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Carbon Sequestration and Aggregation Potentials of Soils Overlying Different Geological Formations in Selected Parts of Anambra State, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Background: Soil organic carbon sequestration and aggregation play important roles in maintaining soil fertility, improving soil structural stability and mitigating climate change. Geological formations influence soil physicochemical properties, which may affect carbon storage capacity and aggregate stability.
Aim: This study assessed soil carbon stocks and aggregation indices in soils developed over four geological formations in selected areas of Anambra State, Nigeria.
Study Design: A comparative field and laboratory investigation was conducted across the Alluvial Plain, Ameki, Imo Shale and Ogwashi-Asaba formations.
Methodology: Soil samples from secondary-forest sites were examined at three depth intervals (0–30, 30–60 and 60–90 cm). Particle-size distribution, soil organic carbon, soil carbon stock and aggregation indices were assessed using laboratory methods and statistical analyses.

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Results: Soil texture ranged from sandy loam in the Alluvial Plain to loamy sand in Ameki and Ogwashi-Asaba and clay loam in Imo Shale. Organic carbon was highest in the Alluvial Plain (0.97 g kg^{-1}) and lowest in Ogwashi-Asaba (0.23 g kg^{-1}). Corresponding carbon stocks were 4.40 and 1.10 t C ha^{-1}, respectively. Mean weight diameter ranged from 0.50 mm in Ameki to 0.64 mm in Imo Shale. Imo Shale recorded the highest state of aggregation (22.08%) and aggregate stability (28.04%), whereas Ogwashi-Asaba recorded the lowest values (12.13% and 14.61%, respectively). Carbon stock declined with increasing depth. Organic carbon was positively correlated with aggregate stability (r = 0.33), while state of aggregation and aggregate stability were strongly correlated (r = 0.80).
Conclusion: The findings indicate differences in carbon stocks and aggregation indices among the studied geological formations and support consideration of site-specific soil management practices.

Keywords: *Geological formations; soil organic carbon; soil carbon stock; carbon sequestration potential; soil aggregation; mean weight diameter; aggregate stability; state of aggregation; parent material.*

1. Introduction

Recently, climate change associated with an increase in the atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases, emitted by fossil fuel combustion, land-use changes and alteration of SOC has become a global concern. Soil is a major carbon reservoir with great potential to store carbon twice the potential of the atmosphere or vegetation (Alexander *et al.*, 2015). SOC stocks act as major carbon inventories in the environment that help sequester atmospheric CO_2, acting as its prominent sink (Gomes *et al.*, 2019) and contributing significantly to reducing the effects of existing and impending climate change (IPCC, 2014). Carbon sequestration is an important option not only to mitigate climate change but also to enhance soil fertility and productivity of the agroecosystem. SOC sequestration through appropriate and environmentally suitable agricultural methods must be promoted to counterbalance the increasing levels of CO_2 in the atmosphere due to disturbance in the terrestrial environment (Stockmann *et al.*, 2013).

Soils formed from contrasting parent materials can differ in the clay and mineral characteristics associated with soil organic carbon stabilisation (Yu *et al.*, 2023). A comparison across a geoclimatic gradient also identified variation in the contributions of stable aggregates and fine mineral fractions to soil organic carbon (Wasner *et al.*, 2024). In a separate field setting, combined biochar and trichocompost treatments improved soil organic carbon and aggregate stability, illustrating the potential relevance of management practices to both attributes (Younus *et al.*, 2026).

Soil aggregation and carbon (C) sequestration play vital roles in conserving soil, maintaining soil health, and sustaining crop productivity (Modak *et al.*, 2020). As soil aggregation is central to mechanisms of C sequestration, understanding how an aggregate stores and interacts with SOC is essential for developing management strategies towards enhancing of C sequestration at regional and global scales (Amin *et al.*, 2020). The interaction between C sequestration and aggregate stability could reduce soil nutrient loss, increase resistance to soil erosion, increase crop yields, and mitigate global warming through long-term soil C sequestration (Okolo *et al.*, 2020). Therefore, investigating the influence of geological formations on carbon sequestration and soil aggregation is crucial for sustainable soil management and climate change mitigation. It is also an important step towards addressing issues associated with food insecurity, soil degradation and climate change. A study of alluvial soils reported associations between wet aggregate stability, texture and soil organic carbon stock (Kumari *et al.*, 2021). Experimental findings further indicate that the ability of soils to form aggregates can support the development of protected soil organic matter (Even & Cotrufo, 2024). Nevertheless, the combined variation in soil carbon stock and aggregation indices among the Ameki, Alluvial Plain, Ogwashi-Asaba and Imo Shale formations, including differences across the sampled depths in the selected parts of Anambra State, remains insufficiently characterised. This site-specific comparison constitutes the research gap addressed in the present study. Thus, this study aims to examine soil carbon sequestration and aggregation potentials of soils overlying different geological formations in selected parts of Anambra State, Nigeria.

