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SOIL ORGANIC CARBON SEQUESTRATION UNDER TREE CROPLAND AT VARYING PARENT MATERIALS AND DEPTHS IN SOUTHEASTERN NIGERIA: A GEOSPATIAL PERSPECTIVE

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ABSTRACT: *Knowledge of carbon storage in soils across varying parent materials and depths under tree crop vegetation is essential for mitigating global carbon emissions. This study evaluated the geospatial pattern of the soil organic carbon (SOC) pool. The experiment was a two-factor factorial arranged in a randomized complete block design (RCBD). The factors consisted of soil depth at three levels (0–19, 20–39, and 40–100 cm) and parent material at five levels: Coastal Plain Sands (CPS), Shale (SHL), Imo Clay Shale (ICS), Sombreiro–Warri Deltaic Formation (SDD), and Mangrove Swamp Deposit (MSD). Three replicates of core and auger soil samples were randomly collected at the respective depths in each study location. Kriging interpolation was employed for the geospatial assessment of the SOC pool, while analysis of variance (ANOVA) was performed on the data. Significant means were separated using Fisher's Least Significant Difference (LSD) test at the 5% probability level. The results showed that soils derived from CPS had the highest ($P \leq 0.05$) SOC pool (575.80 Mg C ha^{-1}), followed by those from ICS across the soil depths. The overall trend in carbon sequestration was CPS > ICS > SHL > MSD > SDD. Semi-variogram models and their parameters indicated that the SOC pool varied spatially within and across locations. The findings demonstrate that parent material significantly influences soil organic carbon storage, and that SOC varies considerably even among soils developed from the same parent material. Therefore, site-specific soil management practices should be adopted for different soils and regions to promote sustainable agriculture and environmental conservation.*

KEYWORDS: Geospatial, Parent Materials, Semi-variogram, Sequestration, Soil depth, and Soil organic carbon.

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INTRODUCTION

Carbon sequestration is an important soil ecosystem service that plays a crucial role in the global carbon cycle, helping to mitigate climate change while enhancing soil quality and fertility (Ibe, 2021). Lal (2017) noted that as anthropogenic activities continue to elevate atmospheric carbon dioxide levels, the need for awareness creation and the promotion of soil carbon storage through sustainable land management practices has become increasingly imperative. Managed tree croplands (MTC), which encompass agroforestry and horticultural systems where trees are cultivated alongside crops or as monoculture plantations, have emerged as effective systems for enhancing soil carbon stocks (Akpa et al., 2016). Similarly, Sathvara et al. (2023) reported that these systems offer multiple benefits, including improved biodiversity, water retention, and soil health, thereby supporting more resilient agricultural landscapes.

Food and Agriculture Organization (FAO, 2023) reported that the significance of soil carbon sequestration is underscored by the potential of tree-based farming systems to contribute substantially to greenhouse gas mitigation strategies. Globally, soils are estimated to store more than three times the amount of carbon found in the atmosphere, emphasizing their role as vital carbon sinks. In this context, Southern Nigeria, with its diverse agro-ecological zones and a wide variety of tree species utilized for both subsistence and commercial purposes, presents a unique opportunity for studying carbon sequestration dynamics. The diverse climatic conditions of the region, coupled with variations in parent materials, influence soil properties and, consequently, the carbon storage potential within these ecosystems (Amanze et al. 2024b; Ibe et al. 2025; Ukabiala et al. 2025).

Akpa et al. (2014) noted that soil carbon sequestration (SCS) occurs through various biological, chemical, and physical processes involving the accumulation of organic carbon in soil. Nwagbara and Ibe (2015) reported that soil organic matter is derived from plant residues, root exudates, and microbial activities, all of which play a pivotal role in enhancing soil structure, fertility, and overall productivity. According to Lekwa et al. (2020), tree croplands, leaf litter, decaying roots, and other organic inputs contribute significantly to the formation of soil organic matter, which is essential for maintaining soil health and facilitating nutrient cycling. Amanze et al., (2024b) emphasized that an adequate understanding of the mechanisms of organic matter decomposition is central to optimizing carbon sequestration in agroforestry systems, particularly in regions with diverse soil types and parent materials.

