

Original Research Article

An Evaluation of Soil Development and Productivity on an Agrarian Hillslope of the Jos Plateau, Nigeria

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ABSTRACT

Soil development and productivity are closely related terms affecting crop yields. The objective of this study is to evaluate the nature of soil development and productivity on an agrarian hillslope of the Jos Plateau, Nigeria. The study was conducted through observation of four soil profiles, each located at the summit, back slope, foot slope, and toe slope of the study area, respectively. Fieldwork and morphological observations followed the guidelines provided in the Soil Survey Manual. Standard laboratory procedures were used to analyse soil properties. Soils were of medium texture with significant structural development. Soils were generally acidic, although soil pH buffering capacity values were low and ranged from 350.60 to 908.80 mg kg⁻¹ pH⁻¹. The study shows that the correlation ($r = -0.67$) between pH buffer capacity and clay is significantly negatively moderate. Soil productivity indices ranged from moderate to high, whereas the Erosion Risk Index ranged from low to moderate across the landscape of the study area. Soil development in the study area varied with respect to topographic position. Soils were poorly developed with the absence of diagnostic horizons at the summit to back slope positions. Soil development increased appreciably from the foot slope to the toe slope positions.

Keywords: erosion risk, organic matter, pH buffer capacity, soil profile, slope position

INTRODUCTION

A complex and ongoing process that is essential both for crop production and environmental sustainability is soil development. The development of soil is a fascinating process that involves the interaction of various factors (climate, parent material, organisms and relief) over time (Weil and Brady, 2017). Understanding these factors and their various processes is imperative for harnessing soil resources for crop production. The stages of soil development involve physical, chemical and biological weathering, horizon differentiation and

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maturation. Soil development is a dynamic process, with soil continually evolving based on environmental changes and interaction with the environment (USDA, 2017).

Furthermore, closely related to soil development is soil productivity. Soil productivity is the capacity of soil to support plant growth and optimise crop yield (Delgado, 2003). This vital aspect of agriculture depends on the soil's ability to provide a suitable environment for plant roots, including essential nutrients, water, and aeration. Soil productivity is not just a measure of the present yield but a predictor of future agricultural success (Lobo et al., 2005). A greater understanding of the factors that affect soil productivity (such as soil physical, chemical and biological properties, environmental, management and other limiting factors) have been noted to improve soil management practices (Delgado, 2003).

The effort to comprehensively investigate the connections between soil development and productivity on hillslope terrains remains an active area of research. The hillslope chosen for this study does not have complex slope characteristics and rock out crops making it ideal for a study relating topographic features to soil development and productivity. Therefore, the objective of this study is to evaluate the nature of soil development and productivity in relation to topographic features on an agrarian hillslope. The data obtained from this study will contribute to a deeper understanding of soil processes on hillslopes, ultimately enhancing conservation strategies aimed at promoting greater sustainability and productivity.

MATERIALS AND METHODS

Study Area and Field work

The study site is in Tumu-Sarari on the fringes of the Jos Plateau. The area is situated between latitudes $10^{\circ} 4' 16.12''\text{N}$ and $10^{\circ} 4' 7.54''\text{N}$, and between longitudes $8^{\circ} 54' 50.44''\text{E}$ and $8^{\circ} 55' 39.23''\text{E}$. The geology of the area is basement complex and younger granites (Directorate of Overseas Surveys, 1977). The climate is tropical continental with distinct wet and dry seasons. A detailed description of climatic characteristics is presented in Figures 1 to 3.