2. Materials and Methods

2.1 Site Description

2.1.1 Location and Climate

Anambra State lies within latitudes 5° 40' N and 6° 45' N and longitudes 6° 35' E and 7° 21' E with Delta State to the west, Imo State to the south, Enugu State to the east and Kogi State to the north as its boundaries. It is characterised by two seasonal climatic conditions: rainy and dry seasons with most rainfall occurring during the rainy season from March to October with peaks in July and September; and a short break in late July or August known as August break. The dry season extends from November to February with the harmattan occurring between the months of December and January. The mean annual rainfall is 2804.55 mm concentrated mainly in eight months of the year (NIMET, 2024). It has an average temperature of 27 °C with mean annual minimum and maximum temperatures in the ranges of 22 to 24 °C and 26 to 29 °C respectively (NIMET, Amawbia, 2024). The relative humidity ranges from 75 to 95% (NIMET, Amawbia, 2024).

2.1.2 Geology and Soils

Anambra State falls within the Anambra Basin which has about 12,000 m of sedimentary rocks (Akinyemi *et al.*, 2013). It comprises ancient Cretaceous Delta, somewhat similar to the Niger Delta, with Nkporo Shale, the Mamu Formations, the Ajali Sandstone, the Nsukka Formations, Ogwashi-Asaba Formation, Imo Formations and Ameki group as the main deposits with

outcrops of sandstone occurring at Abagana, Nsugbe and Nanka (Ezeigwe, 2015). These formations have given rise to ferrallitic, hydromorphic and alluvial soils.

2.1.3 Vegetation and Land use

The native vegetation was originally rainforest characterised by very tall, big trees with thick undergrowth and numerous climbers (Ezeigwe, 2015). However, as a result of human activities, the vegetation now consists of a mixture of arable crop farms, tree crops and bush regrowth. Agriculture, hunting and cottage industries are the predominant means of livelihood in the area (Orji-Uzor & Obasi, 2012). The major plant species in the area include Oil palm (*Elaeis guineensis*), Cassava (*Manihot* spp), Ogbono (*Irvingia gabonensis*), Maize (*Zea mays)*, Cocoyam (*Colocasia esculentus*), Rice (*Oryzea sativa*), Yam (*Discorea* spp), Mango (*Magnifera indica*), Plantain (*Musa* spp) (Chikere-Njoku, 2015).

2.2 Soil Sampling

Using the geological map, soil samples were collected randomly from secondary forests overlying four geological formations: Ameki (Abagana, Njikoka), Alluvial Plain (Attani, Ogbaru), Ogwashi-Asaba (Umeze, Ihiala) and Imo Shale (Ifite Ogwari, Anyamelum) at nine locations and three depths: 0-30, 30-60 and 60-90 cm using an auger. A total of 72 samples were collected. The samples were labelled and packed in polyethylene bags for transport to the laboratories for analyses using standard procedures.



Fig. 1. Geological Map of Anambra State
Source: Soil Survey Unit, Department of soil Science, University of Nigeria, Nsukka (2024)

2.3 Laboratory Analyses

The soil samples were air-dried, gently crushed and then sieved through a 2 mm sieve. Particle size distribution was determined using the Bouyoucos hydrometer method (Gee & Or, 2002), with 0.1 N NaOH as dispersant. The SOC content was determined by the wet dichromate acid oxidation method (Nelson & Sommers, 1982). Soil aggregation was determined by wet sieving methods as described by Kemper and Rosenau (1986). Soil carbon stock was calculated using Odunze (2017) as follows: SCS= Org. C x d x Bd X10000)/1000)

Where; SCS = Soil Carbon Stock (t C ha^{-1}); Org C = organic carbon concentration (g kg^{-1}); d = soil depth (m); Bd = Bulk density at depth (Mg mm^2 = 1ha; 1000 kg = 1ton.

2.4 Statistical Analysis

Data collected were subjected to a two-way analysis of variance to analyse variations in soil carbon stock and aggregation indices across the geological formations and between soil depths. Fisher's least significant difference (F-LSD) was used for mean separation at 95% confidence level. The magnitude and type of relationship between SOC, soil aggregation indices and carbon stock were assessed using correlation analysis. IBM SPSS Statistics software (version 23; IBM Corp., 2015) was used for data analysis.