Oyetola (2014) postulated that parent materials are fundamental in determining soil characteristics and are critical to understanding soil-formation processes. Lekwa and Whiteside (1986) reported that the mineral composition, texture, and depth of parent materials strongly influence soil drainage, nutrient availability, and overall fertility, including soil carbon storage. Soils originating from different parent materials therefore exhibit significant variations in their carbon storage capacity (Soropa et al., 2021). These authors noted that soils derived from shale parent material often possess higher mineral fertility and carbon retention due to their fine texture and rich mineral composition, whereas sandy soils derived from sandstone parent materials generally show lower carbon storage potential because of greater leaching losses and reduced organic matter retention (Amanze et al., 2024a). Conversely, sandy soils derived from Sombreiro–Warri deltaic deposits may exhibit relatively higher carbon storage as a result of organic matter–rich sediment accumulation (Amanze et al., 2024c).

Akpa et al. (2014) believed that the advent of spatial analysis and geospatial technologies has revolutionized our understanding of soil properties and dynamics. Ibe et al. (2025) showed that geographic information systems (GIS) and remote sensing provide powerful tools for mapping and analyzing spatial patterns of soil properties, including carbon stocks. This approach enables researchers to delineate areas with high carbon storage potential and identify factors contributing to variations in soil carbon across different landscapes. By applying these technologies to study soil carbon in tree croplands, researchers can develop precision models that inform land management practices and policy interventions.

Tree cropland vegetation and soils constitute a major terrestrial carbon pool with the potential to absorb and store carbon dioxide from the atmosphere. They capture and release large amounts of carbon and have the capacity to influence atmospheric carbon dioxide concentrations and climate dynamics (Lal and Okigbo, 1990; Lekwa *et al.*, 2020). Despite the recognized benefits of tree croplands in carbon sequestration, there is a dearth of research addressing the spatial dynamics of soil carbon storage in croplands across different parent materials in southeastern Nigeria. Therefore, this study aims to investigate the spatial variability of carbon sequestration in soils under tree croplands at varying depths and across different parent materials.

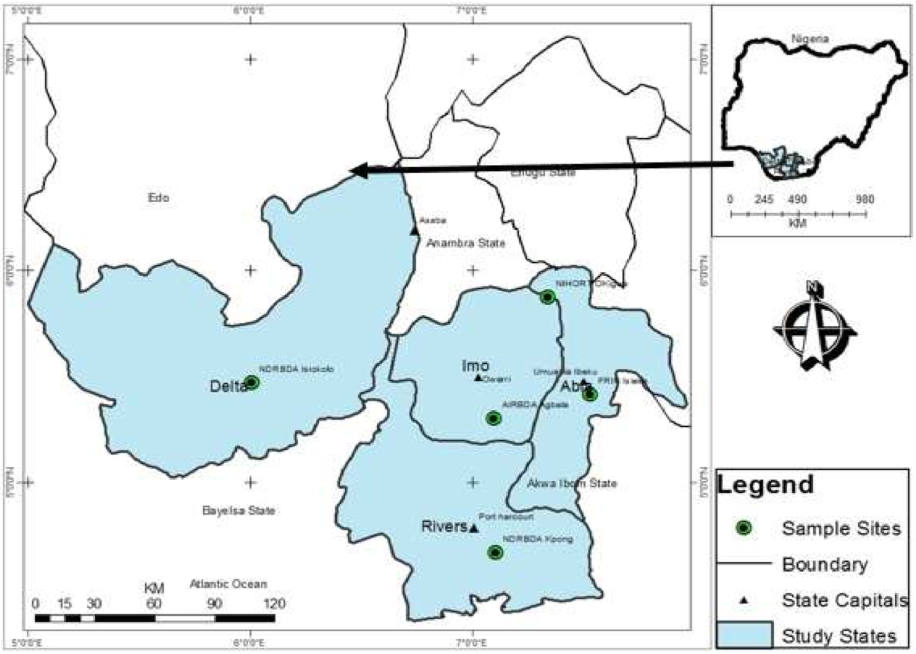
MATERIALS AND METHODS

Locations of the study

The study was carried out in parts of Southern Nigeria. The area lies within latitudes 4°–7° N of the equator and longitudes 5°–9° E of the Greenwich Meridian, occupying a land area of about 282,672.48 km², which represents about 21.6% of the total land area of Nigeria (Lal and Okigbo, 1990).