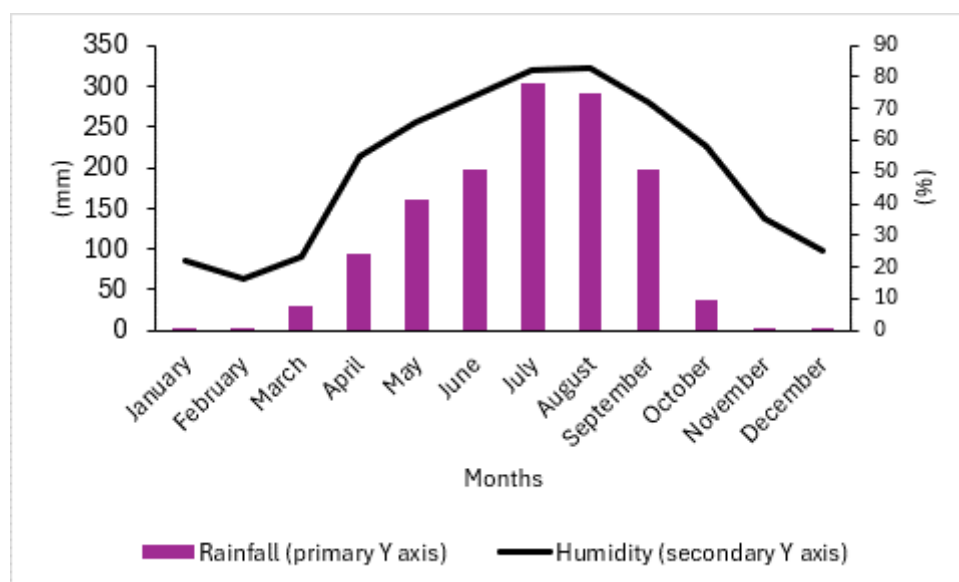


Figure 1: Mean monthly rainfall and humidity of the study area (1971–2000)

Source: Authors' construct using climate data base as documented in Climwat 2.0 software developed by FAO (2021b).

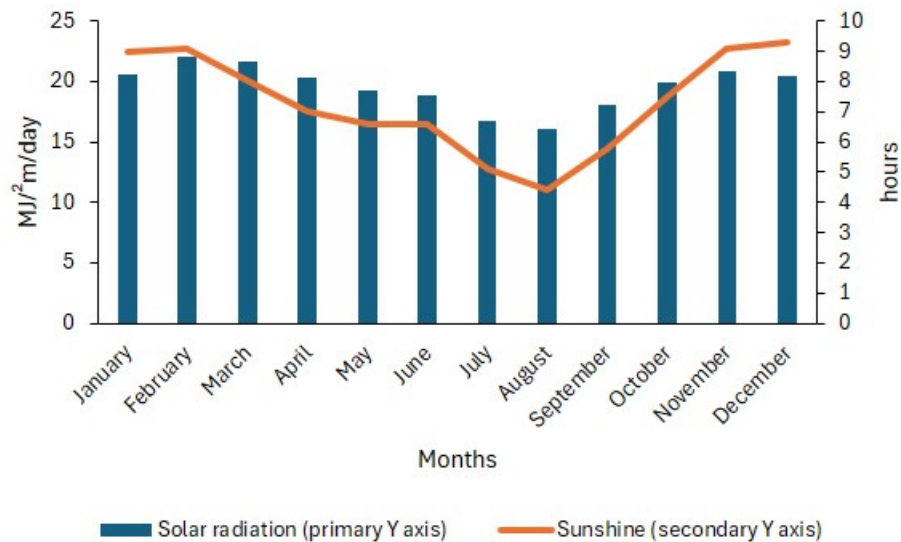


Figure 2: Mean monthly solar radiation and sunshine hours of the study area (1971–2000)

Source: Authors' construct using climate data base as documented in Climwat 2.0 software developed by FAO (2021b).

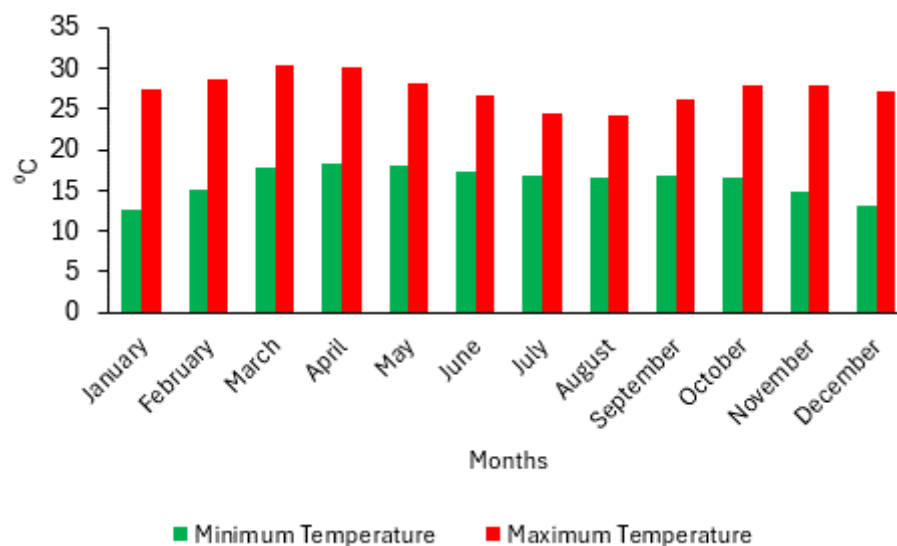


Figure 3: Mean monthly temperature characteristics of the study area (1971–2000)

Source: Authors' construct using climate data base as documented in Climwat 2.0 software developed by FAO (2021b).

