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DISTRIBUTION OF SOIL ORGANIC CARBON AND IMPORTANT SOIL NUTRIENT RATIOS ALONG TOPOSEQUENCE IN HUMID TROPICS OF NIGERIA

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ABSTRACT

Landscape attributes including soil-environmental factors are the dominant factors impacting soil organic carbon (SOC) and nutrient ratio distribution in areas with rolling terrain, homogeneous parent material, and uniform climate patterns. This study investigated the depth distribution of SOC, and nutrient ratios (C:N, C:P, and N:P ratios) in soil developed on coastal plain sand in Calabar. Soil samples were collected from nine identified profile pits, air-dried, crushed, sieved, and subjected to laboratory analysis. The results showed that the values of SOC and nutrient ratios (C:N, C:P, and N:P ratios) gradually decreased with soil depth along toposequence in each aspect position. In the north- and East-facing aspects, the depth distribution of SOC followed the order; upper slope > lower slope>middle slope. While, in the South-facing slope, the distribution was in the order of lower slope> middle slope >upper slope. The North-facing aspect contained maximum SOC ($\leq$ 16.6 gkg^{-1}) than the East-facing ($\leq$ 16.0 gkg^{-1}) and South-facing ($\leq$ 13.2 gkg^{-1}) aspect. The mean C:N ratios were < 10 in all toposequence and aspect positions. C:N and N:P ratios significantly and positively influence topsoil SOC in the study area. C:N ratio was significantly and positively influenced by pH, clay ratio, SOC, clay, and Hillshade. C:P and N:P ratios were influenced by SOC and TN. SOC and nutrient ratios (C:N, C:P, and N:P) can be used as an indicator of soil fertility and productivity to advance an understanding of the above-ground plant community and below-ground soil nutrients at various depths along the toposequence.

Key words: exponential functions, carbon stoichiometry, soil-environmental covariates, profile distribution model

INTRODUCTION

Soil organic carbon (SOC), total nitrogen (TN) and available phosphorus (AvP), and their stoichiometry, hereafter referred to as nutrient ratios are very important indicators of soil fertility and productivity (Jiménez *et al.,* 2011; Ouyang *et al.,* 2017). The SOC plays a significant role in global C cycling, and often serves as an indicator of soil quality (Poeplau *et al.,* 2011; Fan *et al.,* 2015; Obalum *et al.,* 2017; Isong *et al.,* 2022), and plays important agronomic functions associated with soil fertility (von Lützow *et al.,* 2006; John *et al.,* 2020). It influences the physical structure of the soil, the soil's ability to store water, supply nutrients for crop production, and overall soil sustainability (Hussain *et al.,* 2021). Similarly, soil N and P are the main nutrient elements for plant growth, which affect photosynthesis and other processes associated with primary production (Ndzeshala *et al.,* 2023; Ebido *et al.,* 2024; Ugwu *et al.,* 2024). Furthermore, nutrient ratios (C:N, C:P and N:P) are good indicators of soil fertility and are widely used as tools to advance an understanding of the interactions between above-soil plant community and the characteristics of soil nutrients in terrestrial ecosystems (Mooshammer *et al.,* 2014; Zechmeister-Boltenstern *et al.,* 2015). Therefore, a better understanding of the depth distribution pattern of SOC, N, P, and soil nutrient ratios is important for proper soil nutrient management in agroecosystems.

The management of soil is necessary for several environmental, agricultural, and policy reasons. In this regard, information is needed on the depth and catenary differentiation of soils. Such information, from the crop production viewpoint, would assist in assessing the productive values of soils, developing strategies for soil conservation, reducing wastage of input in an agricultural field situated on uneven topography (Oku *et al*., 2010). Studying the depth distribution of soil nutrients is of particular importance for several reasons. Most importantly, it can help in the identification of the depths at which nutrients are most concentrated and can inform the selection and adoption of soil management practices. As reported by some authors (Brady and Weil, 2008; Esu, 2010), the interaction between natural and anthropogenic factors brings about the exchange of materials which could cause significant changes in soil physical and chemical properties from surface soil to sub-soils.

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Wide variability of soil properties and nutrients along toposequence and with depth can pose serious constraints to sustainable crop production. One way to assess heterogeneity in soils is by digital soil mapping (DSM). Currently, the profile distribution model, geostatistics, and machine learning algorithms are the focus of DSM and are the main methods for estimating the distribution of soil properties across the globe. Modeling spatially varied nutrients and soil properties within a field relies on geospatial technologies and uses remote sensing data and digital elevation model (DEM), micro-climatic data, geology, etc. (Zeraatpisheh *et al.,* 2019; John *et al.,* 2020; John *et al.,* 2021).

Profile distribution models have been used to model SOC across the globe (Wendt and Hauser, 2013; Chen *et al.,* 2015; Bai *et al.,* 2016); however, such investigation has not been implemented in coastal plain sand soil. Studies on soil-landscape relationships in the rolling terrain around Calabar Municipality utilizing DEM and satellite imagery are rare. A clear understanding of the depth-wise and lateral distribution of soil fertility indicators like OC, CN, and other important properties and their relationship is imperative in this soil. Therefore, this study was designed to study the depth distribution of soil C, N, C/N, and pH in identified toposequence and their relationship with environmental covariates.

MATERIALS AND METHODS

Description of the Study Area

The study was conducted in Calabar, Cross River State, and the study area lies between latitude 4°55'30" to 5°0'0"N and longitude 8°19'30" to 8°24'0" E (Figure 1). This area falls within the humid tropical rainforest zone and is characterized by two distinct seasons; the rainy season (from Apr. to early Nov.) with double peaks usually in Jul. and Sep. and the dry season (from Nov. to Mar.). The average annual rainfall is 2500 mm. The average minimum and maximum temperatures of the areas are about 22 ˚C and 30 ˚C, respectively with a mean relative humidity of 83%. The environmental factors including elevation (1-102 m), slope (0-40.26%), aspect (-1-359.33), land surface temperature (LST) (22.30-29.16 ˚C) varied greatly (Figure 2). The soils of the study area are developed on coastal plain sand parent material. They are characterized by udic moisture regimes and isohyperthemic temperature regimes, respectively. Based on USDA soil taxonomic classification, the soil order of the area is Ultisols, and the soil is classified as Typic kandiudults. The principal crops grown in the area include maize, sugar cane, cassava, groundnut, oil palm, and vegetable crops including okra, *Telfairia occidentalis*, pepper, water leaf, *Amarathus cruentus,* etc.

