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Influence of slope position on soil organic carbon, soil structure and hydraulic properties in cultivated humid tropical coastal plain sands

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ABSTRACT

Slope position plays a key role in regulating soil redistribution, soil structural and hydraulic functioning in cultivated landscapes, but the effect of these interrelated aspects has not been properly examined together. Therefore, soil samples were collected from upper, middle, and lower slope positions and analysed for soil organic carbon (SOC), soil structural and hydraulic parameters. Although all slope positions exhibited a loamy sand texture, particle-size fractions varied along the slope. Sand content was highest at the middle slope, whereas silt and clay were enriched at the lower slope, indicating downslope deposition of fine materials. The SOC concentration increased from 12.5 g kg^{-1} at the upper slope to 19.3 g kg^{-1} at the lower slope, with SOC stocks increasing from 13.3 to 18.6 Mg ha^{-1}. Bulk density declined downslope (1.48 to 1.34 Mg m^{-3}), while total porosity increased, reflecting improved soil structure in depositional areas. Aggregate stability was highest at the lower slope, where larger macroaggregates and greater mean and geometric aggregate diameters were observed, with saturation and field capacity water contents showing similar trends. Regression analysis showed that bulk density and macroporosity decreased with SOC stocks, whereas total porosity, aggregate stability, saturated water content, and field capacity increased with SOC, with field capacity showing the strongest response (R^2 = 0.46). Saturated hydraulic conductivity showed little variation among slope positions. In general, the findings show that slope position controls soil structural and hydraulic behaviour via erosion, organic carbon distribution, and aggregate-driven pore development, underscoring the importance of slope-specific soil management.

Contribution/Originality: This manuscript is an original work that has not been published or submitted elsewhere. The study provides an integrated assessment of how slope position influences soil organic carbon, soil structure, and hydraulic properties in cultivated humid tropical coastal plain sands. All authors have approved the manuscript for submission.

1. INTRODUCTION

Soil organic carbon (SOC) plays a central role in regulating soil structural behaviour, supporting ecosystem functions, and sustaining environmental quality. Its importance arises from its direct effect on soil structure, nutrient cycling, and hydrological processes. Globally, soils represent the largest terrestrial carbon (C) reservoir, containing substantially more C than the atmosphere and all vegetation combined (IPCC, 2021; Minasny et al., 2017), underscoring the need to understand SOC behaviour in the highly dynamic soil environment. Carbon enters soil systems mainly through the decomposition of plant residues (Deis, Fort, Lin-Yang, Balda, & Pou, 2025; Paul, 2016; Reyes, 2015) and occurs as a continuum from fresh organic fragments to stable humified forms (Lehmann & Kleber, 2015; Sollins, Homann, & Caldwell, 1996).

Soil organic carbon enhances soil aggregation and pore continuity through the formation of stable organo-mineral complexes and the promotion of micropore development, thereby improving infiltration capacity, water-holding capacity, and groundwater recharge (Blanco-Canqui et al., 2013; Six, Conant, Paul, & Paustian, 2002). In addition, SOC increases nutrient availability and cation exchange capacity, buffers soil temperature fluctuations, and strengthens resistance to crusting and erosion, collectively improving soil structural stability and hydraulic functioning (Brady & Weil, 2008; Yu et al., 2020). Because SOC binds mineral particles into aggregates, any factor influencing SOC distribution is likely to alter soil physical structure and associated hydraulic functions.

The spatial distribution of SOC is widely recognised to vary across landscapes (Patton, Lohse, Seyfried, Godsey, & Parsons, 2019; Schwanghart & Jarmer, 2011; Yu et al., 2020), thus influencing the variation of soil structural and hydraulic properties with soil slope position (Ayele, Demissie, Jemberrie, Jeong, & Hamilton, 2020; Ceddia et al., 2009). These variations are largely driven by the redistribution of SOC associated with mineral materials or as separate materials via the erosional processes of detachment, transportation and deposition (Lal, 2003; Li & McCarty, 2018; Van Hemelryck, Fiener, Van Oost, Govers, & Merckx, 2010; Wang, Fan, Liu, & Qu, 2023; Wilson, Kampf, Wagenbrenner, MacDonald, & Gleason, 2021).

Slope position influences soil redistribution primarily through gravitational forces and runoff-driven erosion, both of which intensify with increasing slope gradient (Liu et al., 2024). Soil detachment and downslope transport are further exacerbated by inappropriate land management practices, particularly on fragile, erosion-prone tropical soils (Issaka & Ashraf, 2017; Umoh, Essien, Utin, & Udom, 2020). As a result, slope position governs the spatial organisation of soil texture, SOC, and hydrological pathways across landscapes.

Numerous studies have demonstrated that slope position is a major driver of SOC variability and soil physical property distribution (Li & McCarty, 2018; Patton et al., 2019; Wang et al., 2023; Yu et al., 2020). These relationships arise because slopes control surface and subsurface hydraulic connectivity, thereby regulating overland flow intensity and the redistribution, transport, and accumulation of soil minerals and SOC (Bracken, Turnbull, Wainwright, & Bogaart, 2015; Dialynas et al., 2016; Quinton, Govers, Van Oost, & Bardgett, 2010). Slope position also influences microclimate, soil moisture availability, vegetation cover, and pedogenic processes (Wang et al., 2023; Yimer, Ledin, & Abdelkadir, 2007). The influence of slope position is likely amplified by the inherent characteristics of humid tropical coastal plain sands, which are typically low in organic carbon, weakly structured, and highly susceptible to detachment and erosion (Igwe & Obalum, 2013; Madueke et al., 2021).

Also, investigations have examined slope position-driven soil variability in humid tropical coastal plain sands. Terrain-based modelling and field investigations have shown that slope and curvature strongly saturated hydraulic conductivity and water retention along coastal plain sand toposequences (Obi, Ogban, Ituen, & Udoh, 2014). Other studies have examined surface infiltrability and infiltration model performance in relation to slope position or aspect, improving understanding of spatial patterns in water transmission (Ogban, Ibotto, Utin, Essien, & Arthur, 2022; Ogban & Okon, 2020).

Related research has shown the effect of slope position on soil erodibility, aggregation, and sediment redistribution, with upper slopes typically exhibiting coarser textures, reduced aggregation, and greater erosion risk, and lower slopes showing finer materials and improved structural stability (Eneje & Adanma, 2007; Ogban et al., 2022). Slope-based soil evaluations have further linked these patterns to land capability and management implications in cultivated coastal plain sand landscapes (Madueke et al., 2021). Similarly, Utin and Essien (2021) evaluated the effects of slope position on selected soil properties and maize growth on coastal plain sands, highlighting the agronomic implications of topography but focusing primarily on crop performance and basic soil attributes. More broadly, related studies across tropical and subtropical landscapes (e.g. (Bufebo, Elias, & Agegnehu, 2021; Seifu, Elias,

& Gebresamuel, 2020; Singh et al., 2023; Zhu et al., 2022) have documented slope-induced variation in basic soil physicochemical attributes.

