bulk density and SOC, illustrated in Figure 2, revealed an inverse relationship: as bulk density increased across all locations, SOC decreased. This pattern is consistent with the understanding that compacted soils tend to have fewer pore spaces and lower organic matter content, limiting carbon sequestration. Therefore, both soil physical properties and organic matter inputs play critical roles in determining SOC distribution within these forested communities.

Table 3. SOC for the different locations.

Location	Depth (cm)	SOC (t C/ha)
Gana	0-15	31.33
	15-30	51.91
Saniko	0-15	37.52
	15-30	81.04
Agbarha-Otor	0-15	58.05
	15-30	136.81

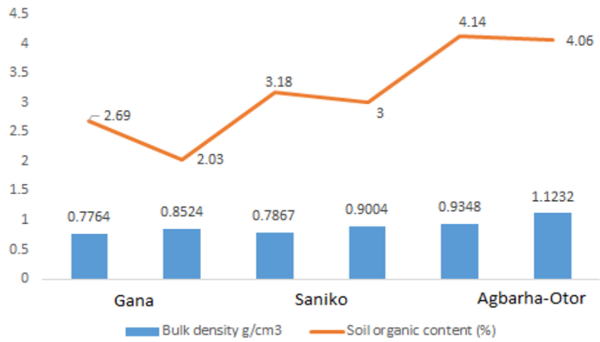

Figure 2. Correlation between bulk density (BD) and SOC.

3.2. Discussion.

The findings from this study were comparable with reports from other researchers in different regions. The bulk density values for the three locations varied slightly, with Gana recording the lowest bulk density (0.7764 g/cm³). The high value (1.1232 g/cm³) observed in samples from Agbarha-Otor may be attributed to local atmospheric conditions, which were thought to be influenced by lower temperatures in the vicinity of gas flaring activities compared to Gana. It is possible that this lower temperature contributed to the accumulation of soil organic matter. The estimated soil bulk density range of 0.7764–1.1232 g/cm³ in this study was lower than the 1.3 g/cm³ and 1.45 g/cm³ reported by Liu et al. [11]. This difference may have resulted from variations in sampling depth, as Liu et al. collected samples at 40 cm, compared to the 15 cm and 30 cm depths used in this investigation. This finding supports the general observation that bulk density increases with soil depth. The values obtained in this study were also consistent with a recent continental assessment of soil bulk density, which reported mean values of approximately 0.83 g/cm³ in woodlands and 1.26 g/cm³ in croplands within the 0–20 cm topsoil layer, reflecting lower density in soils with higher organic matter and higher density in more compacted agricultural soils [12].

The low temperatures in the Niger Delta may have contributed to the increased accumulation and slower decomposition of organic matter. Other studies have similarly indicated that low temperatures are a major factor promoting organic matter buildup. High bulk density, in turn, indicated low soil porosity and excessive soil compaction, which can reduce air and water movement and limit root penetration. The SOM values obtained in this study were lower than those reported by Siddiqui et al. [13], which ranged from 2.6% to 10.5%. However, the results were consistent with other findings [14, 15], which reported organic matter levels of 4.2% and 3.8%, respectively. Temperature strongly influenced SOM by regulating microbial activity, decomposition rates, and carbon storage. Higher temperatures generally increased microbial metabolism and accelerated organic matter breakdown, leading to greater carbon loss from soils. Conversely, lower temperatures slowed decomposition, allowing organic matter to accumulate and remain stabilized within soil aggregates. Temperature also affected soil moisture, further influencing microbial activity and SOM preservation. These interactions played a major role in soil fertility, carbon sequestration, and climate regulation, as rising temperatures could enhance greenhouse gas emissions while reducing SOC storage.

The SOC values estimated in this study, ranging from 31.33 to 136.81 t C/ha, fell within the range reported in recent high-resolution global assessments, which showed that agricultural soils typically contained between 31 and 132 t C/ha at 30 cm depth, depending on region and management practices [16]. Results from Liu et al. [11] were also consistent with the values obtained in this study. Since sampling depth is a crucial consideration in SOC assessment, Ali et al. [1] noted that differences in depth could affect precision and variability, and that SOC was generally higher in moist soils than in dry soils. The findings of this study support the claim by the United Nations Food and Agriculture Organization [17] that adequate water availability facilitates nutrient uptake by plants. Conversely, low carbon content can reduce water retention capacity, causing the loss of important nutrients required for soil health. The study conducted by the IPCC in 2003 reported mean SOC values of 31.33 t C/ha and 51.91 t C/ha for Gana at 15 cm and 30 cm, respectively, which agreed with the 15 cm values reported in this study but were lower than the 30 cm values. In contrast, recent assessments reported SOC stocks of 49.2 ± 3.5 t C/ha in natural forest soils and 57.8 ± 4.1 t C/ha in agricultural soils at 30 cm depth, which exceeded the mean values obtained in this study. In addition, industrial activities such as construction and agricultural operations can disturb soil structure, resulting in significant carbon emissions. Therefore, further investigation is required to understand how gas flaring and other industrial activities affect atmospheric conditions and soil carbon accumulation, even though previous studies have focused on the benefits of afforestation. Such research would enhance the development of sustainable soil management strategies.

4. Conclusions

The results revealed that SOC is an essential factor that must be given due consideration in soil management and climate change mitigation strategies. The findings from this study varied among Gana, Saniko, and Agbarha-Otor. The observed disparities could be attributed to local air conditions influenced by gas flaring activities, particularly in Gana. Additionally, differences in soil profiles at varying depths likely contributed to the observed variations in SOC. Bulk density also varied across the three locations, with Gana recording the lowest value and Agbarha-Otor the highest. The SOM content measured at 15 cm and 30 cm depths showed similar patterns: the highest levels were observed in Agbarha-Otor, followed by Saniko and Gana. A comparison between bulk density and SOC indicated an inverse relationship, where increasing bulk density corresponded to decreasing soil organic carbon. These findings suggest that soils with lower bulk density can retain higher amounts of organic carbon, highlighting the importance of soil conservation as a strategy for climate change mitigation. Despite these valuable insights, the study had some limitations. The investigation was restricted to three communities within Ughelli North Local Government Area, which may limit the generalization of the findings to other parts of the Niger Delta region. Soil sampling was limited to two depths (0–15 cm and 15–30 cm), potentially overlooking deeper soil carbon dynamics. Seasonal variations and long-term environmental changes were not considered, which could affect SOC distribution and accumulation over time. Future research should expand sampling to include additional locations across the Niger Delta to provide broader regional representation. Studies should also examine deeper soil profiles and incorporate seasonal monitoring to better understand temporal variations in SOC. Furthermore, investigations into the long-term impacts of gas flaring and other anthropogenic activities on soil carbon sequestration and soil health are needed. Implementing sustainable land management practices, such as afforestation, reduced tillage, and organic soil amendments, is recommended to enhance soil carbon storage and improve ecosystem resilience in the region.

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Author Contribution

Authors should clearly specify the roles and contributions of each individual involved in the research to ensure proper attribution of credit and transparency regarding responsibilities. In this study, the specific contributions were as follows: Otache Monday Abel developed the research idea or hypothesis and also designed the research methods and experiments, Afitijagun Iyabo Priscilla collected, gathered, and organized the data, Otache Monday Abel and Afitijagun Iyabo Priscilla analyzed and interpreted the data, Otache Monday Abel and Godwin Kparobo Agbajor, wrote the manuscript and contributed to drafting and revising, while the funding acquisition was handled by Otache Monday Abel.

Competing Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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