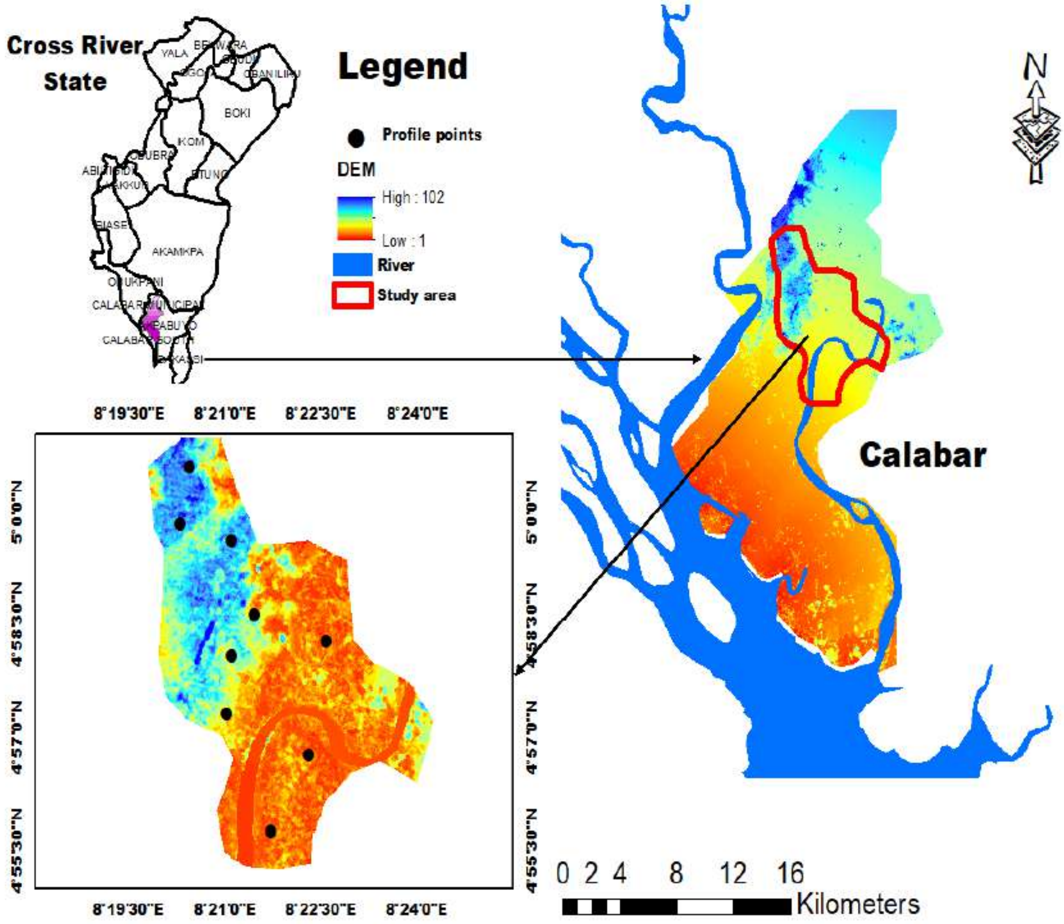


Figure 1: Map showing the position of the profile points in the study area

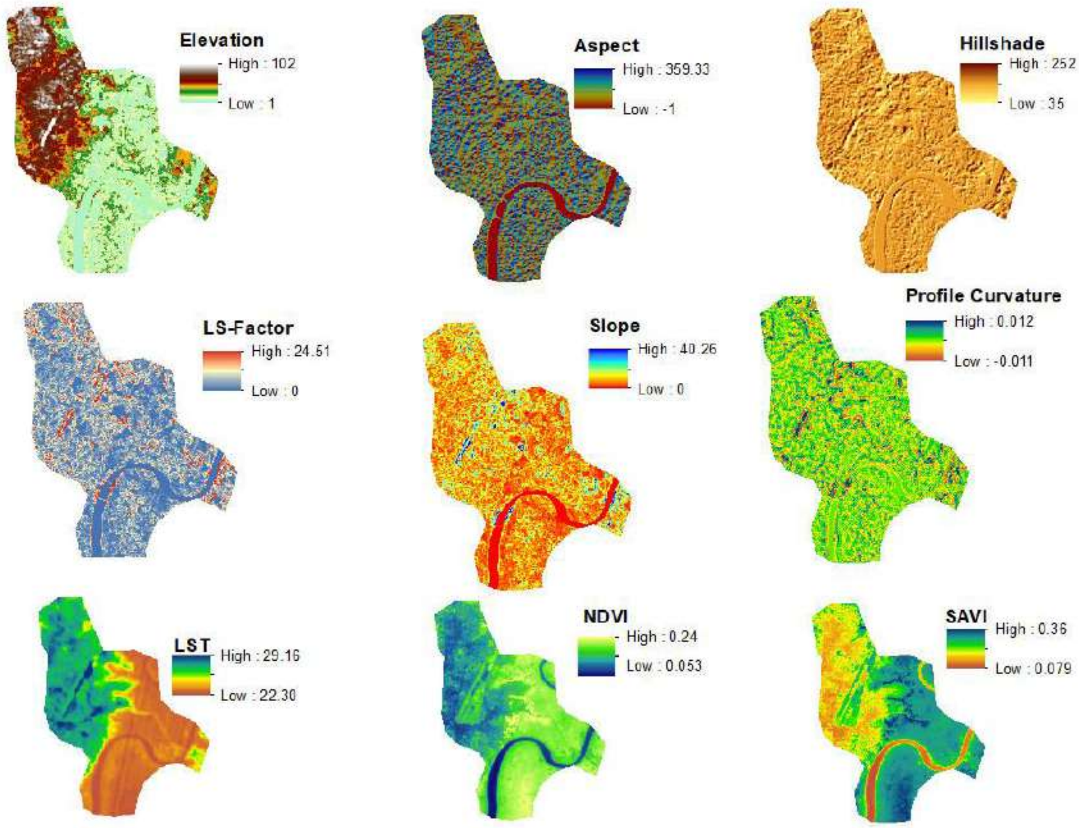


Figure 2: Environmental factors of the study area
Note: L-S factor - length- slope factor, NDVI - normalized vegetation index, LST - land surface temperature, SAVI - soil adjusted vegetation index

Field Study

Soil samples were collected from nine identified positions indicating differences in aspect and slope. The entire study area was demarcated into nine units, and nine profile pit was dung correspondingly. Soil samples were collected at the identified horizon which are within each soil profile. Three soil samples were taken and bulked for each horizon depth across the aspect and slope positions, and a total of 38 soil samples were collected altogether. The collected samples were air-dried at room temperature and later crushed to pass through a 2 mm mesh sieve, bagged, and labeled for soil routine analysis.

Laboratory Analysis

Particle size distribution will be determined by Bouyoucos hydrometer method (Gee and Or, 2002). Soil pH was measured potentiometrically in a soil-water suspension (at a soil-water ratio of 1:2.5) using a glass electrode pH meter following the procedure described by Udo *et al*. (2009). The SOC was determined by the dichromate wet oxidation method of Walkley and Black as outline by Estefan *et al*. (2013) Total nitrogen (TN) content of the soil was determined by wet-digestion, distillation and titration procedures of the Kjeldahl method as described by Estefan *et al*. (2013). Available phosphorus (AvP) was extracted by the Bray-1 method and the colour was developed in soil extract using the ascorbic acid blue method (Nelson and Sommers, 1982). Exchangeable bases (Ca^+, Mg^+, K^+ and Na^+) were extracted by saturating the soil with neutral 1*M* NH_4OAc (Estefan *et al*., 2013), and Ca and Mg in the extract were determined using atomic absorption spectrophotometer (AAS) while K was determined by flame photometry. The soil nutrient ratios (C:N, C:P and N:P) were calculated from the measured laboratory soil properties. The SOC, TN and AvP were converted to common dimensional units (g kg^{-1}) before estimation of C: N, C:P and N:P. Clay ratio was estimated following equation 1:

$$\text{Clay ratio} = \frac{(\%\ \text{sand} + \%\ \text{silt})}{\%\ \text{clay}} \quad \ldots (1)$$

Statistical Analysis

The data from laboratory analysis was subjected to descriptive statistics. Depth distribution curves were plotted using ggplot2 in *R* package. Statistical analysis was done using SigmaPlot 14 statistical package.

Fitting curves to depth distributions

This study adopted the exponential decay function (equation 1) to model SOC as presented below. The exponential function (i.e., profile distribution model) was used in modeling the vertical distribution of SOC due to its mathematical simplicity and its apparent similarity to the SOC decline with the soil depth. The allometric, exponential, and logistic functions can be applied to model the distribution of SOC with depth as reported in many studies (Wendt and Hauser, 2013; Chen *et al.,* 2015; Bai *et al.,* 2016):

$$C = ae^{-bD} \text{ ....(2)}$$

where C is the SOC concentration (%), D is the absolute depth (m), and a and b are the parameters of exponential functions.

Field observed SOC data were fitted to the exponential decay curve by a dynamic curve fitting tool using non-linear regression with the aid of the SigmaPlot 14 statistical package, to obtain their respective model parameters. For each SOC profile, the goodness of fit of the models was judged using the coefficient of determination (R^2) and standard error of the estimate (SEE).

RESULTS AND DISCUSSION

Descriptive Characterization of Soil Properties

The descriptive statistics reveal information about the magnitude of data and range of variability (Table 1). The results showed numerical differences among studied soil properties across toposequence and aspect. Generally, for soils in North-facing aspect (NFA), sand contents were > 670 g kg^{-1}, while silt and clay were less than 37 g kg^{-1} and 240 g kg^{-1}, respectively. Similarly, soils in South-facing aspect (SFA), sand contents were > 770 g kg^{-1}, while silt and clay were less than 40 g kg^{-1} and 200 g kg^{-1}, respectively. However, soils in East-facing aspect (EFA) had sand contents > 700 g kg^{-1}, silt content up to 150.3 g kg^{-1} and clay < 200 g kg^{-1}. The mean soil organic carbon (SOC) was low in all positions (< 10 g kg^{-1}) except in the lower slope in EFA where it was 12.4 g kg^{-1}with moderate variability. Similarly, following Landon's (2014) rating, the mean TN, and exchangeable cations (Ca^{2+} and K^{+}) were all low in the area irrespective of toposequence and aspect. However, the mean exchangeable Mg^{2+} was moderate in middle slope (1.8 cmol kg^{-1}) in North-facing aspect, upper slope (1.85 cmol kg^{-1}) and middle slope (1.66 cmol kg^{-1}) in South-facing aspect (SFA), and lower slope (1.5 cmol kg^{-1}) in East-facing aspect (EFA). Other positions all had low Mg^{2+} contents. The observed mean pH was all strongly acidic. The mean C:N ratios in our study were all > 10 except in the upper slope in East-facing aspect (EFA). Similarly, the mean C:P ratios were within the agronomic level require to support crop growth (100-300), except in the upper slope in East-facing aspect (EFA) where 376.14 was recorded. C:P ratio reflects the relative availability of phosphorus compared to carbon. Ratios above 300 indicate P limitation, while ratios below 100 suggest P excess (Liu *et al.,* 2021). Furthermore, the result also showed that the mean N:P ratios were below the agronomic level require to support crop growth (7-20). N:P ratio in soils provides insight into the relative availability of N and P. Ratios around 10-15 are typical for many crops and soil, with ratios below 7 indicating N limitation and above 20 indicating P limitation (Qiu *et al.,* 2008). The results also showed that the mean clay ratios were a little above 3 in all the toposequence. Maintaining a silt to clay ratio in the range of 2:1 to 3:1 is generally ideal for supporting healthy crop growth, allowing for optimal moisture retention, nutrient availability, and soil structure.