However, the studies mentioned above have together emphasised surface infiltration, erodibility indices, or agronomic outcomes, often examining hydraulic, structural, or carbon properties in isolation. Soil organic carbon is commonly assessed as concentration rather than stock, and aggregate size distribution and stability metrics are rarely integrated with detailed hydro-physical measurements such as saturated hydraulic conductivity, water retention characteristics, and macroporosity. Consequently, the mechanistic understanding of how topography simultaneously regulates SOC redistribution, soil structural integrity, and water movement and retention remains limited under humid tropical conditions. Addressing these gaps is essential for understanding erosion-driven soil functioning and for developing slope-specific soil management strategies in cultivated landscapes of humid tropical coastal plain sands. This study was therefore guided by the hypothesis that slope position significantly influences SOC content, soil structure and hydraulic behaviour. Specifically, it was hypothesised that finer soil particles, SOC, carbon stock, and aggregate stability increase downslope, while sand content and bulk density are highest at more eroded upper slope positions. Accordingly, the objectives of this study were to: (i) examine particle size distribution, bulk density, and SOC dynamics along the slope; (ii) evaluate aggregate size distribution, aggregate stability, and key hydraulic properties across slope positions; and (iii) investigate the relationship of SOC stocks with soil structure and hydraulic parameters.

2. MATERIALS AND METHODS

2.1. Study Area

The study was carried out at two sections of the Teaching and Research Farms of the University of Uyo – the Use Offot Main Farm of the Faculty of Agriculture and the Internship Farm behind the Faculty of Agriculture of the University, both located along Nwaniba area of Uyo, Akwa Ibom State, Nigeria. Akwa Ibom State of Nigeria lies between latitudes 5°00' and 5°10' N and longitudes 7°50' and 8°00' E. The area is within the humid tropical rainforest, characterised by distinct wet and dry seasons. The wet season generally lasts from April to October, and the dry season lasts from November to March (NearWeather, 2026; Nigerian Erosion and Watershed Management Project (NEWMAP) Akwa Ibom State Project Management Unit, 2017). Historically, a short dry spell of about two weeks known as the "August Break" occurs between late July and early September (Nigerian Erosion and Watershed Management Project (NEWMAP) Akwa Ibom State Project Management Unit, 2017). The annual average rainfall is 3500 mm with high peak intensities ranging from 60-120 mm h^{-1} with temperature ranging from 28 to 32°C, and the relative humidity is about 70% (Nigerian Erosion and Watershed Management Project (NEWMAP) Akwa Ibom State Project Management Unit, 2017).

The study sites are located on the geological formation of coastal plain sands. The parent material consists of unconsolidated coastal plain sands, and the soils are classified as Ultisols in the USDA soil taxonomy system, corresponding to Alisols of the World Reference Base (Food and Agriculture Organization of the United Nations (FAO), 2015). The soils are deep, permeable and characterised by a narrow texture range having loamy sand to sandy loam surface layers over sandy clay loam to sandy clay subsoil with inherently low organic matter content and low structural stability (Ogban & Ekerette, 2001).

The study sites function as student demonstration plots and are consequently subjected to intensive cultivation involving a variety of crops, including cassava, fluted pumpkin, pepper, tomato, cucumber, and maize, with cassava being the dominant crop.

2.2. Soil Sampling

A total of 30 soil samples were collected from 10 transects on slopes across the farms in which cassava was cultivated. Five transects were sampled from each of the two sections of the farm during the pre-cultivation season of 2021 (February 2021). Samples were taken at the upper, middle, and lower positions along each slope transect at a depth of 0–7.2 cm. Slope positions were classified qualitatively based on their relative location along the slopes rather than on the basis of slope gradient, and were used to represent differences in dominant soil-water and geomorphic processes, including erosion, material transport, and deposition. Accordingly, slope position was treated as a categorical landscape variable independent of local slope angle. Related studies have expressed slope position in a similar way, including Chen et al. (2023); Jourgholami, Ramineh, Zahedi Amiri, and Labelle (2019) and Zhu et al. (2022). Undisturbed core samples were obtained using sampling cores measuring 7.2 cm in height and 6.8 cm in diameter from the surface soil along the three positions of the ten slopes for the determination of saturated hydraulic conductivity (K_{sat}), saturated water content, field capacity, macroporosity, and bulk density. In addition, disturbed bulk samples were collected for particle size analysis and SOC determination. A separate set of samples was taken using a spade for the assessment of aggregate size distribution. The core samples were secured with cloth and rubber bands and appropriately labeled, while the bulk samples were placed in labeled polythene bags to avoid contamination and prevent soil loss.

2.3. Laboratory Methods

The core samples were used to determine K_{sat}, soil water contents, and bulk density. Core samples held securely with a cloth and rubber ring were first placed in a basin and water was added to about three-quarters of its height. The samples were allowed to saturate by capillarity for 12 hours, after which the saturated weights were recorded. The saturated water content was then measured using the constant-head permeameter method (Dane & Topp, 2002) and the K_{sat} (m s^{-1}) was calculated as follows, Equation 1.

$$\mathrm{K_{sat}} = \frac{\mathrm{QL}}{\mathrm{A\Delta ht}} \qquad (1)$$

Where Q is water discharge (m^3), L is length of soil column (length of core sampler) (m), A is cross sectional area (m^2) of core sampler, Δh is pressure head difference causing the flow and t is time (s).

After the determination of K_{sat}, the core samples were transferred onto a wire gauze placed on a container for 48 h to allow for drainage to field capacity under gravity (Bacq-Labreuil, Crawford, Mooney, Neal, & Ritz, 2019; Shaxson & Barber, 2003; Zhu et al., 2022). This was to allow for all macropores (>60µm) to be drained.

The core samples were then transferred to the oven and dried for 24 h to constant weight at a temperature of 105°C before the calculation of bulk density, ρ_b (Mg m^{-3}) using the mass/volume relationship as follows, Equation 2:

$$\rho_b = \frac{M_s}{V_t} \qquad (2)$$

Where M_s is mass of dry soil (Mg), V_t is total volume of soil (m^3) calculated from the internal volume of the core sampler. Total porosity was determined from bulk density, assuming particle density of 2.65 Mg m^{-3}, being average particle density of mineral soils. Water content at saturation (θ_s), field capacity (θ_{FC}) and macroporosity (M_a) were determined on a gravimetric basis but were expressed in volumetric basis by multiplication with ρ_b.

The bulk soil samples were air-dried and sieved with a 2mm sieve and stored securely in sample bags for the determination of particle size distribution and SOC concentration. Particle size distribution was determined using the Bouyoucos hydrometer method as described by Udo, Ogunwale, Akinrinde, and Ojanuga (2009) after dispersion with sodium hexa-metaphosphate solution. The textural class of the soil was determined using textural triangle. Soil organic carbon content was determined using the Walkley-Black Wet Oxidation Method as modified by Nelson and Sommers (1996). Soil organic carbon stock (SOCS) (Mg ha^{-1}) was subsequently calculated as follows, Equation 3.

$$\mathrm{SOCS\ (Mg\ ha^{-1})} = \mathrm{C} \times \rho_b \times \mathrm{D} \times 100 \qquad (3)$$

Where C is SOC concentration, measured in percent (%), and expressed as a fraction in the calculation, ρ_b is bulk density (Mg m^{-3}), D is sampling depth (m).