Elevation data at 30-meter resolution obtained from the Shuttle Radar Topography Mission (SRTM) were used to produce an elevation model of the study area with the aid of the System for Automated Geo-scientific Analysis (SAGA) software. The topographic features of the research area are depicted in Figure 4. In the field, a stratified sampling strategy was used. Topographic features were used to stratify the research site. Consequently, the area of the summit, back slope foot slope and toe slope units were approximately 2.85, 2.28, 3.70 and 30 hectares, respectively. To reflect the average soil properties in each topographic unit, a purposive sampling technique was employed (Barnekow et al., 2019) which involved excavating a single soil profile pit in each stratum to minimize environmental disturbance especially due to the relatively small area of the topographic units. Additionally, samples of soil were taken from every

genetic horizon. Guidelines from the soil survey manual were used to characterise morphological features (USDA, 2017).

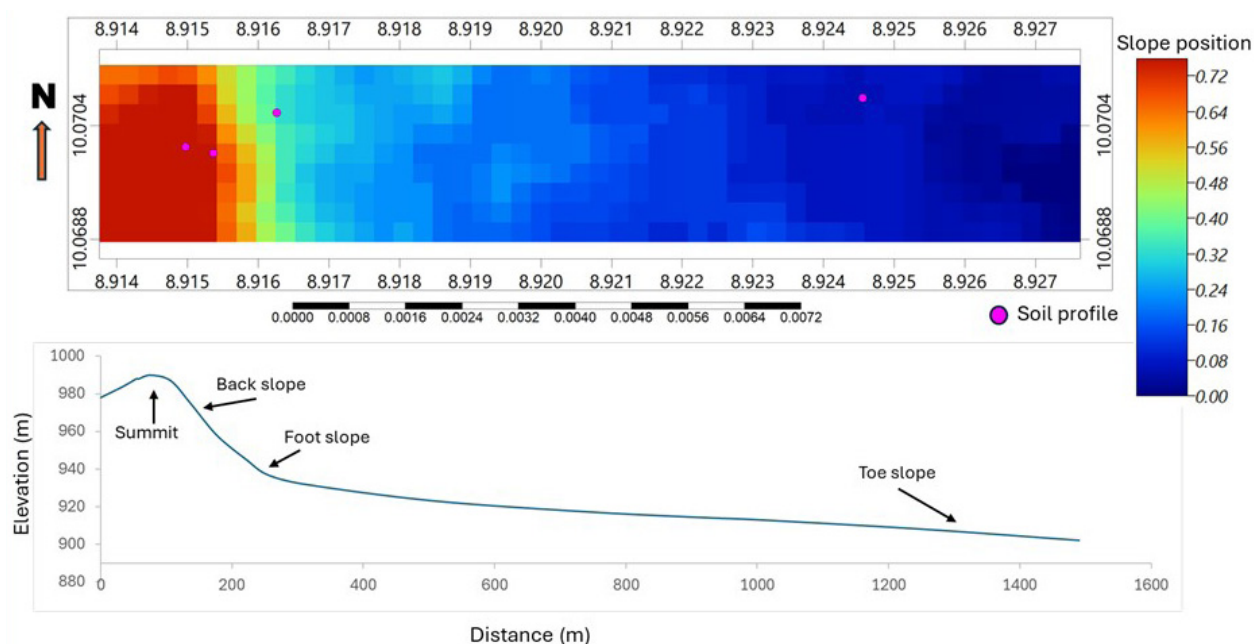


Figure 4: Map of study area showing topographic features and location of profile pits

Source: Authors' construct using SRTM 30-meter resolution data

Vegetation distribution was evaluated using the normalized difference vegetation Index (NDVI) using Sentinel-2 imagery (equation 1): where B8 is the Near-Infrared (NIR) band at a 10-meter resolution and B4 is the red band at a 10-meter resolution. NDVI was calculated for the following time periods 2015-10-23, 2015-12-22, 2023-10-21, and 2023-01-11.

$$NDVI = \frac{B8 - B4}{B8 + B4} \quad \text{Equation 1}$$

Laboratory Analysis

Soil samples collected from the field on the 15th of April 2023 were passed through a 2mm mesh sieve and then determining percentage gravel content. The particle size distribution was established by dispersing soil samples in 5% sodium hexametaphosphate solution, followed by shaking on a reciprocating shaker and then using the hydrometer method (Hossain et al., 2021). Bulk density was determined using the clod method (Al-Shammery et al., 2018). This is accomplished by coating soil aggregates with paraffin and determining their volume using the displacement method. Moreover, the pH of the soil was measured using a 1:1 soil/solution ratio in a 0.01M CaCl_2 solution whereas the pH buffer capacity and lime requirement were ascertained using Kissel and Sonon's (2014) single addition $\text{Ca}(\text{OH})_2$ technique. The ignition method, as described by Ivezić et al. (2016) was used to measure the amount of organic matter. This was accomplished by raising the temperature of 0.500 to 1.000g portions of oven-dry soil to a temperature of 500 °C for 2 hours.