Changes in SOC with Depth Between Toposequence Positions and Aspect

In the studied soils, SOC content with respect to soil depth on the various aspect (North-facing aspect, South-facing aspect, and East-facing aspect), and toposequence (lower slope, middle slope, and upper slope) differs (Figure 3). All aspect positions showed exponential decline in SOC through the entire soil profile depth from the surface to the mobile-immobile regolith interface. In the North-facing aspect, the maximum SOC (16.6 g kg^{-1}) was observed at the depth of 0-16 cm on upper slope soil, while the lowest value (2.3 g kg^{-1}) was obtained at the depth of 99-166 cm in the middle slope. Similarly, in the South-facing aspect, the maximum SOC (13.3 g kg^{-1}) was observed at the depth of 0-25 cm on lower slope soil, while the lowest value (3 g kg^{-1}) was obtained at the depth of 105-168 cm in upper slope. Also, in the East-facing aspect, the maximum SOC (16 g kg^{-1}) was observed at the depth of 0-20 cm on upper slope soil, while 93-143 cm soil depth had the lowest value of 4 g kg^{-1} SOC.

The SOC was generally rated low, being lower than the critical limits of Landon (2014). Low organic carbon in tropical soils is often attributed to continuous cultivation and burning of plant residues which destroy most of the organic materials that would have contributed more to the soil organic matter (Obalum *et al*., 2012; Fasina *et al.,* 2015; Zechmeister-Boltenstern *et al*., 2015; Afu *et al.*, 2019). Organic carbon content decreases with depth which could be attributed to a decrease in plant materials with depth, thus confirming the reports of Dorji *et al.* (2014), Nahusenay and Kibebew (2016), Afu *et al.* (2019) and Alarima *et al.* (2020) who also reported a decrease in organic matter with soil depth. Surface soils were higher in SOC than subsoils, similar to the observation for coarse-textured soils of the derived savannah (Obalum *et al*., 2013).

The values of SOC contents gradually decreased with depth from the surface soil to a deeper layer along the different toposequence in each aspect position. In the North- and East-facing aspects, the distribution of SOC was upper slope > lower slope > middle slope (Figure 3). However, in the South-facing slope, the distribution was in the order of lower slope > middle slope > upper slope (Figure 3). Consistent with our expectations, the North-facing

Table 1: Descriptive characteristics of studied soil properties

Soil properties	Units	Upper slope				Middle slope				Lower slope			
		Min	Max	Mean	CV	Min	Max	Mean	CV	Min	Max	Mean	CV
North-Facing Aspect (NFA)													
Sand	g kg^{-1}	696	766	724	3.83	656	716	678	3.87	706	776	750	3.60
Silt	g kg^{-1}	270	470	370	27.0	170	470	245	61.20	170	47	29	37.80
Clay	g kg^{-1}	187	267	239	14.9	237	327	297	13.70	177	277	221	16.50
Clay ratio	ratio	2.74	4.34	3.27	21.47	2.06	3.22	2.42	22.19	2.61	4.65	3.62	20.34
pH	unitless	4.90	5.10	4.98	1.70	4.60	4.80	4.72	2.00	4.70	5.00	4.82	2.70
SOC	g kg^{-1}	3.7	16.6	8.5	61.60	2.30	15.8	7.9	76.30	3.6	16.0	8.2	2.70
TN	g kg^{-1}	1.0	1.6	1.2	19.50	0.50	1.2	0.82	40.00	1.0	1.20	1.10	7.70
AP	g kg^{-1}	0.030	0.033	0.032	3.40	0.031	0.032	0.032	2.00	0.031	0.033	0.032	2.00
C:N	ratio	2.31	15.09	7.50	66.4	4.60	13.17	8.54	42.80	3.27	13.33	7.47	53.90
C:P	ratio	112.39	507.49	262.31	60.50	70.04	489.16	247.68	75.80	109.62	495.97	254.52	61.50
N:P	ratio	32.53	48.60	37.04	18.30	15.23	37.15	25.78	11.40	29.86	37.19	33.19	8.30
Ca	Cmol kg^{-1}	3.20	3.50	3.34	4.00	3.20	3.60	3.37	5.10	3.30	3.60	3.44	3.30
Mg	Cmol kg^{-1}	1.20	1.50	1.36	8.40	1.60	2.00	1.80	10.10	1.40	1.60	1.48	7.40
K	Cmol kg^{-1}	0.10	0.13	0.12	11.60	0.11	0.14	0.12	10.30	0.11	0.13	0.12	7.70
South-Facing Aspect (SFA)													
Sand	g kg^{-1}	686	826	771	8.40	696	836	784	7.10	706	826	788	7.10
Silt	g kg^{-1}	17	67	39.5	66.60	17	57	27	64.20	17	47	290	42.70
Clay	g kg^{-1}	107	297	189	46.90	107	287	189	35.80	127	267	182	33.10
Clay ratio	ratio	2.48	8.34	4.89	45.32	2.36	8.34	5.24	53.82	2.75	6.87	4.91	34.92
pH	unitless	4.6	4.8	4.7	1.78	4.7	5.0	4.8	2.94	4.6	4.8	4.7	1.73
SOC	g kg^{-1}	5.3	14	9.32	34.34	3.0	11.6	7.47	58.28	2.4	13.2	7.4	63.89
TN	g kg^{-1}	10	1.3	1.2	10.7	1.1	1.3	1.2	7.10	0.6	1.3	1.0	29.10
AP	g kg^{-1}	30.75	32.91	31.99	3.40	31.45	34.21	32.75	3.70	30.20	34.19	32.71	5.30
C:N	ratio	4.41	11.67	7.95	35.29	2.5	11.67	6.54	64.17	1.85	14.67	8.31	72.90
C:P	ratio	154.92	445.15	287.19	37.24	91.21	377.23	234.94	59.18	72.33	399.51	224.52	61.91
N:P	ratio	33.70	38.51	36.02	6.02	32.52	39.50	36.67	8.26	17.54	39.18	31.55	30.63
Ca	cmol kg^{-1}	3.20	3.50	3.32	3.80	3.20	3.40	3.34	2.70	3.20	4.10	3.72	10.10
Mg	Cmol kg^{-1}	1.70	2.00	1.85	7.00	1.20	1.90	1.66	17.40	0.90	2.00	1.27	39.20
K	cmol kg^{-1}	0.10	0.12	0.11	7.40	0.11	0.13	0.12	7.10	0.09	0.13	0.11	14.80
East Facing Aspect (EFA)													
Sand	g kg^{-1}	676	766	739	5.70	716	82.60	781	5.96	666	756	702.7	6.70
Silt	g kg^{-1}	37	87	54	41.50	37	7.70	48.3	40	117	167	150.3	19.20
Clay	g kg^{-1}	147	287	207	28.20	97	247	170	36.1	127	167	147	13.60
Clay ratio	ratio	4.98	6.87	5.89	16.06	3.04	9.31	5.55	48.10	2.48	5.80	4.11	32.98
pH	unitless	4.6	4.8	4.7	2.47	4.6	5.1	4.9	4.91	4.6	4.9	4.7	3.01
SOC	g kg^{-1}	10.4	14.8	12.4	17.96	5.2	12.1	8.22	34.76	4.0	16	8.95	57.62
TN	g kg^{-1}	1.0	1.2	1.1	10.82	0.9	1.1	0.98	9.80	1.0	1.4	1.2	13.94
AP	g kg^{-1}	0.032	0.034	0.033	1.72	0.032	0.034	0.033	1.70	0.032	0.034	0.032	3.64
C:N	ratio	10.4	1.33	11.57	8.92	4.73	13.44	8.66	41.70	3.08	13.33	7.58	61.02
C:P	ratio	313.53	456.79	376.14	73.31	156.72	368.45	246.11	126.46	126.46	486.32	272.58	56.51
N:P	ratio	29.84	37.03	32.34	12.58	26.46	37.03	32.34	12.58	29.28	44.15	37.75	6.47
Ca	Cmol kg^{-1}	3.30	4.20	3.62	10.90	3.40	3.70	3.52	4.30	3.40	3.70	3.57	4.30
Mg	Cmol kg^{-1}	1.10	1.5	1.35	12.80	1.30	1.60	1.45	8.90	1.40	1.60	1.50	6.70
K	Cmol kg^{-1}	0.11	0.13	0.12	8.10	0.10	0.12	0.11	8.50	0.11	0.13	0.12	9.40