Specific locations of the study within the area included the Forestry Research Institute of Nigeria (FRIN), Isieke; the National Horticultural Research Institute (NIHORT), Okigwe; the Anambra–Imo River Basin Development Authority (AIRBDA), Agbala; and the Niger Delta Basin Development Authority (NDBDA), Kpong and Isiokolo, located in Abia, Imo, Rivers, and Delta States, Southern Nigeria (Figure 1).

Figure 1: Map of Southern Nigeria Showing the Study Area



Geology, climate, and vegetation of the study area

The soils of FRIN- Isieke were derived from Coastal Plain Sands of Bende Ameke formation (Lekwa and Whiteside, 1986; Nuga and Akinbole, 2012). Soils of NIHORT-Okigwe were derived from shale of the Ajali formation (Ojanuga, 1977). While soils of AIRBDA-Agbala are underlain by Imo clay shale of Imo formation of the tertiary period. The residuum of this shale formation is the parent material of the soils (Ojanuga, 1997). Soils of NDBDA-Kpong were derived from sombreiro Warri deltaic deposit (Deltaic plain sands), and the soils of NDBDA-Isiokolo were derived from mangrove swamp deposit (Deltaic clayey/silty sands) (FDALR, 1990). The drainage of the area encompasses the entire land surface dissected and drained by many streams and creeks (Ibe, 2014).

The areas have a tropical humid climate with average rainfall of 2,500 mm (Nwagbara and Ibe, 2015; NIMET, 2025). Maximum and minimum air temperatures of 35° C and 21° C, respectively, with annual average daily sunshine hours of 6.25 hours. Similarly, it has an annual daily solar radiation of about 2.25 kWh/m^2/m^2/day varying between 3.5 kWh/m^2/m^2/day at the coastal areas and 7.0 kWh/m^2/m^2/day at the northern boundary. Relative humidity ranged from 65 % to 92 %. (NIMET, 2025).

The vegetation of the study area is typical of tropical rainforest vegetation. The secondary bush, which dominates the area, is the remnant of the tropical rainforest, which is fast disappearing in the area. Some of the forest species found in the area include: African oil bean (*Pentaclethra macrophylla),* oil palm (*Elaeis guineensis,),* plantain / banana (*Musa* spp.), rafia palm (*Raphia* spp.). Grasses and broadleaf weeds that dominate the entire area include *Panicum maximum, Pennisetum purpureum, Cyperus* spp., *Axonopus compressus,* and *Aspilia africana*.

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Description of the tree cropland

The tree cropland in each location/parent material was characterized by tree plant species that were largely similar across all locations. Such tree species included pine (*Pinus caribaea*), oil palm (*Elaeis guineensis* Jacq.), bush mango (*Irvingia gabonensis* var. wombulu), sweet orange (*Citrus sinensis*), and plantain (*Musa paradisiaca*). The land was managed through periodic weed clearing. Leaf litter was left intact on the soil surface, and cover crops, such as *Centrosema pubescens, Calopogonium mucunoides,* and *Pueraria phaseoloides,* were allowed to grow and cover the soil.

Soil sampling and samples preparation

Stratified random sampling, as modified by Smith (1976), was used for the collection of soil samples. Three (3) sampling points were located in each site using the stratified random sampling method in consideration of the sizes of the respective study locations. At each point, three (3) mini-pits with dimensions of 0.5 m × 0.5 m × 1 m were excavated, and soil samples were collected at depths of 0–19, 20–39, and 40–100 cm. Therefore, three samples were collected from each depth at each location. Each mini-pit was georeferenced, as presented in Table 1.

Table 1: Geographical information of sampling points in each study area

Parent Material	Soil Unit No	Latitude	Longitude	Elevation (masl)
CPS	CPS-01	05°25′41″N	07°31′13″E	182
	CPS-02	05°25′16″N	07°31′18″E	180
	CPS-03	05°25′08″N	07°31′10″E	181
SHL	SHL-01	05°50′28″N	07°18′35″E	186
	SHL-02	05°52′43″N	07°18′45″E	178
	SHL-03	05°52′28″N	07°18′17″E	183
ICS	ICS -01	05°19′55″N	07°05′17″E	97
	ICS -02	05°17′54″N	07°05′36″E	98
	ICS -03	05°18′14″N	07°05′54″E	100
SDD	SDD -01	04°41′42″N	07°24′10″E	30
	SSD -02	04°40′24″N	07°24′20″E	27
	SSD -03	04°40′19″N	07°24′30″E	25
MSD	MSD -01	05°29′00″N	05°59′16″E	15
	MSD -02	05°28′38″N	05°59′51″E	20
	MSD -03	05°28′10″N	06°00′02″E	18