Soil nitrogen was determined using the Kjeldahl procedure (FAO, 2021a). This entails wet digestion of a sample to convert organic nitrogen into ammonium nitrogen ($\text{NH}_4^{+}\text{-N}$), followed by quantification of the

nitrogen content. The Productivity and Erosion Risk Index is calculated with the following multi-factorial model (Delgado, 2003; Lobo et al., 2005):

$$PI = \sum_{i=1}^n (A_i \times B_i \times C_i \times K_i) \quad \text{Equation (2)}$$

Where:

PI = Soil Productivity Index

A_i = air water relations factor of horizon i

B_i = mechanical resistances to the crop root exploration in horizon i ; and

C_i = potential fertility of horizon i .

K_i = weighting factor of the respective horizon

All these factors are evaluated in each soil horizon n , up to a depth of 100 cm if the soil has a depth equal to or greater than this value, or up to the effective soil depth, if it is less than 100 cm.

$$ERI = \frac{\eta}{10(1 - \alpha)} \quad \text{Equation (3)}$$

Where:

ERI = Erosion Risk Index

α = soil runoff potential factor

η = terrain/slope factor

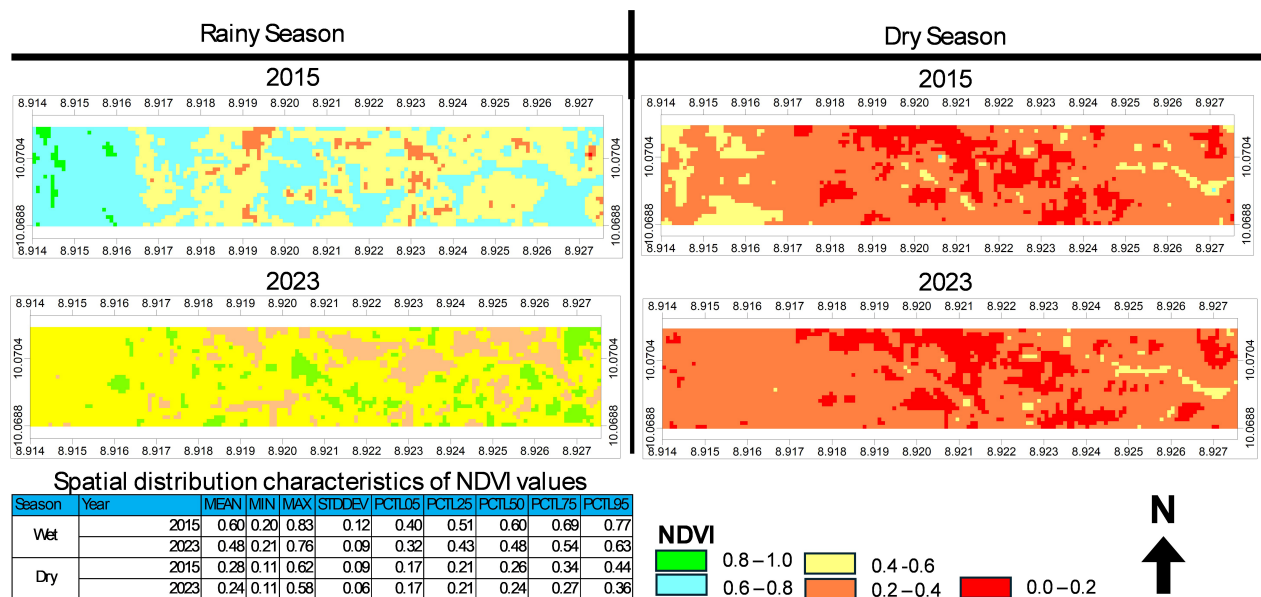


Figure 5: Vegetation characteristics of the study area

Source: Authors' construct using Sentinel 2 imagery.