Min - Minimum, Max - Maximum, CV (%) - coefficient of variation

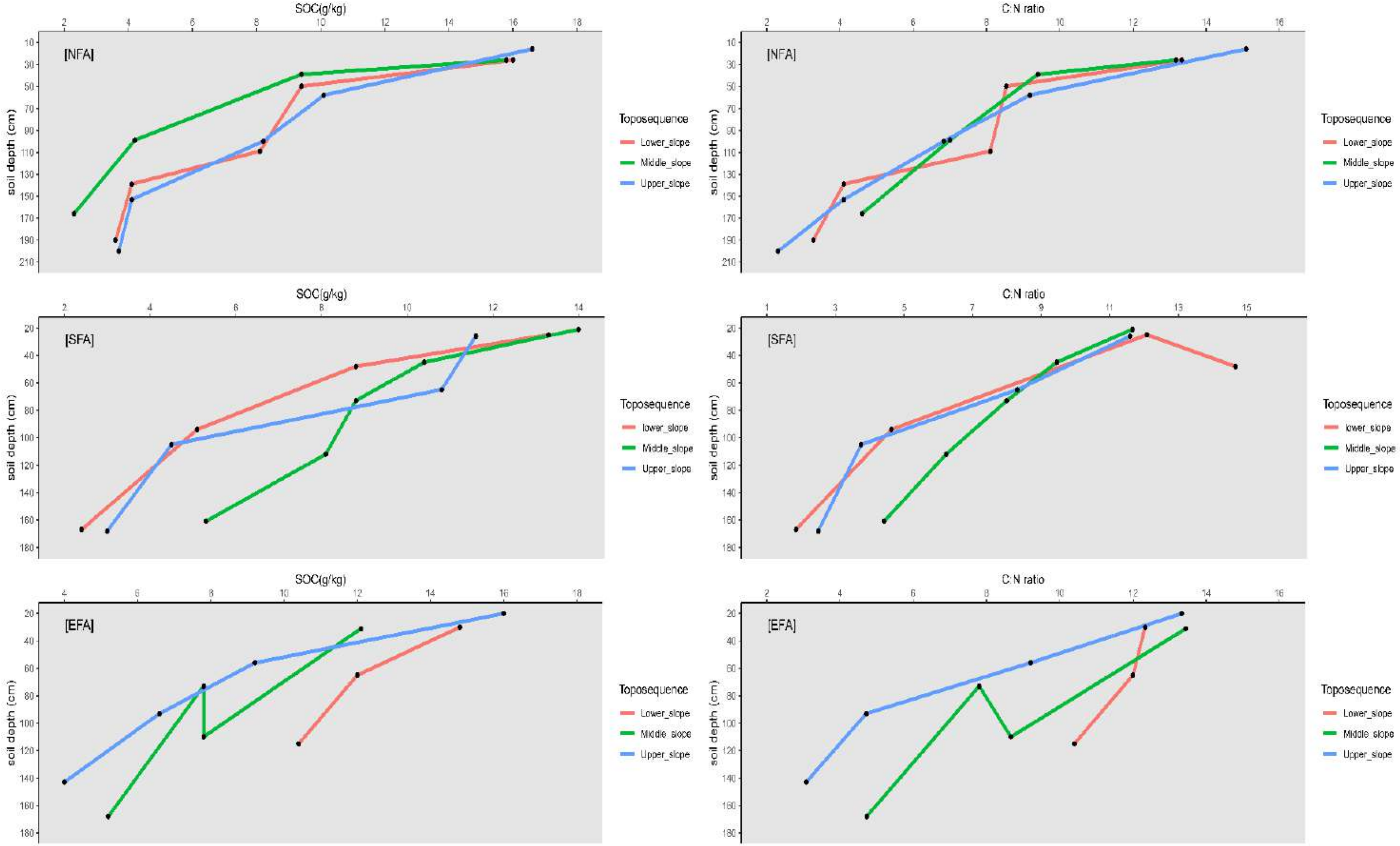


Figure 3: Profile distribution of soil organic carbon (SOC) and C:N ratio in North-facing aspect (NFA), South-facing aspect (SFA) and East-facing aspect (EFA)

site contained higher SOC (≤ 1.66%) than the South-facing (≤ 1.33%) and East-facing (≤ 1.60%) sites. Also, contrary to our expectations, the upper slope contained a larger SOC than the middle and lower slopes. The higher SOC recorded for the upper slope could be attributed to more farming activities that left crop residue to the soil, with concomitant accumulation of organic materials, while the higher SOC in the lower slope than the middle slope could be attributed to erosion as a result of the steep slope preceding it. The low SOC content of most of the soils cannot sustain crop production on a long-term basis. Therefore, the organic matter content has to be substantially increased through effective crop residue management and the use of organic manure.

In line with our results, Guzman and Al-Kaisi (2011) found that soils on foot slopes and toe slopes had a higher SOC content than those in summit slope positions. Furthermore, Liu *et al.* (2015) reported that higher nutrient levels at lower elevations may result from nutrient enhancement derived from middle and upper slopes.

Changes in C:N, C:P and N:P Ratios with Depth along Different Toposequences and Aspects

The relationship between SOC and TN as represented by the ratio of SOC to TN, expressed as C:N was used as an indicator of soil quality. The C:N ratios in the soil profiles increase exponentially with soil depth. In the North-facing aspect (Figure 3), the maximum C:N ratio (15.1) was observed at the depth of 0-16 cm on upper slope soil, while the lowest value (2.3) was obtained at the depth of 153-200 cm in the middle slope. Similarly, in the South-facing aspect (Figure 3), the maximum C:N ratio (14.67) was observed at the depth of 25-48 cm on lower slope soil, while the lowest value (1.85) was obtained at the depth of 94-167 cm in the upper slope. Also, in the East-facing aspect (Figure 3), the maximum CN ratio (13.3) was observed at the depth of 0-20 cm on upper slope soil, while 93-143 cm soil depth had the lowest value of 3.1 C:N ratio.

When assessing soil carbon and nitrogen nutrient balance, and to detect the extent of soil nitrogen mineralization capacity, the C:N ratio is used as a sensitive indicator. From an agricultural production point of view, the literature showed that cropping and land-use systems with C:N ratio < 10 is rated as good, 10.1-14 as a medium, and > 14 as poor soil systems (Landon, 2014; Tesfahunegn and Gebru, 2020). Topsoil C:N ratios in our study were nearly all > 10 in all toposequence and aspect (Figure 3). A C:N ratio (14 < C:N ≤ 25) implies that soil organic matter is accumulating slower than it is decomposing and that there is net mineralization of N in the soil (Wei *et al.,* 2009; Zhao *et al.,* 2015), whereas soils with a CN ratio of less than 10 have more nitrogen relative to carbon. (Yimer *et al.,* 2007; Kassa *et al*., 2017). This abundance of nitrogen supports the growth and activity of soil microorganisms, which can rapidly decompose organic matter. Higher C:N ratios were mostly found in the lower slope (Figure 3), which could be associated with the low oxidation (decomposition) rate of organic sources. Low decomposition of organic matter leads to soils having poor soil structure and high bulk density and low availability of soil nutrients. The depth distribution of C:P ratios are also shown in Figure 4. In the North-facing aspect (Figure 4), the maximum C:P ratio of 507.49 was obtained. Similarly, in the South-facing aspect (Figure 4), the maximum C:P ratio of 445.15 was obtained, whereas in the East-facing aspect (Figure 4), the maximum C:P ratio of 486.32 was obtained. Further results show the depth distribution of N:P ratios across various aspects and toposequence (Figure 4). Phosphorus is often a limiting nutrient in many soils, and its availability is affected by the C:P ratio. The C:P ratio obtain in this study indicates that a lower availability of phosphorus relative to carbon in the studied soil (Liu *et al.,* 2021). This can deter microbial efficiency in utilizing phosphorus, leading to impair plant growth. However, an excessively high C:P ratio may indicate phosphorus limitation, which can restrict plant productivity and affect overall soil functioning ((Jiao *et al.,* 2019; Liu *et al.,* 2021).

In the North-facing aspect (Figure 4), the maximum N:P ratio of 48.60 was obtained. Similarly, in the South-facing aspect (Figure 4), the maximum N:P ratio of 39.50 was obtained, whereas in the East-facing aspect (Figure 4), the maximum C:P ratio of 44.15 was obtained. N:P ratio in soils provides insight into the relative availability of N and P. Ratios around 10-15 are typical for many crops and soil, with ratios below 7 indicating N limitation and above 20 indicating P limitation (Qiu *et al.,* 2008). Soil N and P imbalance can lead to reduced crop yields and influence the overall health of the soil (Jiao *et al.,* 2019; Liu *et al.,* 2021). Li *et al.* (2012) suggested that variations in soil C:N:P stoichiometry might result from different vegetation and land management practices. For instance, in the North-facing aspect, the topsoil (0-16 cm) C:N, C:P, and N:P ratios of 15.1, 0.051, and 0.0034, respectively, were obtained, which were lower than the average Chinese values reported in Tian *et al.* (2010), which were 14.4, 136, and 9.3, respectively. However, the values were higher in the topsoils than the subsoils. These high values in topsoil in comparison to other soil layers may be due to topsoil samples containing humified litter.

It was observed that SOC concentration and the various nutrient elements such as N and P showed a declining trend as soil depth increased. This is typified by C:N, C:P, and N:P ratios. Lalisa *et al.* (2010) also reported that SOC, TN, and TP declined with depth for cereal farms. The present observations may have to do with how soil micro- and macro-aggregates differentially influence SOC and nutrient elements in degraded tropical agroecosystems (Ifeanyi-Onyishi *et al*., 2024).