Loose soil samples collected with hand trowel were used for the determination of mean weight diameter of water stable aggregates using the method described by Carter and Gregorich (2008). In this method, portions of air-dried samples were first passed through a 4 mm sieve size. One hundred grams (100g) of the < 4mm soil sample were placed on the topmost sieve in a nest of sieves of 2.00, 1.00, 0.5 and 0.25 mm and pre-soaked in water for 10 min. Then, the nested sieves with the sample were oscillated vertically 20 times in water at the rate of one (1) oscillation per second. Soil sample at the topmost sieve was always below water surface during each oscillation. At the end of wet sieving, resistant aggregates on each sieve were oven-dried and recorded as percentages of the original mass, while mean weight diameter (MWD) (mm) and geometric mean diameter (GMD) (mm) were calculated as follows, Equations 4 - 5.

$$MWD = \sum_{i=1}^{n}(x_i \text{ x } w_i) \quad (4)$$

Where x_i= Mean diameter of each aggregate size class (mm), w_i= Proportion (fraction) of the total soil sample retained on that sieve, n= Number of sieve classes used.

$$GMD = \frac{\sum_{i=1}^{n} w_i \ln(x_i)}{\sum_{i=1}^{n} w_i)} \quad (5)$$

where w_i= Weight proportion (fraction) of aggregates in size class *i*, x_i= Geometric mean diameter of the size class *i*, n= Number of size classes.

2.4. Statistical Analysis

A one-way analysis of variance (ANOVA) was performed to evaluate the effect of slope position, with replication included in the model to account for experimental variability. Slope position was treated as the main fixed factor, while replication served as a blocking factor. Statistical significance was assessed at the 0.05 probability level. Prior to the interpretation of ANOVA results, model assumptions were evaluated. Normality of residuals was tested using the Shapiro–Wilk test applied to Pearson residuals. In addition, normal Q–Q plots were examined to visually assess departures from normality. Homogeneity of variance and model adequacy were evaluated by plotting Pearson residuals against fitted values. A random distribution of residuals around zero without discernible patterns was considered indicative of constant variance and an appropriate model fit. When significant differences among slope positions were detected, mean separation was conducted using Fisher's Least Significant Difference (LSD) test at α = 0.05. Estimated marginal means were calculated, and pairwise comparisons were performed without adjustment for multiple comparisons, consistent with the LSD procedure. Simple linear regression was also performed to assess the relationship between SOC stocks with soil structural and hydraulic parameters. Statistical analyses were conducted using R statistical programme (R Core Team, 2025).

3. RESULTS

3.1. Soil Particle Size Distribution, Bulk Density and Organic Carbon

Soil physical properties exhibited a coherent pattern along the slope, reflecting systematic redistribution of soil particles and organic matter across landscape positions. Particle-size fractions varied significantly with slope position, with sand content peaking at the middle slope and declining toward the lower slope, while silt and clay contents were significantly greater ($p \geq 0.05$) at the lower slope. Despite these differences, sand dominated the particle-size distribution at all positions, accounting for 836, 846, and 807 g kg^{-1} at the upper, middle, and lower slopes, respectively, resulting in a loamy sand texture across the entire slope (Table 1).

These textural gradients were also observed in the coordinated changes in soil SOC concentration, SOC stocks, bulk density, and porosity (Figure 1). Soil organic carbon in the upper 7.2 cm increased progressively downslope, with significantly higher concentrations at the middle (15.3 g kg^{-1}) and lower slopes (19.3 g kg^{-1}) compared with the upper slope (12.5 g kg^{-1}). A similar downslope trend was observed for SOC stocks, which increased from 13.3 Mg ha⁻¹ at the upper slope to 15.5 Mg ha⁻¹ at the middle slope and 18.6 Mg ha⁻¹ at the lower slope. In contrast, bulk density decreased downslope, reaching its highest value at the upper slope.

Table 1. Mean ± standard error of particle size distribution along studied slope positions.

Slope position	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Texture
Upper slope	836±2.7^b	64±2.9^b	100±3.5^b	ls
Middle slope	846±3.6^a	53±2.7^b	100±3.6^b	ls
Lower slope	807±3.5^c	75±4.9^a	118±6.7^a	ls

Note: Means with same letters along the columns are not significantly different ($p \geq 0.05$).
ls = loamy sand.

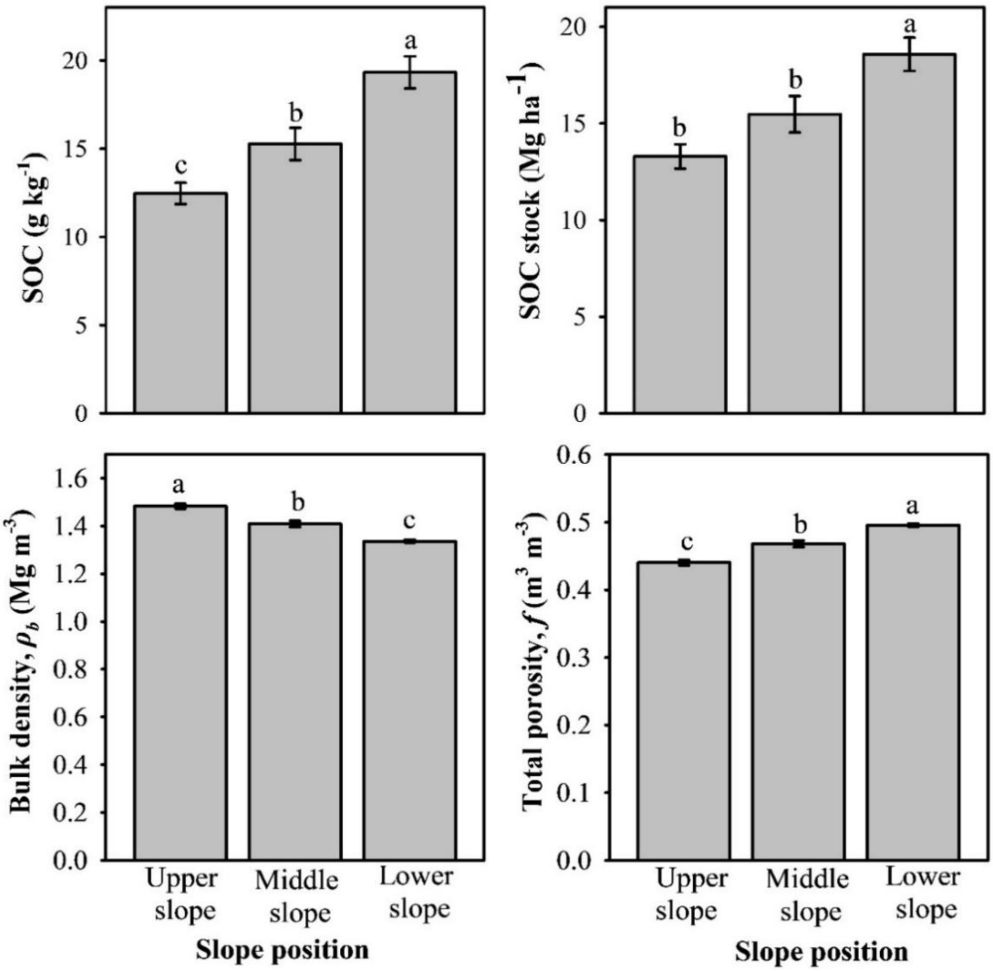

Figure 1. Mean organic carbon content, soil organic carbon stocks, bulk density and of soil of three slope positions.
Note: Bars represent means ± standard error. Bars with same letters in each graph represent means that are not significantly different ($p \geq 0.05$).