3. Results and Discussion

3.1 Main Effect of Geological Formation on Soil Particle Size Distribution

Soils on Imo Shale recorded the highest clay and silt fractions (350 and 260 g kg^{-1} respectively), which indicates soils developed from fine-textured formations and suggests reduced permeability and potentially higher nutrient retention capacity (Obumselu *et al.*, 2024). The highest value of fine sand (570 g kg^{-1}) and coarse sand fractions (400 g kg^{-1}) in Ogwashi-Asaba and Ameki soils, respectively, reflect the arenaceous nature of the parent materials (Ugwuoju *et al.*, 2026). The textural classes varied from sandy loam (Alluvial Plain) to loamy sand (Ameki and Ogwashi-Asaba) and clay loam (Imo Shale). The variations in textural classes could be attributed to the nature of their parent materials, similar to the findings of Umeugokwe *et al.* (2022).

Table 1. Main effect of geological formation on soil particle size distribution

Geological Formation	Clay	Silt	Fine Sand	Coarse sand	Texture
			(g kg^{-1})		
Alluvial Plain	180	170	280	370	Sandy loam
Ameki	130	50	250	570	Loamy sand
Imo Shale	350	260	140	250	Clay loam
Ogwashi-Asaba	120	60	400	420	Loamy sand
F-LSD (0.05)	3.12	1.97	2.61	3.82	

F-LSD (0.05) = Fisher's least significant difference at 5% probability level

3.2 Effect of Geological Formation on Organic Carbon, Carbon Stock and Soil Aggregation Indices

The C value (0.97 g kg^{-1}) was highest in Alluvial Plain soils and lowest (0.11 g kg^{-1}) in soils on the Ogwashi-Asaba Formation because of the higher organic matter content in the Alluvial Plain soils. The C value decreased with soil depth. This might be attributed to a decrease in organic material and faunal activities with depth. Similarly, Lawal *et al.* (2013) observed a decrease in C with increasing soil depth and linked it to a reduction in organic material and faunal activities with depth.

Carbon stock ranged from 1.10 to 4.40 t C ha^{-1}. Higher carbon stock would discourage global warming and climate change in the area and vice versa. The trend in carbon stock was Alluvial Plain (4.40 t C ha^{-1}) = Imo Shale (3.55 t C ha^{-1})>Ameki (2.11 t C ha^{-1}) = Ogwashi-Asaba (1.10 t C ha^{-1}) formations (Table 2). The high carbon stock in the Alluvial Plain may be attributed to the high carbon content of the soils. Chris-Emenyonu *et al.* (2020) found the highest soil carbon stock in Imo Shale and attributed it to the higher clay and organic carbon content of soils, as clay has the ability to trap carbon. Carbon stock also tended to decrease with increasing depth, from 3.86 t C ha^{-1} at 0–30 cm to 2.15 t C ha^{-1} at 60–90 cm, following the trend that organic carbon decreases with increasing soil depth. This contradicts the findings of Ahukaemere (2015) who observed an increase in soil carbon stock with increasing soil depth.

The mean weight diameter (MWD) was highest (0.64 mm) in soils on Imo Shale and lowest (0.50 mm) in soils on the Ameki Formation (Table 2). This suggests that soils on Imo shale had larger average aggregate sizes and hence, greater stability of the soil structure (Nimmo & Perkins, 2002). Igwe (2005) reported that soils with good structure and high MWD resist breakdown during rainstorms better than those with poor structure. This suggests that soils on Ameki formation are considered the most vulnerable to erosion under rainfall.

The soils on Imo Shale Formation had the highest values for state of aggregation (22.08 %) and aggregate stability (28.04 %) while soils on Ogwashi-Asaba had the lowest (12.13% for state of aggregation and 14.61% for aggregate stability. This indicates that soils on Imo Shale had greater resistance to mechanical or physico-chemical destructive forces (Singh *et al.*, 2019).

Table 2. Main effect of geological formations and soil depth on soil carbon stock and aggregation indices

Geological formation	OC	SCS	MWD	% SOA	% AS
	g kg^{-1}	t C ha^{-1}	mm		
Alluvial Plain	0.97	4.40	0.63	17.68	24.86
Ameki	0.48	2.11	0.50	14.82	18.33
Imo Shale	0.79	3.55	0.64	22.08	28.04
Ogwashi-Asaba	0.23	1.10	0.57	12.13	14.61
F-LSD (0.05)	0.30	1.35	0.08	5.89	6.49
Soil depth					
0.30 cm	0.89	3.86	0.58	16.20	21.38
30-60 cm	0.50	2.40	0.60	17.60	22.70
60-90 cm	0.46	2.15	0.61	16.25	20.29
F-SLD (0.05)	0.26	1.17	Ns	Ns	Ns

OC= Organic carbon, SCS= soil carbon stock, MWD= mean weight diameter, SOA= state of aggregation, AS= aggregate stability; NS= not significant; F-LSD= Fisher's least significant difference at 5% probability level

3.3 Relationship Between Organic Carbon, Carbon Stock and Aggregation Indices

SOC showed highly significant correlation (P=0.05) with soil carbon stock (r =1.00, r =0.99) indicating SOC as one of the principal sources of carbon stock in the soils (Tables 3a and b). No correlation was observed between SOC and MWD suggesting that other soil properties are also important in the formation of soil aggregates. This is consistent with observations in a humid tropical environment in which free Fe oxides were shown to contribute more to soil aggregation than soil organic carbon (Igwe *et al.,* 1995). Mthimkhulu (2011) and Madikizela (2014) also found no relationship between SOC and MWD in their studies.