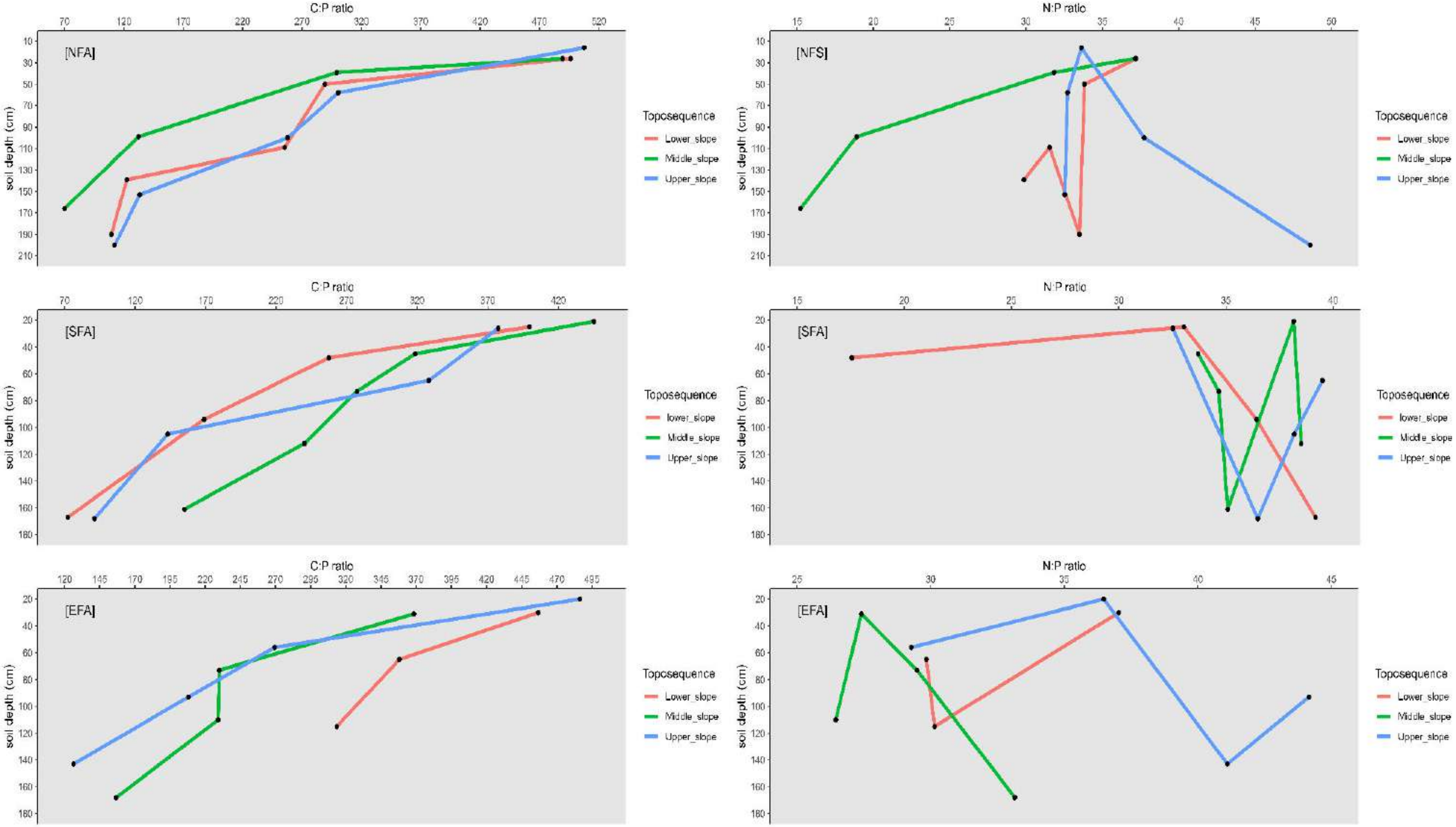


Figure 4: Profile distribution of soil C:P ratio and N:P ratio in North-facing aspect (NFA), South-facing aspect (SFA) and East-facing aspect (EFA)

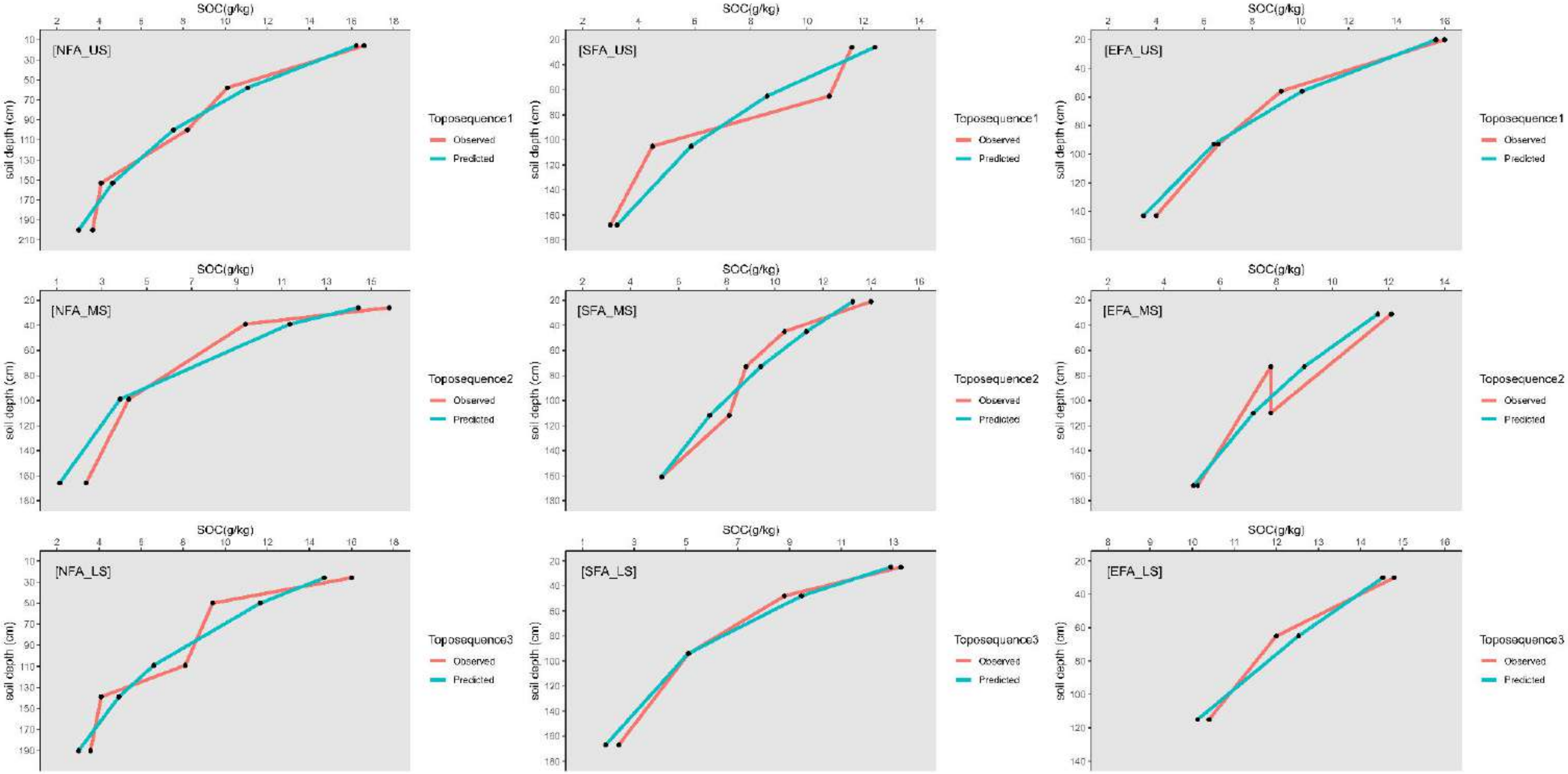


Figure 5: Profile distribution of observed and predicted SOC in north-facing aspect (NFA), south-facing aspect (SFA) and east-facing aspect (EFA) across upper, middle and lower slope. Note: NFA_UP - north facing aspect upper slope, NFA_MS - north facing aspect middle slope, NFA_LS - north facing aspect lower slope, SFA_UP - south facing aspect upper slope, SFA_MS - south facing aspect middle slope, SFA_LS - south facing aspect lower slope, EFA_UP - east facing aspect upper slope, EFA_MS - east facing aspect middle slope, EFA_LS - east facing aspect lower slope

Modeling Soil Organic Carbon Distribution Across Soil Depths

In our investigation, the fitting results in the upper slope North-facing aspect almost approximate the observed soil organic carbon (Figure 5). Similarly, in the East-facing slope, the predicted SOC approximated the observed SOC (Figure 5). However, in the South-facing aspect (Figure 5), the predicted SOC deviated largely from observed SOC. It either underestimated or overestimated SOC as soil depth increases. This result is similar to those reported by Wendt and Hauser (2013), Chen *et al.* (2015) and Bai *et al.* (2016). In the middle slope, in the North-facing aspect, the predicted SSOC approximated the observed soil organic carbon (Figure 5). Similarly in the South-facing slope (Figure 5) and East-facing aspect (Figure 5), the predicted SOC approximated the observed SOC. However, for the lower slope position, the North-facing aspect (Figure 5) predicted SOC deviated largely from observed SOC, whereas in the South-facing slope (Figure 5) and East-facing aspect (Figure 5), the predicted SOC approximated the observed SOC.

This result is an indication that the exponential function is useful in modeling the vertical distribution of SOC in coastal plain sand. For example, in the North-facing aspect, upper slope, the fitted model was $C = 1.877e^{-0.0091D}$ with high R^2 value of 0.989 and a standard error (SE) of 0.0866, all indicating a good fit of this model. The fitting parameters with their respective models R^2 and SE are shown in Table 2. The results from these studies shows the importance of selecting modeling techniques for SOC estimation. The exponential change decline function, in particular, offers a promising alternative to traditional methods, especially in soils with complex profiles. Accurate SOC estimations are crucial for understanding carbon cycling, informing land management practices, and assessing the role of soils in ecosystem services.