RESULTS AND DISCUSSION

Vegetation Characteristics of the Study Area

Figure 5 shows the normalized difference vegetation index (NDVI) of the study area just before the commencement of farming activities and 7 years after the onset of farming activities. No anthropogenic activity had been performed on this site before 2016. Prior to 2016, *Andropogon pseudapricus* grassland dominated the landscape with occasional *Terminalia*, *Syzygium* and *Acacia* shrubs. (Bennett et al., 1978). Manual maize cultivation with the use of hoes began on the summit in the year 2016 without the application of fertilisers or manures. The land was left to fallow during the dry season. Figure 5 indicates that farming activities have resulted in a reduction in mean NDVI values from 0.60 in 2015 to 0.48 in 2023. Furthermore, there is a reduction in maximum NDVI values from 0.83 to 0.75. Also, NDVI values at the 50th percentile were 0.60 and 0.48 for the years 2015 and 2023, respectively. Furthermore, vegetation distribution over the study area is seasonal with the rainy seasons recording higher NDVI values compared to the dry seasons. Similar studies have been conducted by Othman et al. (2018) for tropical environments. Continuous farming in this area could result in loss of more vegetation, degradation of soil structure and depletion of soil organic matter (Weil and Brady, 2017).

Soil Development in the Study Area

The research area's soil morphological characteristics are shown in Table 1. In the foot and toe slope positions, the soil is deep (>90 cm), but at the summit and back slope positions, it is extremely shallow (<26 cm). Diagnostic horizons are absent at the summit and back slope positions. Only the A horizon is observed at the back slope position, and the erosional process could have limited further horizontal development. Consequently, the soil in the summit and back slope positions is classified as Entisols. This is most likely a result of soil formation being limited by erosional processes on these slope sites. Tu et al. (2025) after a study of hill-slope soils concluded that the hillslope shape has a significant impact on soil erosion, with convex hillslopes exhibiting the highest erosion rates, followed by uniform hillslopes, and concave hillslopes showing the least erosion. Additionally, studies have shown that soil erosion on convex hillslopes may be as much as 2.02 times higher than on concave hillslopes and 1.25 times greater than on uniform hillslopes (Tu et al., 2025). Soil classification for foot and toe slope positions is speculated to be Inceptisol due to the presence of an ochric epipedon and the absence of an argillic horizon. However, further studies would reveal the true nature of soil type at these sites.

In the research area, soil colour across slope classes is generally yellowish-red with hues ranging from 2.5 to 7.5. Munsell colour values are usually lower in the A horizon, most likely as a result of higher levels of organic matter content. The observed colour characteristics are typical of soil of the northern Guinea savanna area, as noted by Malgwi et al. (2000). The dominant kind of soil structure is sub-angular blocky. The aggregate size and grade suggest significant soil structure development. This may be because agricultural operations have only been conducted on these soils for the last three years or so, and that anthropogenic activities have had little impact on the structural development of the soil.

In the air-dry moisture states of the A horizons, soil consistencies are typically hard to very hard. Soil consistencies for moist and wet moisture states are friable, non-sticky, and slightly plastic for the summit and back slope positions. This suggests that tillage operations can be performed for these soils at these moisture levels. However, A horizons of the foot and toe slope positions have very friable, slightly sticky and slightly plastic soil consistencies, most likely as a result of higher clay content at these slope positions.

Consequently, tillage activities would best take place at moist moisture states. The very friable consistencies observed at the foot and toe slope positions suggest low stability of soil aggregates to erosion by water.

Details on the physical characteristics of the soil are shown in Table 2. Clay content tends to increase from horizons A to B or BC and from summit to toe slope positions for foot and toe slope positions. The flow of clay particles in suspension by runoff downslope is probably influenced by erosive processes. On the other hand, illuviation processes and in-situ soil weathering due to a higher rate of absorption and retention of precipitation at the foot and toe slope positions are probably responsible for higher clay content in the B horizons. Consequently, soil textures range from sandy loam at the summit to sandy clay loam at the toe slope position.

The research area's soils have a mean bulk density of 1.69 g/cm³ with a range of 1.34 to 2.09. In general, density values tend to rise as soil depth increases. With bulk density values and soil texture features considered, the soil in the slope positions of the foot and toes has a higher degree of compaction, which could have an impact on root growth.