Laboratory analysis

Soil organic carbon content was quantified by Walkley and Black wet oxidation method as described by Nelson and Sommers (1982). The SOC pool was calculated using the equation of Lal et al. (1998):

$\text{Mg C ha}^{-1} = \%\, C \times \rho b \times d \times 1\ \text{ha}/100$ .... Eq. 1

Where, Mg C ha-^{1} = gram carbon per hectare, % C = percentage of C given by laboratory results, ρb = Soil bulk density (milligram per cubic centimeters), d = depth in centimeter, 1 ha (square centimeter)

Experimental design and Data analyses

The study was designed as a 5 × 3 factorial experiment in a randomized complete block design (RCBD). The factors were parent material at 5 levels (coastal plain sands, Shale, Imo Clay Shale, Sombreiro Warri Deltaic Deposit, and Mangrove swamp deposit) and depth at 3 levels (0- 19, 20- 39, 40 - 100 cm). Data collected on the various parameters were analyzed using ANOVA. Significant differences among means were separated using F-LSD at $p \leq 0.05$. Detailed spatial analysis using GIS was carried out. The ordinary kriging (OK) method was used in the ArcGIS 10.1 environment to describe the spatial structures of the spatial maps of the SOC pool (Bhunia et. al. 2016; Ibe, 2021). Three (3) predictive spatial maps were generated using best-fit semi-variogram with ordinary kriging. The generated predictive maps were used to describe the spatial variability of the soil organic carbon pool of the parent materials at 0-19, 20- 39, and 40- 100 cm depths. The OK interpolation method was used for the prediction of the values of the unsampled locations X by assuming that Z^* (X) equals the sum of the known measured values (field measured values). The kriging process was calculated using the following equation (Wang, 1999).

$Z^*(X) = \Sigma \lambda_i * Z(Xi)$ ………………………………………………………….. Eq. 2

Where: Z^* (X) is predicted value at position X

λ_i are the weights

Z(Xi) are the observed values at locations Xi

Semi-variograms were used as the basic tool to examine the spatial distribution structure of the SOC pool. Based on the regionalized variable theory and its intrinsic hypotheses (Neslen and Wendroth, 2003), a semivariogram is expressed as:

$Y(h) = (1/2 N(h) * \Sigma [Z(xi) - Z(xi + h)]^2$ ……………………………………………… Eq. 3

Where: Y (h) is Semivariance, h is Lag distance, Z(xi) is value of the location xi; N (h) is number of pairs of locations separated by a lag distance h, $Z(x_i + h)$ is the value of Z at location $X_i + h$ (Wang and Shao, 2013).

The empirical semivariograms obtained from the data were fitted by theoretical semivariogram models to produce geostatistical parameters, including nugget variance (Co), structure variance (Ci), sill variance (Co + Ci), and distance parameter (⅄). The nugget/sill ratio, Co/(Co + Ci), was calculated to characterize the spatial dependency of the values. In general, a nugget/sill ratio <25% indicates strong spatial dependency and >75% indicates weak spatial dependency; otherwise, the spatial dependency is moderate (Cambardella et al. 1994).

RESULTS AND DISCUSSION

Soil organic carbon pool across the depths and parent materials

The mean values of the soil organic carbon (SOC) pool at varying depths and parent materials are presented in Table 2. The highest SOC pool (133.40 Mg C ha^{-1}) at the 0–19 cm depth was observed in CPS, while the lowest (72.50 Mg C ha^{-1}) was recorded in SDD. At the 20–39 cm depth, the highest SOC pool (111.80 Mg C ha^{-1}) was observed in ICS, whereas the lowest (73.80 Mg C ha^{-1}) occurred in SDD. Furthermore, at the 40–100 cm depth, CPS exhibited the highest SOC pool (334.80 Mg C ha^{-1}), while the lowest (172.20 Mg C ha^{-1}) was again observed in SDD.

Comparatively, soils developed on CPS consistently recorded the highest SOC pool across all depths, whereas soils on SDD exhibited the lowest SOC pool. The overall trend of the SOC pool across parent materials followed the order: CPS > ICS > SHL > MSD > SDD. Additionally, across all parent materials, the 40–100 cm soil depth recorded the greatest SOC pool, which differed significantly ($P \leq 0.05$) from the other depths.