Relationship Between Soil Nutrient Ratios and Soil-Environmental Covariates

Results of the relationship between SOC, C:N ratio, C:P ratio and N:P with soil-enviromental variables are shown in Figure 6. The results showed that SOC was significantly and negatively correlated with clay-ratio ($r = -0.86$, $p < 0.05$) and sand ($r = -0.774$, $p < 0.05$) while it was significantly and positively correlated with TN ($r = 0.745$, $p < 0.05$), clay ($r = 0.772$, $p < 0.05$), NP-ratio ($r = 0.641$, $p < 0.05$), elevation ($r = 0.549$, $p < 0.05$) and C:N ratio ($r = 0.63$, $p < 0.05$) (Figure 6). These results are in line with the report of Nozari and Borůvka (2023) that SOC is moderately correlated with altitude and increases with altitude in a study conducted in the Liberec and Domažlice districts, Czech Republic.

The C:N ratio was significantly and negatively correlated with clay-ratio ($r = -0.672$, $p < 0.05$) , and sand content ($r = -0.495$, $p < 0.05$) while it was significantly and positively correlated pH ($r = 0.684$, $p < 0.05$), SOC ($r = 0.63$, $p < 0.05$), C:P-ratio ($r = 0.563$, $p < 0.05$), clay ($r = 0.55$, $p < 0.05$), available phosphorus ($r = 0.526$, $p < 0.05$), and hillshade ($r = 0.449$, $p < 0.05$) (Figure 6). Similarly, C:P ratio was significantly and negatively correlated with clay-ratio ($r = -0.85$, $p < 0.05$) and sand ($r = -0.766$, $p < 0.05$), whereas, it shows significant and positive correlation with SOC ($r = 0.985$, $p < 0.05$), TN ($r = 0.78$, $p < 0.05$), clay ($r = 0.77$, $p < 0.05$), N:P ratio ($r = 0.716$, $p < 0.05$), elevation ($r = 0.617$, $p < 0.05$), and C:N ratio ($r = 0.563$, $p < 0.05$) (Figure 8c). The N:P ratio significantly and negatively correlated with sand ($r = -0.48$, $p < 0.05$), clay ratio ($r = -0.44$, $p < 0.05$), and aspect ($r = -0.426$, $p < 0.05$) and also significantly but positively correlated with SOC ($r = 0.64$, $p < 0.05$), TN, ($r = 0.97$, $p < 0.05$) clay ($r = 0.435$, $p < 0.05$), C:P ratio ($r = 0.716$, $p < 0.05$), Mg ($r = 0.469$, $p < 0.05$), and clay ($r = 0.435$, $p < 0.05$) (Figure 8d). The observed relationships are indicative of the intricate connections among the various soil properties which can hardly be observed when using raw data obtained directly from laboratory analysis (John *et al.,* 2021; John *et al.,* 2022).

Factors Affecting Topsoil SOC and Nutrient Ratios

The results indicate that the C:N ratio was significantly and positively influenced by pH, clay ratio, OC, clay and Hillshade. Also, C:P ratio was significantly and positively influenced by OC and N:P ratio and negatively influenced by TN, while N:P ratio was significantly and positively influenced by TN and C:P ratio and negatively influenced by OC. According to Li *et al.* (2016), topsoil has greater soil C:N, C:P, and N:P ratios than the subsoil or deeper soil because of the litter from plant residues which is responsible for releasing nutrients. Landscape attributes, including soil-environmental

Table 2: Model parameters and fitting results of SOC values using an exponential model

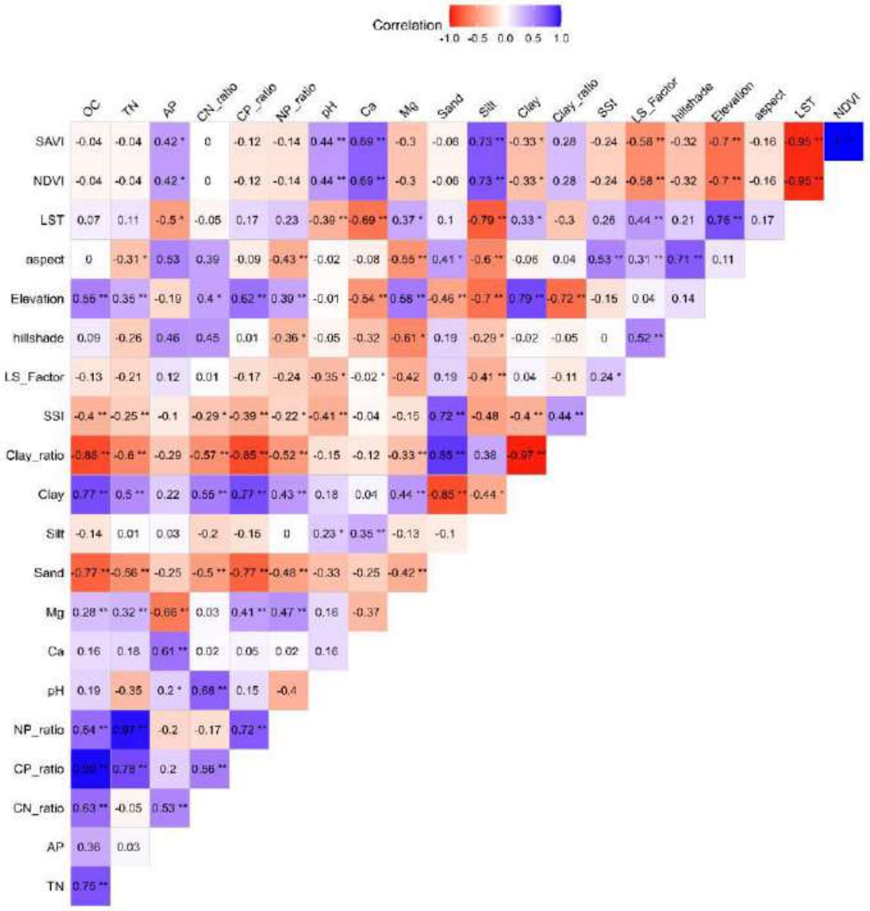
Aspect	Toposequence	Exponential model	R^2	SE
North-facing aspect	Upper slope	$C = 1.877e^{-0.0091D}$	0.989	0.0866
	Middle slope	$C = 2.319e^{-0.0182D}$	0.966	0.192
	Lower slope	$C = 1.89e^{-0.0096D}$	0.948	0.866
South-facing aspect	Upper slope	$C = 1.589e^{-0.0095D}$	0.931	0.194
	Middle slope	$C = 1.519e^{-0.0066D}$	0.969	0.092
	Lower slope	$C = 1.808e^{-0.0135D}$	0.994	0.065
East-facing aspect	Upper slope	$C = 1.997e^{-0.012D}$	0.992	0.0775
	Middle slope	$C = 1.403e^{-0.0061D}$	0.957	0.102
	Lower slope	$C = 1.651e^{-0.0042D}$	0.979	0.0649

SE - Standard Error of Estimate

Table 3: Factors affecting topsoil SOC and nutrient ratios

SOC		C:N ratio		C:P ratio		N:P ratio	
predictors	coefficient	predictors	coefficient	predictors	coefficient	predictors	coefficient
C	–2.61 (3.81)*	C	–34.97**	C	–0.0048	C	3.74E-05
C:N ratio	0.119 (7.29)**	pH	6.98***	Clay ratio	–9.51E-05	Clay ratio	5.35E-06
Clay ratio	–0.020 (-0.71)	Clay ratio	0.99**	OC	0.027086**	OC	–0.0025***
Sand	0.012(1.52)	OC	4.45**	Clay	9.77E-06	Clay	–5.74E-07
Clay	0.016 (2.28)	Clay	0.12**	TN	–0.316**	TN	0.030***
N:P ratio	419.31 (10.14)***	Sand	–0.063	Sand	1.35E-05	Sand	–7.69E-07
Elevation	–0.0023 (-2.80)	HillShade	0.040**	C:N ratio	0.00033	C:P ratio	0.085***
				N:P ratio	11.744**		
R^2	0.99		0.99		0.99		0.99
F-stat	74.51**		78.02**		59436.73***		13039.19***

SOC - soil organic carbon, Figures in parenthesis are the t-statistics, *, **, *** - significant levels of 10 %, 5% and 1 % respectively