Table 1: Morphological features across topographic positions

Location	Horizon	Depth (cm)	structure	Colour*	air-dry	SOIL CONSISTENCE	
						moist	wet
Summit	Ap	0–10	strong platy breaking to sub-angular blocky	7.5YR 3/2	slightly hard	friable	non-sticky, slightly plastic
	AC	10–25	Rock structure	7.5YR 3/3	very hard	friable	sticky, slightly plastic
	C	>25					
Back slope	A	0–26	strong sub-angular blocky	7.5YR 3/2	hard	friable	non-sticky, slightly plastic
	R	>26					
Foot slope	A	0–12	strong sub-angular blocky	2.5YR 2/4	hard	very friable	slightly sticky, slightly plastic
	B	12–60	strong sub-angular blocky	7.5YR 4/6	very hard	very friable	slightly sticky, plastic
	BC	60–90	strong sub-angular blocky	7.5YR 4/6	very hard	very friable	slightly sticky, slightly plastic
	C	> 90					
Toe slope	A	0–15	strong sub-angular blocky	2.5YR 2/4	very hard	very friable	slightly sticky, slightly plastic
	B	15–65	strong sub-angular blocky	5YR 5/3	Extremely hard	very friable	slightly sticky, plastic
	BC	65–90	strong sub-angular blocky	2.5YR 4/2	very hard	very friable	non-sticky, non-plastic

Source: Author's data from fieldwork

Note: *Colour was determined for wet soil aggregates using the Munsell colour chart

Distribution of pH and pH-Buffer Capacity in Soils

The distribution of soil pH and pH-buffer capacities is presented in Table 3. Mean soil pH in the study area is 5.65 with minimum and maximum values of 4.98 and 6.36, respectively. Consequently, soil reaction ranges from slightly to moderately acidic in A horizons at the summit to upper slope positions. However, at the foot-to-toe slope positions, the soils are moderately to strongly acidic.

This could be due to the leaching of basic cations out of the soil profile as a result of absorption and retention of greater amounts of water from precipitation and overland flow from summit positions. The pH values are, however, within the range observed by Olowolafe (2002) for basement complex soils in the northern guinea savanna. Though Olowolafe (2002) and Fasina and Adeyanju (2006) noted that the low pH values in these soil types could, in addition, be attributed to the acidic nature of the basement complex rocks from which the soils were derived. Also, the highly significant ($P < 0.01$) positive high correlation

(0.812) between pH and organic matter could be attributed to the effect of organic matter in neutralising soil acidity upon release of basic cations to the soil through mineralisation.

Similarly, the ability of soils to resist change in pH is referred to as pH buffer capacity. The values of pH buffer capacity in these soils range from 350.60 to 908.80 with a mean of 571.46 mg kg⁻¹ pH⁻¹. Analysis of these values with the classifications provided by Thomas et al. (2004) indicates that pH buffer capacity in these soils is low. Furthermore, correlation analysis (Table 5) shows a significant ($P < 0.05$) moderate negative correlation (-0.668) between pH buffer capacity and clay content. In contrast, Weil and Brady (2017) noted that finely textured clay soils tend to have greater buffering capacities than coarse-textured soils. The negative correlation of pH buffer capacity with clay content could be due to the presence of low-activity clays in these soils, as the soils are relatively young in profile development.

The low pH buffer capacities observed in these soils imply that plants would experience greater shock from sudden changes in soil pH. A low pH buffer capacity implies that less lime is required to raise soil pH to desirable levels. Lime requirement is the amount of lime (CaCO₃) required to raise an acidic soil's pH to an optimal level (Kissel and Sonon, 2014). Figure 6 shows the amount of lime (CaCO₃) per kilogram of soil that would be required to raise soil pH to 6.5 in the study area. The lime requirement is a function of soil pH and pH buffer capacity (Kissel and Sonon, 2014).

Table 2: Physical soil characteristics of the study area

Slope Position	Location	Horizon	Depth	Bulk Density	Clay	Silt	Sand	Gravel	Textural Class
Summit	10.070100° N, 8.914970° E	Ap	0–10	1.32	18	16	66	39	Very gravelly sandy loam
		AC	10–25	2.09	22	10	68	37	Very gravelly sandy clay loam
		C	>25	nd	nd	nd	nd	nd	nd
Back slope	10.070010° N, 8.915360° E	A	0–26	1.39	16	12	72	48	Very gravelly sandy loam
		R	>26	nd	nd	nd	nd	nd	nd
Foot slope	10.070580° N, 8.916260° E	A	0–12	1.34	14	22	64	11	Sandy loam
		B	12–60	1.73	26	12	62	7	Sandy clay loam
		BC	60–90	1.79	30	14	56	10	Sandy clay loam
		C	>90	nd	nd	nd	nd	nd	nd
Toe slope	10.070790° N, 8.924550° E	A	0–15	1.86	26	26	48	10	Sandy clay loam
		B	15–65	1.97	44	14	42	38	Very gravelly clay
		BC	65–90	1.69	26	12	62	48	Very gravelly sandy clay loam

Source: Author's data obtained from laboratory studies

Note: nd = not determined; Units of depth = cm; bulk density = g/cm³; clay silt, sand, gravel, organic matter = %