(1.48 Mg m^{-3}) and lowest at the lower slope (1.34 Mg m^{-3}), while total porosity exhibited the inverse pattern, increasing from the upper to the lower slope.

3.2. Aggregate Size Distribution and Aggregate Stability

Figure 2 illustrates how different size classes of soil aggregates were distributed across the three slope positions examined. Large macroaggregates (>2 mm) were more abundant at the lower slope, accounting for 13%, compared with 8% at the upper slope and 7% at the middle slope. In contrast, the smaller macroaggregate classes (2–0.25 mm) showed no significant variation among the slope positions. The microaggregate fraction (<0.25 mm) was higher at the upper (19%) and middle (20%) slopes than at the lower slope (15%). Across all slope positions, aggregate distribution followed a clear bell-shaped pattern: proportions were lowest in the 4–2 mm class, increased steadily to reach a maximum in the 1–0.5 mm class, and then declined through the 0.5–0.25 mm and <0.25 mm fractions. Consistent with these trends, both the Mean Weight Diameter (MWD) and Geometric mean diameter (GMD) were significantly higher at the lower slope than the middle slope positions (Table 2).

3.3. Soil Hydraulic Functions

Soil water-retention properties also varied along the slope (Table 3). Mean K_{sat} decreased downslope with values of 4.78 x 10^{-5} ms^{-1}, 4.23 x 10^{-5} ms^{-1} and 4.03 x 10^{-5} ms^{-1} observed at upper slope, middle slope and lower slope positions, respectively, with no significant differences (p≥0.05) among them. In contrast, saturated water content (θ_s) and field capacity water content (θ_{FC}) increased from the upper to the lower slope, showing significant differences between them. The volume of macropores (M_a) did not differ significantly between upper slope (0.18 m^3m^{-3}) and middle slope (0.17 m^3m^{-3}), but that of the lower slope (0.15 m^3m^{-3}) was the highest significant.

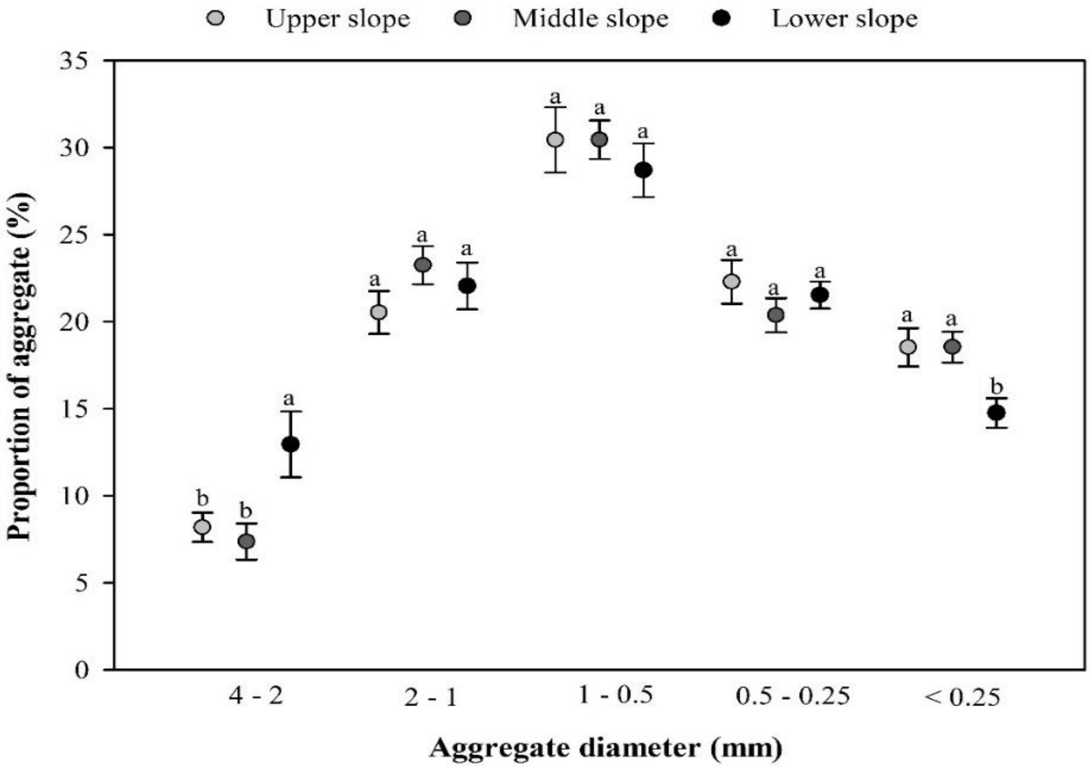

Figure 2. Mean ± standard error with error bars showing proportion of soil aggregates across size classes in the three slope positions.

Note: Means with same letters are not significantly different (p≥0.05).

Table 2. Mean ± standard error of weight diameter and geometric mean diameter of soils of the three slope positions.

Slope position	Mean weight diameter, MWD (mm)	Geometric mean diameter, GMD (mm)
Upper slope	0.89±0.03[b]	0.60±0.02[b]
Middle slope	0.90±0.03[b]	0.61±0.02[b]
Lower slope	1.03±0.05[a]	0.70±0.03[a]

Note: Means with same letters along the columns are not significantly different (p≥0.05).

Table 3. Mean ± standard error of soil hydraulic parameters of the three slope positions.

Slope position	K_{sat} (x10^{-5} m s^{-1})	θ_s m^3m^{-3}	θ_{FC} m^3m^{-3}	M_a m^3m^{-3}
Upper slope	4.78±0.71[a]	0.43±0.00[c]	0.25±0.01[c]	0.18±0.00[a]
Middle slope	4.23±0.41[a]	0.46±0.01[b]	0.29±0.01[b]	0.17±0.01[a]
Lower slope	4.03±0.50[a]	0.49±0.01[a]	0.34±0.00[a]	0.15±0.00[b]

Note: Means with same letters along the columns are not significantly different (p≥0.05).
K_{sat} – saturated hydraulic conductivity, θ_s – saturated water content, θ_{FC} – field capacity water content, M_a – Macroporosity.