Table 2. Effect of Parent Material and Depth on Soil Organic Carbon Sequestration

Parent Material	0-19 cm	20-39 cm	40-100 cm
CPS	133.40	107.60	334.80
SHL	88.00	104.10	326.80
ICS	102.10	111.80	313.80
SDD	72.50	73.80	172.20
MSD	95.60	96.00	217.90
$LSD_{(0.05)}$ For parent materials = 27.34**			
$LSD_{(0.05)}$ For Depth = 3.49**			
$LSD_{(0.05)}$ For Interaction = 47.36**			

CPS = Coastal Plain Sands, SHL = shale, ICS = Imo clay Shale, SDD = Sombreiro Warri Deltaic Deposit, MSD = Mangrove Swamp Deposit

The variation in values of the SOC pool across soil depths and parent materials increased with depth across the parent materials, which agrees with Amanze et al. (2024a) and Akpa et al. (2016), who reported that the SOC pool depends on soil depth. However, the observed increase in SOC with soil depth contradicts the findings of Okebalam (2016) and Amanze et al. (2024a), who reported that the SOC pool decreased with increasing depth. The higher SOC pool observed in soils on Coastal Plain Sands (CPS) could be attributed to greater turnover of plant residues from litter fall, as well as a higher abundance of macropores resulting from the coarse texture of the soils, which is influenced by the nature of the parent material (Amanze et al., 2024b). These macropores may act as collectors of organic residues, leading to their increased accumulation in the soil rather than loss through surface runoff. Conversely, the lowest SOC pool observed in soils on the Mangrove Swamp Deposit (MSD) parent material may be due to the dominance of micropores, which reduces the soil's capacity to collect and store SOC. Furthermore, the increase in SOC with soil depth may be attributed to reduced temperature and aeration at greater depths, which decreases the rate of SOC loss through decomposition. Ibe et al. (2025) noted that increased soil aeration and temperature accelerate organic carbon loss by enhancing microbial activity and oxidation processes, and vice versa. This implies that soils on

CPS are likely to exhibit greater biodiversity and improved physicochemical conditions, resulting in better soil quality and health compared to soils derived from other parent materials under managed tree crops.

Geostatistical parameters of the fitted semi-variogram for SOC pool across the parent materials at the various depths

Geostatistical parameters of the fitted exponential semivariogram model for the SOC pool are shown in Table 3. The semivariogram parameters explained the spatial semi-variance of the SOC pool effectively, with nugget (Co) values ranging from 0.074 to 0.302. The nugget-to-sill ratio (N:S) was < 25%, indicating strong spatial dependence (0.084–0.124) of the SOC pool. This suggests that structural factors, particularly parent materials, were the primary drivers of spatial variability in the SOC pool within the study area. This finding agrees with Ibe (2021), who reported that soil mineralogy, largely influenced by parent material, is a key factor governing soil carbon sequestration. The fitted model exhibited a very short range, indicating localized spatial dependence of the SOC pool. The variation in spatial dependence across soil depths may be attributed to differences in soil response to varying parent materials (Akpa et al., 2014; Lekwa et al., 2020).

Table 3. Geostatistical parameters of the fitted semi-variogram exponential model for SOC pool at varying depths

Depth (cm)	Range (m)	Nugget $(MgC/ha)^2$	Sill $(MgC/ha)^2$	N:S	R^2	ME (MgC/ha)	RMSE (MgC/ha)
0-19	20.2	0.074	0.886	0.084	0.667	0.341	0.543
20-39	18.8	0.281	3.127	0.089	0.624	0.0023	0.379
40-100	19.6	0.302	5.608	0.124	0.646	0.0018	0.346

R^2 = Coefficient of determination, RMSE = Root mean Square Error, N:S = Ratio of nugget and sill expression, ME = Mean Error

Geospatial maps of SOC pool across the parent materials at the various depths

The predictive maps showing the spatial variability of the SOC pool at various soil depths across the different parent materials are presented in Figs. 2–4. At the 0–19 cm soil depth (Fig. 2), the highest SOC pool was observed in the eastern and central zones of the study area, corresponding to soils developed from Coastal Plain Sands and Imo Clay Shale. The increased SOC storage in the topsoil derived from Coastal Plain Sands was possibly due to the ease with which organic deposits from litterfall are incorporated into the soil, thereby reducing potential losses of organic matter through surface runoff and wind erosion. This assertion corroborates the findings of Amanze et al. (2024a), who reported that medium- to coarse-textured soils derived from Coastal Plain Sands are characterized by medium to large-pore spaces, which enhance the trapping and storage of materials, including organic matter.