Table 3: Selected chemical soil properties of the study area

Slope Position	Location	Horizon	Depth	Bulk Density	Clay	Silt	Sand	Gravel	Textural Class
Summit	10.070100° N, 8.914970° E	Ap	0–10	1.32	18	16	66	39	Very gravelly sandy loam
		AC	10–25	2.09	22	10	68	37	Very gravelly sandy clay loam
		C	>25	nd	nd	nd	nd	nd	nd
Back slope	10.070010° N, 8.915360° E	A	0–26	1.39	16	12	72	48	Very gravelly sandy loam
		R	>26	nd	nd	nd	nd	nd	nd
Foot slope	10.070580° N, 8.916260° E	A	0–12	1.34	14	22	64	11	Sandy loam
		B	12–60	1.73	26	12	62	7	Sandy clay loam
		BC	60–90	1.79	30	14	56	10	Sandy clay loam
		C	>90	nd	nd	nd	nd	nd	nd
Toe slope	10.070790° N, 8.924550° E	A	0–15	1.86	26	26	48	10	Sandy clay loam
		B	15–65	1.97	44	14	42	38	Very gravelly clay
		BC	65–90	1.69	26	12	62	48	Very gravelly sandy clay loam

Source: Author's data from laboratory studies

Table 4: Soil productivity and erosion risk index of the study area

Slope Position	Location	Horizon	Depth	Bulk Density	Clay	Silt	Sand	Gravel	Textural Class
Summit	10.070100° N, 8.914970° E	Ap	0–10	1.32	18	16	66	39	Very gravelly sandy loam
		AC	10–25	2.09	22	10	68	37	Very gravelly sandy clay loam
		C	>25	nd	nd	nd	nd	nd	nd
Back slope	10.070010° N, 8.915360° E	A	0–26	1.39	16	12	72	48	Very gravelly sandy loam
		R	>26	nd	nd	nd	nd	nd	nd
Foot slope	10.070580° N, 8.916260° E	A	0–12	1.34	14	22	64	11	Sandy loam
		B	12–60	1.73	26	12	62	7	Sandy clay loam
		BC	60–90	1.79	30	14	56	10	Sandy clay loam
		C	>90	nd	nd	nd	nd	nd	nd
Toe slope	10.070790° N, 8.924550° E	A	0–15	1.86	26	26	48	10	Sandy clay loam
		B	15–65	1.97	44	14	42	38	Very gravelly clay
		BC	65–90	1.69	26	12	62	48	Very gravelly sandy clay loam

Source: Author's data from laboratory studies

Note: ERI = erosion risk index; SG = slope gradient; SP = slope position; depth in cm, PI = Soil Productivity Index, C = potential fertility of horizon i, K = weighting factor of the respective horizon, α = soil runoff potential factor, η = terrain/slope factor.

Table 5: Correlation between pH and pH-buffer capacity (pH-BC) with selected soil properties

	Clay	Silt	Sand	OM	pH
pH	–0.361	0.166	0.244	0.812*	–
pH-BC	–0.668*	0.391	0.406	0.221	0.151

Source: Author's data from laboratory studies

Note: *Correlation is significant ($p < 0.05$)