3.4. Relationship Between Soil Organic Carbon and Hydro-Physical Properties

Regression analysis showed that SOC stocks were significantly related to several soil structural and hydraulic parameters (Figure 3; Table 4). Bulk density and macroporosity decreased with increasing SOC stocks, whereas total porosity and aggregate stability indices (MWD and GMD) increased, indicating consistent improvements in soil structure (e.g., field capacity, $R^2 = 0.46$; total porosity, $R^2 = 0.36$). Saturated water content also increased with SOC stocks, while the microaggregate fraction declined and the proportion of large macroaggregates increased. Relationships between SOC stocks and soil texture were comparatively weaker, with decreasing sand content and increasing clay content at higher SOCS levels. In general, SOC stocks explained a greater proportion of variability in soil structural and water-retention properties than in particle-size fractions, emphasizing the stronger linkage between carbon accumulation and soil physical functioning.

4. DISCUSSION

The differences observed in SOC, soil structure and hydraulic properties reflect a pattern of soil redistribution along the slopes. Differences in sand, silt, and clay contents across slope positions indicate selective erosion at upper positions and progressive downslope transport and deposition of finer materials. While sand content peaked at the middle slope and declined toward the lower slope. The enrichment of silt and clay at the lower slope confirms its role as a depositional zone for fine particles mobilised by runoff. The accumulation of sand and silt at the lower slope, together with the concentration of sand at the middle slope, indicates the greater transportability of finer soil particles and the increased resistance of larger-diameter particles (e.g., sand) to runoff-driven transport, leading to their increased deposition at the middle slope position. Similar topography-induced particle sorting and transportation have been documented by previous research, attributed to gravitational and hydrological processes.

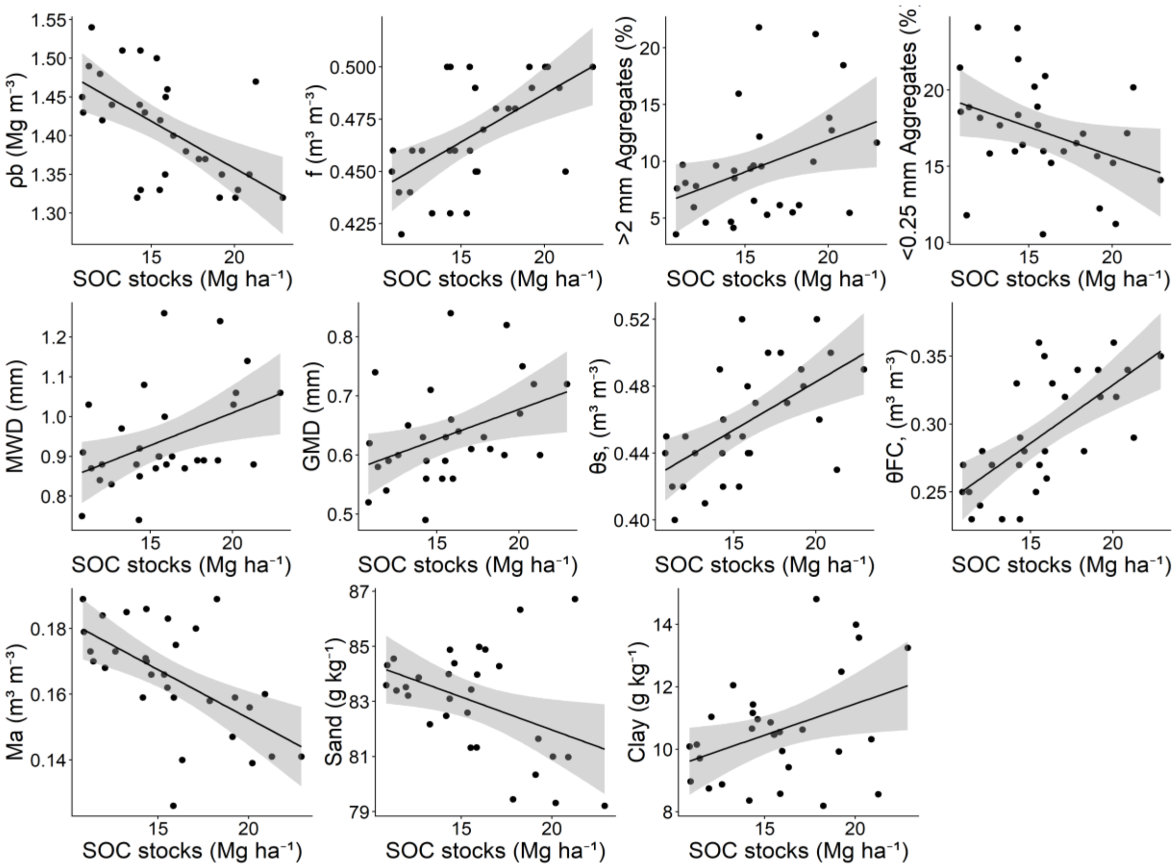

Figure 3. Regression plots of some soil structural and hydraulic parameters with soil organic carbon stocks.

Note: SOC = soil organic carbon; ρ_b, = bulk density; f = total porosity; MWD = mean weight diameter; GMD = Geometric mean diameter, K_{sat} = saturated hydraulic conductivity; SWC = θ_s saturated water content; FC = θ_{FC}.

Table 4. Regression equation, R^2 and p-value for the regression of soil structural and hydraulic parameters with soil organic carbon stocks.

Response variable	Regression equation	R^2	p value
Bulk density (Mg m^{-3})	y = -0.012x + 1.60	0.35	0.01
Total porosity (m^3m^{-3})	y = 0.005x + 0.40	0.36	0.00
Large macroaggregates (>2 mm) (%)	y = 0.561x + 0.65	0.15	0.03
Microaggregates (<0.25 mm) (%)	y = -0.383x + 23.28	0.14	0.05
MWD (mm)	y = 0.016x + 0.68	0.19	0.02
GMD (mm)	y = 0.010x + 0.47	0.17	0.02
θ_s (m^3m^{-3})	y = 0.006x + 0.37	0.30	0.01
θ_{FC} (m^3m^{-3})	y = 0.009x + 0.16	0.46	3.49×10^{-5}
M_a (m^3m^{-3})	y = -0.008x + 0.21	0.36	0.01
Sand (g kg-1)	y = -0.239x + 86.75	0.17	0.03
Clay (g kg-1)	y = 0.200x + 7.45	0.16	0.03

Note: MWD – mean weight diameter, GMD – geometric mean diameter, θ_s – saturated water content, θ_{FC} – field capacity water content, M_a – macroporosity, x = organic carbon stocks (explanatory variable), y = the response variable.

Zhu et al. (2022) and the influence of surface areas of soil particles (Tromp-van Meerveld et al., 2008; Wilson et al., 2021). Although these particle-size differences were significant, all slope positions retained a loamy sand texture, indicating that parent material uniformity constrained the extent of textural differentiation. Nevertheless, even modest increases in silt and clay content at the lower slope had pronounced consequences for SOC dynamics and soil functioning. The enrichment of finer soil particles downslope coincided with higher SOC concentrations and SOC stocks, indicating that SOC was redistributed together with sediment during erosion and deposition. This pattern aligns with findings by Berhe et al. (2012) and Buraka, Elias, and Lelago (2022), who reported enhanced SOC accumulation in depositional landscape positions due to sediment-bound SOC inputs.