Conversely, the minimum SOC pool values observed in the southern and western parts of the study area, as well as in the extreme northeastern zones—areas underlain by shale, Sombreiro–Warri deltaic deposits, and mangrove swamp deposits—may be attributed to the finer texture of soils derived from these parent materials. Such fine-textured soils are dominated by micropores, which may restrict the incorporation and stabilization of organic materials, as previously reported by Akpa et al. (2016).

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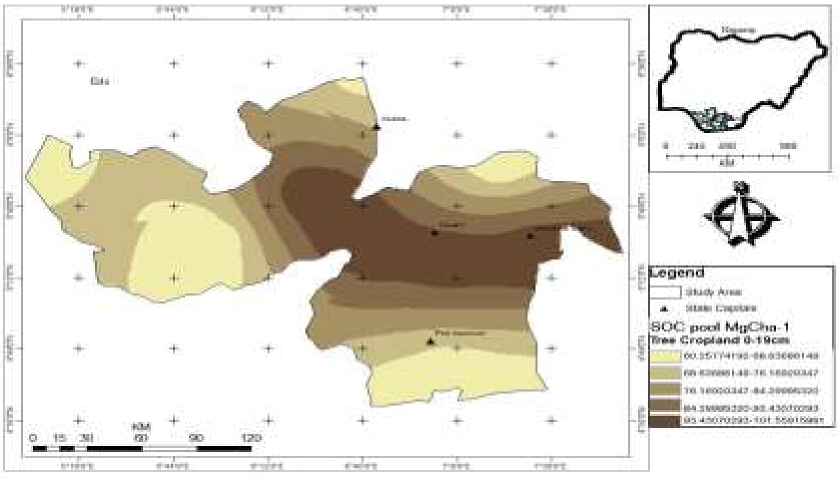
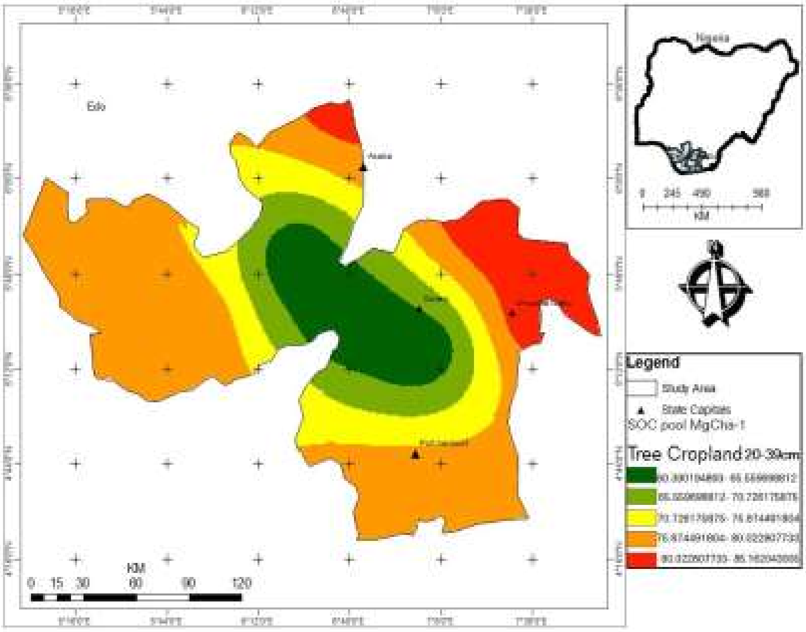
Figure 2: Predictive maps showing the spatial variability of soil organic carbon pool at 0-19 cm depth



The map in Fig. 3 showed that the highest concentration of the SOC pool at the 20–39 cm soil depth occurred within the northeastern zone of the study area, which is dominated by shale and Sombreiro–Warri deltaic deposits. The increased SOC pool at the 20–39 cm depth in soils derived from shale and deltaic deposits may be attributed to a reduced rate of soil organic matter decomposition, resulting from poor aeration and lower soil temperature at these depths compared to soils formed from other parent materials. This condition is primarily induced by the higher microporosity of these soils, which restricts air transmission to the subsurface layers, thereby limiting the oxidation of organic materials.