	OC	TN	AP	CN_ratio	CP_ratio	NP_ratio	pH	Ca	Mg	Sand	Silt	Clay	Clay_ratio	SSI	LS_Factor	hillshade	Elevation	aspect	LST	NDVI
SAVI	-0.04	-0.04	0.42 *	0	-0.12	-0.14	0.44 **	0.69 **	-0.3	-0.06	0.73 **	-0.33 *	0.28	-0.24	-0.58 **	-0.32	-0.7 **	-0.16	-0.95 **	1 **
NDVI	-0.04	-0.04	0.42 *	0	-0.12	-0.14	0.44 **	0.69 **	-0.3	-0.06	0.73 **	-0.33 *	0.28	-0.24	-0.58 **	-0.32	-0.7 **	-0.16	-0.95 **	
LST	0.07	0.11	-0.5 *	-0.05	0.17	0.23	-0.39 **	-0.69 **	0.37 *	0.1	-0.79 **	0.33 *	-0.3	0.26	0.44 **	0.21	0.76 **	0.17		
aspect	0	-0.31 *	0.53	0.39	-0.09	-0.43 **	-0.02	-0.08	-0.55 **	0.41 *	-0.6 **	-0.06	0.04	0.53 **	0.31 **	0.71 **	0.11			
Elevation	0.56 **	0.35 **	-0.19	0.4 *	0.62 **	0.39 **	-0.01	-0.54 **	0.58 **	-0.46 **	-0.7 **	0.79 **	-0.72 **	-0.15	0.04	0.14				
hillshade	0.09	-0.26	0.46	0.45	0.01	-0.36 *	-0.05	-0.32	-0.61 *	0.19	-0.29 *	-0.02	-0.05	0	0.52 **					
LS_Factor	-0.13	-0.21	0.12	0.01	-0.17	-0.24	-0.35 *	-0.02 *	-0.42	0.19	-0.41 **	0.04	-0.11	0.24 *						
SSI	-0.4 **	-0.25 **	-0.1	-0.29 *	-0.39 **	-0.22 *	-0.41 **	-0.04	-0.15	0.72 **	-0.48	-0.4 **	0.44 **							
Clay_ratio	-0.88 **	-0.6 **	-0.29	-0.57 **	-0.85 **	-0.52 **	-0.15	-0.12	-0.33 **	0.85 **	0.38	-0.97 **								
Clay	0.77 **	0.5 **	0.22	0.55 **	0.77 **	0.43 **	0.18	0.04	0.44 **	-0.85 **	-0.44 *									
Silt	-0.14	0.01	0.03	-0.2	-0.15	0	0.23 *	0.35 **	-0.13	-0.1										
Sand	-0.77 **	-0.56 **	-0.25	-0.5 **	-0.77 **	-0.48 **	-0.33	-0.25	-0.42 **											
Mg	0.28 **	0.32 **	-0.66 **	0.03	0.41 **	0.47 **	0.16	-0.37												
Ca	0.16	0.18	0.61 **	0.02	0.05	0.02	0.16													
pH	0.19	-0.35	0.2 *	0.68 **	0.15	-0.4														
NP_ratio	0.64 **	0.97 **	-0.2	-0.17	0.72 **															
CP_ratio	0.99 **	0.78 **	0.2	0.56 **																
CN_ratio	0.63 **	-0.05	0.53 **																	
AP	0.36	0.03																		
TN	0.75 **																			

Figure 6: Correlation coefficients between environmental variables and soil properties

Note: ** and * significant at 1% and 5 % level of significance, respectively

factors are usually the most important factors influencing the distribution of SOC and nutrient ratios (Li *et al.,* 2012). This research, which was conducted in areas with rolling terrain, homogeneous parent material, and uniform climate patterns showed these attributes to significantly and positively influenced SOC in the study area. Similar studies found texture, pH value, and topography to contribute to variations in SOC and its storage (Xia *et al.*, 2016; Jiang *et al.,* 2017).

CONCLUSION

In this research the main findings were that values of SOC and nutrient ratios including C:N, C:P and N:P ratios were found to gradually decreased with soil depth which followed exponential function along the different toposequence in each aspect position studied. Hence, SOC and nutrient ratios (C:N, C:P and N:P) can be used as an indicator of soil fertility and productivity to advance an understanding of the above-ground plant community and below-ground soil nutrient at various depths. The low nutrient levels observed in the area require the application of organic manures as well as residue of harvested crops to increase SOC and nitrogen levels. Ongoing research and methodological refinements will continue to improve the understanding of SOC and nutrient ratios dynamics and their implications for soil fertility management.

REFERENCES

Afu S.M., Isong I.A. and Awaogu C.E. (2019). Agricultural potentials of floodplain soils with contrasting parent material in Cross River State, Nigeria. *Global J. Pure Appl. Sci.,* **25,** 13-22. https://doi.org/10.4314/gjpas.v25i1.3

Afu S.M., Isong I.A. and Aki E.E. (2017). Variability of selected physico-chemical properties of soil overlying different parent materials in Odukpani, Cross River State. *Int. J. Plant Soil Sci.,* **20 (6),** 1-14. https://doi.org/10.9734/IJPSS/2017/38317

Alarima C.I., Annan-Afful E., Obalum S.E., *et al.* (2020). Comparative assessment of temporal changes in soil degradation under four contrasting land-use options along a tropical toposequence. *Land Degr. Dev.*, **31**, 439-450. https://doi.org/10.1002/ldr.3461

Bai J., Zhang G., Zhao Q., *et al.* (2016). Depth-distribution patterns and control of soil organic carbon in coastal salt marshes with different plant covers. *Sci. Reports,* **6,** 34835. https://doi.org/10.1038/srep34835

Brady N.C. and Weil R.R. (2008). *The Nature and Properties of Soils.* Prentice-Hall Press, New York, New York, USA

Chen C., Hu K.L., Li H., Yun A.P. and Li B.G. (2015). Three-dimensional mapping of soil organic carbon by combining Kriging method with profile depth function. *PLoS One*, **10 (6),** e0129038. https://doi.org/10.1371/journal.pone.0129038

Dorji T., Odeh I.O.A., Field D.J. and Baillie I.C. (2014). Digital soil mapping of soil organic carbon stocks under different land use and land cover types in montane ecosystems, eastern Himalayas. *For. Ecol. Manage.,* **318,** 91-102. https://doi.org/10.1016/j.foreco.2014.01.003

Ebido N.E., Nnadi A.L., Adeoluwa O.O., Ndubuaku U.M., Obalum S.E., Ugwuoju C.L., Ajoagu G.M. and Baiyeri K.P. (2024). Influence of brewery waste and animal manure-based compost on the growth of green amaranth in sandy tropical soils. *Organic Farming,* **10 (1),** 69-79. https://doi.org/10.56578/of100104

Estefan G., Sommer R. and Ryan J. (2013). *Methods of Soil, Plant and Water Analysis: A manual for the West Asia and North Africa.* International Center for Agricultural Research in the Dry Areas (ICARDA). https://repo.mel.cgiar.org/handle/20.500.11766/7512

Esu I.E. (2010). *Soil Characterization, Classification, and Survey.* HEBN Publishers Plc., Ibadan, Nigeria, 232 pp.

Fan H., Wu J., Liu W., Yuan Y., Hu L. and Cai Q. (2015). Linkages of plant and soil C: N: P stoichiometry and their relationships to forest growth in subtropical plantations, *Plant Soil,* **392,** 127-138. https://doi.org/10.1007/s11104-015-2444-2

Fasina A.S., Raji A., Oluwatosin G.A., Omoju O.J. and Oluwadare D.A. (2015). Properties, genesis, classification, capability and sustainable management of soils from South-Western Nigeria. *Int. J. Soil Sci.,* **10 (3),** 142-152. https://doi.org/10.3923/ijss.2015.142.152

Gee G.W. and Or D. (2002). Particle size analysis. In: Dane J. and Topp G.C. (eds). *Methods of Soil Analysis, Part 4: Physical Methods,* pp 255-294. Soil Science Society of America, Madison. https://doi.org/10.2136/sssabookser5.4.c12

Guzman J.G. and Al-Kaisi M.M. (2011). Landscape position effect on selected soil physical properties of reconstructed prairies in southcentral Iowa. *J. Soil Water Conserv.,* **66 (3),** 183-191. https://doi.org/10.2489/jswc.66.3.183

Hussain S., Hussain S., Guo R., *et al.* (2021)**.** Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage. *Plants,* **10.** https://doi.org/10.3390/plants1010200

Isong I.A., John K., Okon P.B., Ogban P.I. and Afu S.M. (2022). Soil quality estimation using environmental covariates and predictive models: An example from tropical soils of Nigeria. *Ecol. Proc.,* **11,** 66. https://doi.org/10.1186/s13717-022-00411-y

Ifeanyi-Onyishi I.F., Ezeaku V.I., Umeugokwe C.P., Ezeaku P.I. and Obalum S.E. (2024). Distribution of soil fertility indices in aggregate size fractions under different land-use types for coarse-textured soils of the derived savannah. *J. Degr. Mining Lands Manage.*, **12 (1),** 6695-6704. http://doi.org/10.15243/jdmlm.2024.121.6695

Jiang F., Wu X., Xiang W.H., *et al.* (2017). Spatial variations in soil organic carbon, nitrogen and phosphorus concentrations related to stand characteristics in subtropical areas. *Plant Soil,* 413, 289-301. https://doi.org/10.1007/s11104-016-3101-0

Jiao S., Li J., Li Y., Jia J. and Xu Z. (2019). Soil C, N, and P distribution as affected by plant communities in the Yellow River Delta, China. *PLoS One*, **14 (12),** e0226887. https://doi.org/10.1371/journal.pone.0226887

Jiménez J.J., Lorenz K., and Lal R. (2011). Organic carbon and nitrogen in soil particle-size under dry tropical forests from Guanacaste, Costa Rica - implications for within site soil organic stabilization. *Catena,* **86,** 178-191. https://doi.org/10.1016/j.catena.2011.03.011