The accumulation of SOC stocks at the lower slope exerted strong control over structural behaviour. Bulk density significantly decreased while total porosity increased downslope (Figure 1), with regression analysis showing these effects to be related with increase in SOC stocks with R^2 of 0.35 (in the case of bulk density) and 0.36 (total porosity) (Figure 3; Table 4). This demonstrates that zones of greater carbon accumulation were characterised by reduced compaction and enhanced pore volume. The increase in SOC alongside with the higher clay and silt contents observed at the lower slope position suggests the effect of possible association of soil minerals with SOC in improving the soil structural condition in depositional areas. Comparable reductions in bulk density within downslope depositional zones have been reported by Bufebo et al. (2021) and Zhu et al. (2022), emphasizing the structural benefits of sediment and organic matter accumulation. In contrast, the higher bulk density observed at the upper slope reflects sustained topsoil removal and exposure of denser subsoil horizons, a characteristic feature of tropical coastal plain sands described by Igwe and Obalum (2013), further intensified by surface disturbance and traffic-induced compaction in cultivated systems (Mondal & Chakraborty, 2023).

These slope-driven SOC gradients were further expressed in soil aggregation patterns. The greater proportion of large macroaggregates (>2 mm) at the lower slope reflects the combined influence of higher SOC stocks, finer particle content, and reduced bulk density, all of which favour aggregate formation and stability. Regression results confirmed this response, showing a significant increase in large macroaggregates with increasing SOC stocks alongside a decline in microaggregate fractions (Figure 3; Table 4). This dominance of macroaggregates in SOC-rich soils has been widely reported in tropical systems, including by Barthès et al. (2008), who highlighted the central role of organic binding agents in stabilizing macroaggregates. Aggregate stability indices further reinforced this pattern. Mean weight diameter (MWD) and geometric mean diameter (GMD) increased significantly with SOC stocks (Figure 3; Table 4), confirming enhanced aggregate stability in SOC-enriched downslope soils. Previous studies across different climatic regions and agricultural management systems also found the preponderance of large macroaggregates and improved aggregate stability in depositional soils (Berhe et al., 2012; Jourgholami et al., 2019; Liu et al., 2015). In contrast, the upper and middle slopes, which exhibited lower SOC stocks, were characterised by higher proportions of microaggregates, typical of eroded tropical landscapes (Igwe & Obalum, 2013). The absence of significant variation in the smaller macroaggregate classes (2–0.25 mm) among slope positions likely reflects the overall similarity in soil texture across the landscape, as also suggested by Sbih et al. (2024).

Furthermore, SOC-mediated structural controls also governed soil hydraulic characteristics along the slope. Although K_{sat} did not vary significantly among slope positions, water retention properties did (Table 3), responding strongly to SOC accumulation (Figure 3; Table 4). Saturated water content increased with SOC stocks (R^2 = 0.30), while field capacity exhibited the strongest relationship among all measured variables (R^2 = 0.46), indicating that SOC accumulation substantially enhanced the soil's ability to retain water. These responses reflect the development of finer pore networks within stable aggregates and organic matter–rich matrices, which increase microporosity and water retention. In contrast, macroporosity decreased downslope with increasing SOC stocks (R^2 = 0.36), indicating the continuous accumulation of silt and clay, which may have clogged the large pores, thus transiting from coarse, rapidly draining pore systems toward finer, water-retentive pore structures in downslope soils. This pattern explains why upper slope soils, despite similar K_{sat}, exhibited lower water-holding capacity due to the dominance of large, poorly connected pores associated with coarse texture and compaction. The lower slope, although less macroporous, retained more water as a result of improved aggregation and increased micropore abundance.

Textural fractions exhibited weaker but significant relationships with SOC stocks, with sand content declining and clay content increasing as SOC stocks increased. These modest trends suggest that while texture influenced SOC distribution through preferential association with finer particles, soil structure and hydraulic properties were more strongly regulated by SOC accumulation than by particle-size composition alone.

In general, these results demonstrate that slope position governs soil structure and hydraulic functioning through a cascade of interlinked processes: erosion-driven particle sorting controls SOC redistribution; SOC accumulation regulates bulk density and porosity; improved pore structure enhances aggregate stability; and aggregate-mediated pore networks ultimately determine soil water-retention characteristics. The regression patterns observed in this study, therefore, represent integrated expressions of a common topographic control rather than independent responses.

The results largely supported the study hypothesis that slope position strongly influences soil structural and hydraulic properties. As expected, finer soil particles (silt and clay), SOC concentration, SOC stocks, aggregate stability, and water-retention capacity increased downslope, while sand, bulk density was highest at the upper slope, reflecting sustained erosion and depositional processes.

Consistent with the study objectives, the findings demonstrate that even subtle textural differences along the slope can generate pronounced contrasts in soil quality when coupled with SOC redistribution. The integrated analysis confirms that SOC accumulation is a key mediator linking topographic position to soil structural and hydraulic characteristics. These results reinforce the need for slope-specific soil management strategies that reduce erosion and organic matter loss at upper slope positions while maintaining the structural and hydraulic benefits that develop in downslope depositional zones.

5. CONCLUSION

This study demonstrates that slope position is a fundamental driver of structural and hydraulic functioning in cultivated coastal plain sands. Despite uniform parent material and consistent loamy sand texture across the slope, erosion–deposition processes generated systematic downslope redistribution of fine particles and SOC, resulting in pronounced contrasts in soil quality among slope positions.

Selective detachment and downslope transportation of finer soil particles and SOC at upper slope positions led to carbon depletion, higher bulk density, weaker aggregation, and reduced water-retention capacity, whereas lower slope positions functioned as depositional zones enriched with silt, clay, and SOC. This enrichment promoted lower bulk density, higher total porosity, enhanced aggregate stability, and improved unsaturated water-retention properties. While saturated hydraulic conductivity remained relatively uniform along the slope, variations in soil structure and pore-size distribution strongly controlled water-holding capacity.

The findings reveal that soil behaviour along cultivated slopes is governed by interconnected processes, in which topography regulates particle and SOC redistribution, SOC accumulation controls soil structure, and aggregate-mediated pore networks determine hydraulic performance. These results highlight the importance of adopting slope-specific soil management strategies that minimise erosion and organic matter loss at upper slope positions while sustaining the favourable structural and hydraulic conditions that develop naturally in downslope depositional areas of coastal plain sands.