Figure 3: Predictive maps showing the spatial variability of soil organic carbon pool at 20 - 39 cm depth



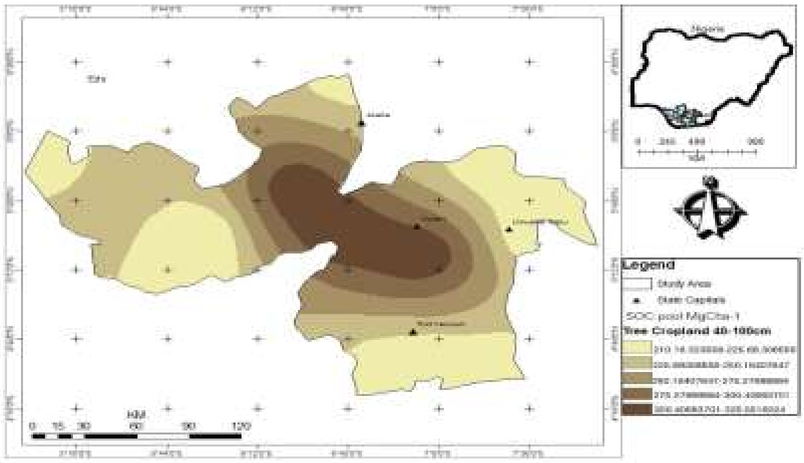
This explanation is consistent with the findings of Lekwa et al. (2020), who reported that soils derived from shale and alluvial (deltaic) deposits are fine-textured and characterized by high micropore content, which limits soil permeability to air, water, and root penetration. Moreover, the periodic burial and accumulation of organic materials through sedimentation processes further enhance the storage of organic carbon at subsurface depths in soils derived from shale and deltaic deposits (Nuga and Akinbole, 2012).

In contrast, the central zone of the study area, underlain by Imo clay shale and mangrove swamp deposits, exhibited the lowest SOC pool at the 20–39 cm soil depth. Meanwhile, the central southeast and central northwest zones, underlain by Coastal Plain Sands and mangrove swamp deposits, recorded moderate SOC pool values at the same depth.

Figure 4 shows that the highest concentration of the SOC pool at the 40–100 cm depth occurred in the central-eastern region, underlain by Imo Clay Shale and mangrove swamp deposits. The extreme northeastern and southern zones exhibited the lowest SOC pool values. Additionally, localized pockets of high SOC pool were observed in the northwestern zone of the study area, extending across all parent materials. The southeastern and northwestern central zones, underlain by mangrove swamp deposits, recorded moderate SOC pool values, with mean error and RMSE values of 0.0018 and 0.346, respectively.

Generally, the coefficient of determination (R^2) of the SOC pool across different parent materials was 0.667. An R^2 value greater than 0.5 indicates a good model fit. The root mean square error (RMSE) was approximately zero (0), suggesting minimal prediction error. This indicates that the theoretical model adequately represents the spatial variability of soil organic carbon (SOC) stocks (Akpa et al., 2014; Ibe, 2021). The analysis suggests that the geographical distribution of SOC across various soil depths was highly variable, which may be attributed to differences in carbon inputs, redistribution processes, stabilization mechanisms, and soil mineralogy. This implies that soil-specific management and cultural practices are necessary to enhance SOC sequestration, as influenced by parent material–dependent soil properties (Amanze et al., 2024c).

Figure 4: Predictive maps showing the spatial Variability of soil organic carbon pool at 40- 100 cm depth



CONCLUSION

The soil organic carbon (SOC) pool is influenced by both the nature of parent material and soil depth. SOC is more highly sequestered in subsurface (residing) soil layers than in surface soils under managed tree crops. Soils developed on Coastal Plain Sands exhibit the greatest capacity for SOC sequestration, whereas soils formed on Deltaic formations show the lowest SOC sequestration capacity under a tree-cropland utilization system. There is a strong and notable dependence of the SOC pool on the nature of parent material. Accordingly, spatial variation in parent materials across a landscape contributes significantly to the heterogeneity of SOC storage. Consequently, this study emphasizes the need to consider geological factors, particularly parent material, in soil carbon management strategies and environmental sustainability plans in Southeastern Nigeria.

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