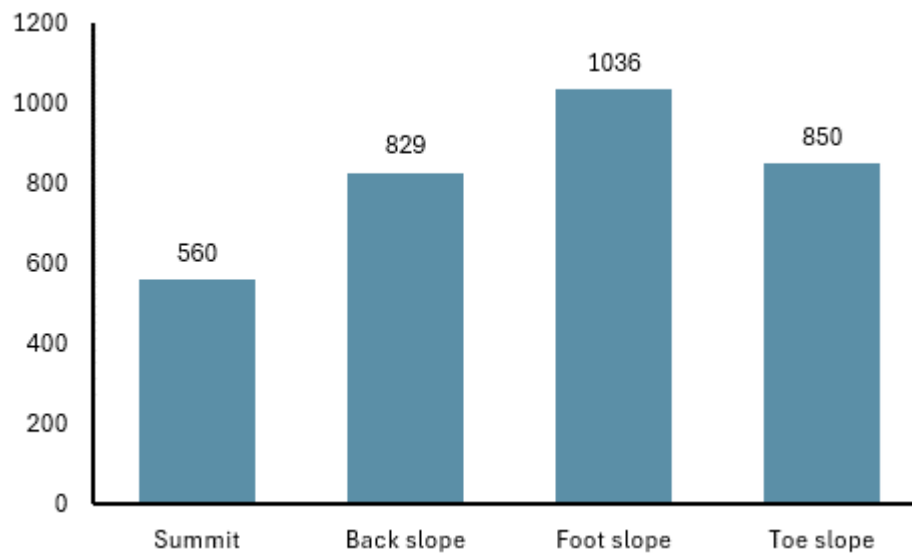


Figure 6: Lime requirement (mg/kg) for surface soils of the study area

Source: Author's data from laboratory studies

Organic Matter, Nitrogen and Soil Productivity

Organic matter levels in this soil are high and range from 3.98 to 5.75% in the surface and subsurface soils. Similarly, nitrogen levels are at moderate levels. High organic matter levels are usually uncommon in the Northern Nigerian Guinea savanna soils, although Olowolafe (2002) reported higher levels of organic matter content in soils derived from basalt. The high levels of organic matter observed in these soils is most likely due to low anthropogenic influence as these soils have just been into cultivation in the last 3 years before the commencement of soil sampling. It has been noted that continuous cultivation leads to rapid loss of organic matter as a result of oxidative processes (Weil and Brady, 2017).

At the toe slope position, organic matter was observed to increase with soil depth. This may not be unrelated to the influence of cycles of deposition of soil material eroded from upper slope positions. These cycles of deposition could either have deposited eroded organic materials at the initial state of soil development or as soil development proceeded, sediments could bury the initial soil at the surface. Hoffmann et al. (2013) observed that hillslopes represent significant source areas for sediment and organic carbon, with considerable amounts of sediment being stored at the base of hillslopes. Additionally, Doetterl et al. (2016) noted that organic carbon within soil may be buried by sediments in depositional areas. According to Berhe and Kleber (2013), "with successive erosion, previously eroded soil organic matter in lower-lying depositional settings tends to get buried by each event and is rendered less accessible and thus, less likely to become decomposed in deeper soil profiles of the depositional environments."

Parameters for soil productivity and erosion risk are presented in Table 4. The results show that the soil productivity index (PI) is highest at the toe slope position (PI = 0.97), whereas the back slope position shows the lowest PI value (PI = 0.22). At the toe slope, PI was mainly affected by the occurrence of shallow soils (subfactor B as a function crop root exploratory capacity). The rate of change in soil productivity, as indicated by variations in PI values per unit of soil eroded by erosion, is what determines the susceptibility of soil erosion. Similarly, Mandal et al. (2021) found that soil quality, productivity index, accessible nutrient status, field water capacity, and soil biological characteristics all decreased as the phases of erosion increased. Table 4 displays variables for estimating ERI. Slope gradient and rainfall aggressiveness (Fournier

Index) had a significant impact on the erosion risk. This is consistent with observations that were made by Asempah et al. (2024) in a study of a tropical savannah landscape. It was found that the locations with the highest erosion risk were mostly those with steep slopes.

CONCLUSION

Soil development in the study area has been largely influenced by topographic characteristics and granitic geology. The findings of this study indicate that, given specific topographic characteristics, there is potential for soil development at summit and back slope locations even in regions characterised by granitic geology. Consequently, this has resulted in the development of Entisols on summit to back slope positions. Furthermore, the soil productivity index was highest and lowest on toes and back slope positions, respectively. The soil has relatively high organic matter and nitrogen levels essential for crop production. However, the soil of the study area is moderately to strongly acidic on average. Furthermore, pH-buffer capacities are low. Also, for soils of the study area, lime should be applied at the rates of 497.79, 690.69, 908.80, and 796.95 mg/kg for surface soils of the summit, back slope, foot slope and toe slope positions, respectively. To ensure sustainable crop production on these soils, management practices involving conservation tillage, biochar application and organic fertilisation would help maintain soil pH at safe levels while also ensuring improved crop productivity. Also, reducing the intensity of cultivation on the summit to back slope positions would help maintain soil productivity in the long term. One significant limitation of this study was the lack of mineralogical analysis, which would have provided further insight into soil development in the research area. Hence, further research, especially at the foot slope and toe slope positions, is recommended to identify diagnostic horizons and for appropriate classification of soils. The purposive sampling technique employed for this study may introduce statistical bias; as such, results may not be easily generalised to an entire unmapped region.

CONFLICT OF INTEREST

The authors declare no conflicts of interest concerning the research, authorship, and publication of this article.

ETHICAL COMPLIANCE

The authors have followed ethical standards in conducting the research and preparing the manuscript.

DECLARATION OF FUNDING

This research did not receive any specific funding.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

The authors confirm that no generative AI or AI-assisted technologies were utilised in the writing, data analysis, or visual creation phases of this manuscript, except occasionally to check for basic grammar and spelling using standard Microsoft Word spell-check or associated Copilot features.

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