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REFERENCES

Ayele, G. T., Demissie, S. S., Jemberrie, M. A., Jeong, J., & Hamilton, D. P. (2020). Terrain effects on the spatial variability of soil physical and chemical properties. *Soil Systems*, *4*(1), 1. https://doi.org/10.3390/soilsystems4010001

Bacq-Labreuil, A., Crawford, J., Mooney, S. J., Neal, A. L., & Ritz, K. (2019). Cover crop species have contrasting influence upon soil structural genesis and microbial community phenotype. *Scientific Reports*, *9*(1), 7473. https://doi.org/10.1038/s41598-019-43937-6

Barthès, B. G., Kouakoua, E., Larré-Larrouy, M.-C., Razafimbelo, T. M., de Luca, E. F., Azontonde, A., . . . Feller, C. L. (2008). Texture and sesquioxide effects on water-stable aggregates and organic matter in some tropical soils. *Geoderma*, *143*(1), 14-25. https://doi.org/10.1016/j.geoderma.2007.10.003

Berhe, A. A., Harden, J. W., Torn, M. S., Kleber, M., Burton, S. D., & Harte, J. (2012). Persistence of soil organic matter in eroding versus depositional landform positions. *Journal of Geophysical Research: Biogeosciences*, *117*(G2), G02019. https://doi.org/10.1029/2011JG001790

Blanco-Canqui, H., Shapiro, C. A., Wortmann, C. S., Drijber, R. A., Mamo, M., Shaver, T. M., & Ferguson, R. B. (2013). Soil organic carbon: The value to soil properties. *Journal of Soil and Water Conservation*, *68*(5), 129A-134A. https://doi.org/10.2489/jswc.68.5.129A

Bracken, L. J., Turnbull, L., Wainwright, J., & Bogaart, P. (2015). Sediment connectivity: A framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms*, *40*(2), 177-188. https://doi.org/10.1002/esp.3635

Brady, N. C., & Weil, R. R. (2008). *The nature and properties of soils* (14th ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Bufebo, B., Elias, E., & Agegnehu, G. (2021). Effects of landscape positions on soil physicochemical properties at Shenkolla Watershed, South Central Ethiopia. *Environmental Systems Research*, *10*(1), 14. https://doi.org/10.1186/s40068-021-00222-8

Buraka, T., Elias, E., & Lelago, A. (2022). Soil organic carbon and its' stock potential in different land-use types along slope position in Coka watershed, Southern Ethiopia. *Heliyon*, *8*(8), e10261. https://doi.org/10.1016/j.heliyon.2022.e10261

Carter, M. R., & Gregorich, E. G. (2008). *Soil sampling and methods of analysis* (2nd ed.). Boca Raton, FL: CRC Press.

Ceddia, M. B., Vieira, S. R., Villela, A. L. O., Mota, L. D. S., Dos Anjos, L. H. C., & De Carvalho, D. F. (2009). Topography and spatial variability of soil physical properties. *Scientia Agricola*, *66*(3), 338–352. https://doi.org/10.1590/S0103-90162009000300009

Chen, K., Pan, Y., Li, Y., Cheng, J., Lin, H., Zhuo, W., . . . Jiang, Y. (2023). Slope position- mediated soil environmental filtering drives plant community assembly processes in hilly shrublands of Guilin, China. *Frontiers in Plant Science*, *13*, 1074191. https://doi.org/10.3389/fpls.2022.1074191

Dane, J. H., & Topp, G. C. (2002). *Methods of soil analysis: Part 4. Physical methods.* Madison, WI: Soil Science Society of America.

Deis, L., Fort, F., Lin-Yang, Q., Balda, P., & Pou, A. (2025). Carbon sequestration, plant cover, and soil health: Strategies to mitigate climate change. *Plants, 14*(23), 3610. https://doi.org/10.3390/plants14233610

Dialynas, Y. G., Bastola, S., Bras, R. L., Marin-Spiotta, E., Silver, W. L., Arnone, E., & Noto, L. V. (2016). Impact of hydrologically driven hillslope erosion and landslide occurrence on soil organic carbon dynamics in tropical watersheds. *Water Resources Research, 52*(11), 8895-8919. https://doi.org/10.1002/2016WR018925

Eneje, R. C., & Adanma, F. I. (2007). Percent clay, aggregate size distribution and stability with depth along a toposequence formed on coastal plain sands. *Online Journal of Earth Sciences, 1*(2), 108–112.

Food and Agriculture Organization of the United Nations (FAO). (2015). *World reference base for soil resources 2014, update 2015.* World Soil Resources Reports No. 106. Rome, Italy: FAO.

Igwe, C. A., & Obalum, S. E. (2013). Microaggregate stability of tropical soils and its roles on soil erosion hazard prediction. In S. Grundas & A. Stępniewski (Eds.), Advances in agrophysical research. In (pp. 175–192). Rijeka, Croatia: InTech.

IPCC. (2021). *Climate change 2021: The physical science basis.* Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Issaka, S., & Ashraf, M. A. (2017). Impact of soil erosion and degradation on water quality: A review. *Geology, Ecology, and Landscapes, 1*(1), 1-11. https://doi.org/10.1080/24749508.2017.1301053

Jourgholami, M., Ramineh, A., Zahedi Amiri, G., & Labelle, E. R. (2019). The Influence of slope positions on the recovery response of compacted soil properties and enzyme activity in an Oriental beech stand in the Hyrcanian forests, Iran. *Sustainability, 11*(7), 1940. https://doi.org/10.3390/su11071940

Lal, R. (2003). Soil erosion and the global carbon budget. *Environment International, 29*(4), 437-450. https://doi.org/10.1016/S0160-4120(02)00192-7

Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. *Nature, 528*(7580), 60-68. https://doi.org/10.1038/nature16069

Li, X., & McCarty, G. W. (2018). Use of principal components for scaling up topographic models to map soil redistribution and soil organic carbon. *Journal of Visualized Experiments*(140), e58189. https://doi.org/10.3791/58189

Liu, S., An, N., Yang, J., Dong, S., Wang, C., & Yin, Y. (2015). Soil organic carbon and aggregation as affected by erosion and deposition. *Soil & Tillage Research, 155*, 123–130.

Liu, S., Wang, R., Yang, Y., Shi, W., Jiang, K., Jia, L., . . . Yu, P. (2024). Changes in soil aggregate stability and aggregate-associated carbon under different slope positions in a karst region of Southwest China. *Science of the Total Environment, 928*, 172534. https://doi.org/10.1016/j.scitotenv.2024.172534

Madueke, C. O., Okore, I. K., Maduekeh, E. C., Onunwa, A. O., Okafor, M. J., Nnabuihe, E. C., . . . Nwosu, T. V. (2021). Characterization and land evaluation of three tropical rainforest soils derived from the coastal plain sands of Southeastern Nigeria. *Agro-Science, 20*(2), 25–36. https://doi.org/10.4314/as.v20i2.5

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., ... Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma, 292*, 59-86. https://doi.org/10.1016/j.geoderma.2017.01.002

Mondal, S., & Chakraborty, D. (2023). Root growth and physiological responses in wheat to topsoil and subsoil compaction with or without artificial vertical macropores. *Heliyon, 9*(8), e18834. https://doi.org/10.1016/j.heliyon.2023.e18834

NearWeather. (2026). *Akwa Ibom State weather today: Temperature, feels like, rain chance & hourly forecast in Akwa Ibom State. NearWeather.com.* Retrieved from https://www.nearweather.com/location/akwa-ibom-state-ng-2350813

Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. In D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, & M. E. Sumner (Eds.), Methods of soil analysis: Part 3. Chemical methods (SSSA Book Series No. 5). In (pp. 961–1010). Madison, WI: Soil Science Society of America and American Society of Agronomy.