John K., Afu S.M., Isong I.A., Chapman P.A., Kebonye N.M. and Ayito E.O. (2021). Estimation of soil organic carbon distribution by geostatistical and deterministic interpolation methods: A case study of the southeastern soils of Nigeria. *Environ. Eng. Manage. J.,* **20 (7),** 1077-1085. https://doi.org/10.30638/eemj.2021.100

John K., Bouslihim Y., Bouasria A., *et al.* (2022). Assessing the impact of sampling strategy in random forest-based predicting of soil nutrients: a study case from Northern Morocco, Geocarto International. https://doi.org/10.1080/10106049.2022.2048091

John K., Isong I.A., Kebonye N.M., Ayito E.O., Agyeman P.C. and Afu S.M. (2020). Using machine learning algorithms to estimate soil organic carbon variability with environmental variables and soil nutrient indicators in an alluvial soil. *Land*, **9,** 487. https://doi.org/10.3390/land9120487

Kassa H., Dondeyne S., Poesen J., Frankl A., and Nyssen J. (2017). Impact of deforestation on soil fertility, soil carbon and nitrogen stocks: the case of the Gacheb catchment in the White Nile Basin, Ethiopia. *Agric. Ecosyst. Environ.,* **247,** 273-282. https://doi.org/10.1016/j.agee.2017.06.034

Landon J.R. (2014). Booker Tropical Soil Manual: A handbook for soil survey and agricultural land evaluation in the Tropics and Subtropics. In: 2000 Symposium, Sugarcane: Research towards Efficient and Sustainable Production (pp. 237-240). Routledge, London. https://www.worldcat.org/title/booker-tropical-soil-manual-a-handbook-for-soil-survey-and-agricultural-land-evaluation-in-the-tropics-andsubtropics/oclc/869641714?referer=di&ht=edition

Lalisa A., Hager H. and Sieghardt M. (2010). Effects of land use types on soil chemical properties in smallholder farmers of central highland Ethiopia, *Ecology,* **29,** 1-14. https://doi.org/10.4149/ekol_2010_01_1

Li C., Zhao L., Sun P., *et al.* (2016). Deep soil C, N, and P storage and stoichiometry in response to land use patterns in the Loess Hilly Region of China. *PLoS ONE,* **11,** e015907. https://doi.org/10.1371/journal.pone.0159075

Li Y., Wu J., Liu S., *et al.* (2012). Is the C: N: P stoichiometry in soil and soil microbial biomass related to the landscape and land use in southern subtropical China? *Global. Biogeochem. Cycles,* **Vol. 26,** GB4002. https://doi.org/10.1029/2012GB004399

Liu Q., Xu H. and Yi. (2021). Impact of fertilizer on crop yield and C: N:P stoichiometry in arid and semi-arid Soil. *Int. J. Environ. Res. Public Health.,* **18 (8),** 4341. https://doi.org/10.3390/ijerph18084341

Liu S.J., Zhang W., Wang K.L., Pan F.J., Yang S., and Shu S.Y. (2015). Factors controlling accumulation of soil organic carbon along vegetation succession in a typical karst region in Southwest China. *Sci. Total Environ.,* **521,** 52-58. https://doi.org/10.1016/j.scitotenv.2015.03.074

Mooshammer M., Wanek W., Hämmerle I., *et al.* (2014). Adjustment of microbial nitrogen use efficiency to C:N imbalances regulates soil nitrogen cycling. *Nature Commun.,* **5,** 1-7 https://doi.org/10.1038/ncomms4694

Nahusenay A. and Kibebew K. (2016). Effects of land use, soil depth and topography on soil physicochemical properties along the toposequence at the Wadla Delanta Massif, Northcentral Highlands of Ethiopia. *Environ. Pollut.,* **5(2),** 57-71. https://doi.org/10.5539/ep.v5n2p57

Ndzeshala S.D., Obalum S.E. and Igwe C.A. (2023). Some utilisation options for cattle dung as soil amendment and their effects in coarse-textured Ultisols and maize growth. *Int. J. Recycl. Org. Waste Agric.,* 12 (1), 123-139. https://doi.org/10.30486/ijrowa.2022.1934239.1284

Nozari S. and Luboš Borůvka L. (2023). The effects of slope and altitude on soil organic carbon and clay content in different land-uses: A case study in the Czech Republic. *Soil Water Res.*, **18 (3),** 204-218

Obalum S.E., Chibuike G.U., Peth S. and Ouyang Y. (2017). Soil organic matter as sole indicator of soil degradation. *Environ. Monit. Assess.*, **189 (4),** Article 176. https://doi.org/10.1007/s10661-017-5881-y

Obalum S.E., Oppong J., Igwe C.A., Watanabe Y. and Obi M.E. (2013). Spatial variability of uncultivated soils in derived savanna. *Int. Agrophys.,* **27 (1),** 57-67. https://dx.doi.org/10.2478/v10247-012-0068-9

Obalum S.E., Watanabe Y., Igwe C.A., Obi M.E. and Wakatsuki T. (2012). Carbon stock in the solum of some coarse-textured soils under secondary forest, grassland fallow and bare footpath in the derived savanna of southeastern Nigeria. *Soil Research*, **50 (2)**, 157-166. https://doi.org/10.1071/SR11096

Oku E., Essoka A. and Thomas E. (2010). Variability in soil properties along an Udalf toposequence in the Humid Forest Zone of Nigeria. *Kasetsart J. (Nat. Sci.),* **44,** 564-573

Poeplau C., Don A., Vesterdal L., *et al.* (2011). Temporal dynamics of soil organic carbon after land-use change in the temperate zone carbon response functions as a model approach. *Global Change Biol.,* **17 (7),** 2415-2427. https://doi.org/10.1111/j.1365-2486.2011.02408.x

Qiu S., McComb A.J. and Bell R.W. (2008). Ratios of C, N and P in soil water direct microbial immobilisation–mineralisation and N availability in nutrient amended sandy soils in Southwestern Australia. *Agric. Ecosys. Environ.,* **127 (1-2),** 93-99. https://doi.org/10.1016/j.agee.2008.03.002

Tesfahunegn G.B., and Gebru T.A. (2020). Variation in soil properties under different cropping and other land-use systems in Dura catchment, Northern Ethiopia. *PLoS ONE,* **15 (2),** e0222476. https://doi.org/10.1371/journal.pone.0222476

Tian H., Chen G., Zhang C., Melillo J.M. and Hall C.A.S. (2010). Pattern and variation of C: N: P ratios in China's soils: a synthesis of observational data. *Biogeochemistry,* **98,** 139-151. https://doi.org/10.1007/s10533-009-9382-0

Udo E J., Ibia T.O., Ogunwale J.O., Ano A.O. and Esu I. (2009). *Manual of Soil, Plant and Water Analysis*. Sibon Books Ltd. Lagos

Ugwu D.O., Joshua P.E., Obalum S.E., Dedan N.K. and Njoku O.U. (2024). Aging-associated fermentation of palm oil-mill effluent enhances its organo-fertilizer value and the desired agronomic effects in low-fertility soils. *Int. J. Recycl. Org. Waste Agric.,* **13 (4),** 132439. https://dx.doi.org/10.57647/ijrowa-xqpd-6789

von Lützow M., Kögel-Knabner I., Ekschmitt K., Matzner E., Guggenberger G. and Marschner B. (2006). Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - A review. *Eur. J. Soil Sci,* **57,** 426-445. https://doi.org/10.1111/j.1365-2389.2006.00809.x

Wei X., Shao M., Fu X., Horton R., Li Y. and Zhang X. (2009). Distribution of soil organic C, N and P in three adjacent land use patterns in the northern Loess Plateau, China. *Biogeochemistry,* **5 (96),** 149-162. https://doi.org/10.1007/s10533-009-9350-8

Wendt J.W. and Hauser S. (2013). An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *Eur. J. Soil Sci.,* **64,** 58-65. https://doi.org/10.1111/ejss.12002

Xia S.W., Chen J., Schaefer D. and Goodale U.M. (2016). Effect of topography and litterfall input on fine-scale patch consistency of soil chemical properties in a tropical rainforest. *Plant Soil*, **404,** 385-398. https://doi.org/10.1007/s11104-016-2854-9

Yimer F., Ledin S. and Abdelkadir A. (2007). Changes in soil organic carbon and total nitrogen concentrations in three adjacent land use types in the Bale Mountains, Southeastern Highlands of Ethiopia. *For. Ecol. Manage.,* **242,** 337-342. https://doi.org/10.1016/j.foreco.2007.01.087

Zechmeister-Boltenstern S., Keiblinger K.M., Mooshammer M., *et al.* (2015). The application of ecological stoichiometry to plant-microbial-soil organic matter transformations. *Ecol. Monogr.* **85,** 133-155. https://doi.org/10.1890/14-0777.1

Zeraatpisheh M., Ayoubi S., Sulieman M. and Rodrigo-Comino J. (2019). Determining the spatial distribution of soil properties using the environmental covariates and multivariate statistical analysis: a case study in semi-arid regions of Iran. *J. Arid Land,* **11 (4),** 551-566. https://doi.org/10.1007/s40333-019-0059-9

Zhao F., Sun J., Ren C., *et al.* (2015). Land use change influences soil C, N, and P stoichiometry under 'Grain-to-Green Program' in China. *Sci. Reports,* **5,** 10195. https://doi.org/10.1038/srep10195