Table 3a. Correlation matrix for organic carbon, soil carbon stock and aggregation indices across the geological formations

	OC	MWD	SOA	AS	SCS
OC	1				
MWD	0.15	1			
SOA	0.29	0.41*	1		
AS	0.33*	0.42*	0.80**	1	
SCS	1.00**	0.17	0.30	0.34*	1

** Correlation is significant at the 0.05 level (2-tailed)*
*** Correlation is significant at the 0.01 level (2-tailed)*
OC: organic carbon, SCS: soil carbon stock, MWD: mean weight diameter, SOA: state of aggregation, AS: aggregate stability

Table 3b. Correlation matrix for organic carbon, carbon stock and aggregation indices in each geological formation

			Alluvial Plain		
	OC	**MWD**	**SOA**	**AS**	**SCS**
OC	1				
MWD	-0.20	1			
SOA	0.15	0.54	1		
AS	-0.34	0.49	0.60	1	
SCS	0.99**	0.28	0.50		1
Ameki					
OC	1				
MWD	-0.09	1			
SOA	-0.49	0.32	1		
AS	-0.52	0.25	0.94**	1	
SCS	0.99**	0.42	0.31		1
Imo Shale					
OC	1				
MWD	-0.29	1			
SOA	0.23	-0.15	1		
AS	0.39	-0.21	0.61	1	
SCS	0.99**	0.32	0.21		1
Ogwashi-Asaba					
OC	1				
MWD	0.26	1			
SOA	0.60	-0.01	1		
AS	0.61	0.04	.99	1	
SCS	1.00**	0.15	0.26		1

*** Correlation is significant at the 0.01 level (2-tailed)*
OC: organic carbon, SCS: soil carbon stock, MWD: mean weight diameter, SOA: state of aggregation, AS: aggregate stability

Several studies have shown that soil organic carbon can improve the formation of soil aggregates and increase the mechanical stability of aggregates by binding soil mineral particles, thereby influencing the coherence of inter-particle bonds (Laskar, 2011; Siddique *et al.,* 2017). This observation is supported by the positive significant relationship between SOC and aggregate stability (r =0.33) (Table 3a).

Significant correlations were observed between MWD and state of aggregation (r =0.41) and aggregate stability (r = 0.42). These associations suggest that an increase in MWD may accompany improvements in the soil's state of aggregation and aggregate stability, thereby providing greater resistance against agents of degradation. The highly significant correlation observed between state of aggregation and aggregate stability (r = 0.80, r = 0.94) may be used to develop linear models describing their relationships (Tables 3a and b).

Aggregate stability was positively correlated with soil carbon stock (r = 0.34) as shown in Table 3a. This association suggests a relationship between aggregate stability and soil carbon storage.

4. Conclusions

The findings indicate that soils developed over different geological formations in the selected areas of Anambra State differed in their organic carbon content, carbon stocks and aggregation characteristics. The Alluvial Plain recorded the highest organic carbon content and carbon stock, whereas Ogwashi-Asaba recorded the lowest values for these properties. Soils overlying Imo Shale had the highest mean weight diameter, state of aggregation and aggregate stability, while soils on Ameki had the lowest mean weight diameter. Soil carbon stock declined with increasing sampling depth, but the aggregation indices did not differ significantly among the depth intervals reported in the study. Organic carbon was strongly associated with carbon stock and showed a positive association with aggregate stability. However, its relationship with mean weight diameter and state of aggregation was weaker, suggesting that other soil properties may contribute to aggregate formation and stability. These findings indicate the value of considering geological formation when assessing soil carbon storage and structural properties. Organic amendments, mulching, cover cropping and agroforestry may be considered for further evaluation as management options, particularly for soils overlying Ameki and Ogwashi-Asaba. Their effectiveness should be assessed under local conditions before specific recommendations are adopted.

5. Limitations

This study was limited to selected secondary forest sites across four geological formations in Anambra State, Nigeria, which may restrict the generalisability of the findings to other locations and land-use systems. Soil sampling was conducted at three depth intervals, providing limited insight into deeper soil carbon storage. Furthermore, seasonal variations in soil carbon dynamics and aggregate stability were not examined. Future studies involving broader geographical coverage and long-term monitoring could provide a more comprehensive understanding of these relationships.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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