Nigerian Erosion and Watershed Management Project (NEWMAP) Akwa Ibom State Project Management Unit. (2017). *Resettlement action plan (RAP) for Etim Umana gully erosion site in Uyo L.G.A. of Akwa Ibom State: Final report.* Retrieved from https://ead.gov.ng/wp-content/uploads/2017/11/AKS-NEWMAP-RAP-Etim-Umana-gully-erosion-site-Cleared-Disclosure-Version.pdf

Obi, J. C., Ogban, P. I., Ituen, U. J., & Udoh, B. T. (2014). Development of pedotransfer functions for coastal plain soils using terrain attributes. *Catena*, *123*, 252–262. https://doi.org/10.1016/j.catena.2014.08.015

Ogban, P. I., & Ekerette, I. O. (2001). Physical and chemical properties of the coastal plain sands soils of South-Eastern Nigeria. *Nigerian Journal of Soil and Environmental Research*, *2*, 6–14.

Ogban, P. I., Ibotto, M. I., Utin, U. E., Essien, O. A., & Arthur, G. J. (2022). Effect of slope curvature and gradient on soil properties affecting erodibility of coastal plain sands in Akwa Ibom State, Nigeria. *Agro-Science*, *21*(2), 12-23. https://doi.org/10.4314/as.v21i2.2

Ogban, P. I., & Okon, A. X. (2020). Effect of slope aspect and position on soil infiltrability in an Ultisol in Akwa Ibom State, Southern Nigeria. *Agro-Science*, *19*(2), 23-30. https://doi.org/10.4314/as.v19i2.4

Patton, N. R., Lohse, K. A., Seyfried, M. S., Godsey, S. E., & Parsons, S. B. (2019). Topographic controls of soil organic carbon on soil-mantled landscapes. *Scientific Reports*, *9*(1), 6390. https://doi.org/10.1038/s41598-019-42556-5

Paul, E. A. (2016). The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. *Soil Biology and Biochemistry*, *98*, 109-126. https://doi.org/10.1016/j.soilbio.2016.04.001

Quinton, J. N., Govers, G., Van Oost, K., & Bardgett, R. D. (2010). The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience*, *3*(5), 311-314. https://doi.org/10.1038/ngeo838

R Core Team. (2025). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Reyes, S. (2015). *How soil and carbon are related*. Australia: Permaculture Research Institute.

Sbih, M., Bounouara, Z., Bensid, Z., Chergui, D., Zerari, A., Meziane, S., & Karam, A. (2024). Aggregate stability and carbon and N dymamics in macroaggregate size fractions with different soil texture. *Eurasian Journal of Soil Science*, *13*(3), 273-283. https://doi.org/10.18393/ejss.1494595

Schwanghart, W., & Jarmer, T. (2011). Linking spatial patterns of soil organic carbon to topography—A case study from south-eastern Spain. *Geomorphology*, *126*(1-2), 252-263. https://doi.org/10.1016/j.geomorph.2010.11.008

Seifu, W., Elias, E., & Gebresamuel, G. (2020). The effects of land use and landscape position on soil physicochemical properties in a semiarid watershed, Northern Ethiopia. *Applied and Environmental Soil Science*, *2020*(1), 8816248. https://doi.org/10.1155/2020/8816248

Shaxson, T. F., & Barber, R. G. (2003). *Optimizing soil moisture for plant production: The significance of soil porosity*. FAO Soils Bulletin No. 79. Rome, Italy: Food and Agriculture Organization of the United Nations.

Singh, D., Mishra, A. K., Patra, S., Mariappan, S., Singh, N., & Kar, S. K. (2023). Spatial variability of soil hydraulic and physical properties in erosive sloping agricultural fields. *Water Science and Engineering*, *16*(1), 57-66. https://doi.org/10.1016/j.wse.2022.10.001

Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, *241*(2), 155-176. https://doi.org/10.1023/A:1016125726789

Sollins, P., Homann, P., & Caldwell, B. A. (1996). Stabilization and destabilization of soil organic matter: Mechanisms and controls. *Geoderma*, *74*(1–2), 65–105. https://doi.org/10.1016/S0016-7061(96)00036-5

Tromp-van Meerveld, H. J., Parlange, J. Y., Barry, D. A., Tromp, M. F., Sander, G. C., Walter, M. T., & Parlange, M. B. (2008). Influence of sediment settling velocity on mechanistic soil erosion modeling. *Water Resources Research*, *44*(6), W06401. https://doi.org/10.1029/2007WR006361

Udo, E. J., Ogunwale, J. A., Akinrinde, E. A., & Ojanuga, A. G. (2009). *Selected methods of soil and plant analysis* (3rd ed.). Ibadan, Nigeria: Soil Science Society of Nigeria.

Umoh, F. O., Essien, O. A., Utin, U. E., & Udom, P. U. (2020). Influence of tillage systems on selected soil physical and chemical properties on coastal plain sands in Southeastern Nigeria. *Nigerian Journal of Agricultural Technology*, *17*, 39–44.

Utin, U. E., & Essien, G. E. (2021). Soil properties and growth of maize as affected by slope position and fertilizer type on coastal plain sands. *International Journal of Sustainable Agricultural Research*, *8*(4), 180-197. https://doi.org/10.18488/journal.70.2021.84.180.197

Van Hemelryck, H., Fiener, P., Van Oost, K., Govers, G., & Merckx, R. (2010). The effect of soil redistribution on soil organic carbon: An experimental study. *Biogeosciences*, *7*(12), 3971-3986. https://doi.org/10.5194/bg-7-3971-2010

Wang, S., Fan, Y., Liu, L., & Qu, J. (2023). Transport/detachment regimes of different size class sediment particles and enlightenments for transport capacity prediction for rain-induced overland flow erosion. *Sustainability*, *15*(10), 7906. https://doi.org/10.3390/su15107906

Wilson, C., Kampf, S. K., Wagenbrenner, J. W., MacDonald, L. H., & Gleason, H. (2021). Hillslope sediment fence catch efficiencies and particle sorting for post-fire rain storms. *Earth Surface Processes and Landforms*, *46*(1), 267-279. https://doi.org/10.1002/esp.5021

Yimer, F., Ledin, S., & Abdelkadir, A. (2007). Changes in soil organic carbon and total nitrogen contents in three adjacent land use types in the Bale Mountains, South-Eastern highlands of Ethiopia. *Forest Ecology and Management*, *242*(2–3), 337-342. https://doi.org/10.1016/j.foreco.2007.01.087

Yu, H., Zha, T., Zhang, X., Nie, L., Ma, L., & Pan, Y. (2020). Spatial distribution of soil organic carbon may be predominantly regulated by topography in a small revegetated watershed. *Catena*, *188*, 104459. https://doi.org/10.1016/j.catena.2020.104459

Zhu, H., Li, H., Liang, C., Chang, X., Wei, X., & Zhao, X. (2022). Spatial variation in soil physico-chemical properties along slope position in a small agricultural watershed scale. *Agronomy*, *12*(10), 2457. https://doi.org/10.3390/agronomy12102457