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Original Research Article

Assessment of the impacts of toposequence on soil properties and quality in Tula, Gombe State, Nigeria

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Abstract

Soil erosion and a decline in fertility are influenced by insidious topography, which results in the problem of food insecurity in developing countries. Tula is a slope terrain, thus, prone to soil degradation due to continuous cultivation, hence the need to assess soil variability and quality to guide on suitable management practices to adopt across the slope classes. Hence, this study was conceived to assess the effect of toposequence on soil properties and quality in Tula, Gombe state Nigeria. Three slope classes were selected (upper, middle and lower slope). Soil samples were collected from each slope class at depths of 0–15 cm and 15–30 cm and analysed for soil physical and chemical properties using standard procedures. The results show that the soil texture varies from loamy sandy to sandy. The bulk density ranges from 1.02 to 1.12 $mg.cm^{-3}$ and were rated medium at <1.6 $mg.cm^{-3}$. Soils on the lower slope were significantly ($p < 0.05$) higher in soil pH. The soils were generally slightly acidic to neutral. Soil organic carbon was medium in the upper and lower slopes (>10 $mg.kg^{-1}$), while the middle slope was low. The exchangeable bases were rated medium to high across the slope. The soils in the upper slope were of high quality (17 = SQ1), soils in the lower slope were moderate in quality (22 = SQ2) due to low effective cation exchange capacity, and soils in the middle slope were poor in quality (26 = SQ3) due to low soil nutrients. The implication to farmers is that crop grown on upper and lower slope will grow better than those on middle slope due to variations in nutrients. The middle slope was more afflicted by denudation processes because its steep slopes favour erosion. In conclusion, our data show that soil nutrient and quality varies across slope classes and different management practices should be adopted based on slope classes for sustainable crop production. Farmers are therefore advised to add more organic manure and crop residues as well as practice terrace farming on the middle slope for sustainability.

Keywords: food security; sustainability; soil characteristics; texture; exchangeable bases; carbon; slopes; topography; Kaltungo.

INTRODUCTION

Climate, parent material, topography, and biotic factors influence soil variation (Takoutsing et al., 2017). However, a large proportion of the local soil variation can be attributed to land use and topography rather than climate and parent material (Hu et al., 2019). A toposequence is a variation in soil properties mainly due to differences in topography, whereas climate, organisms, parent materials and time remain constant (Brady and Weil, 2007). Topography influences the morphological, physical and chemical properties of soil (Jimoh et al., 2020). This gives rise to a succession of soils from the hilltop to the valley bottom known as catena (Aweto and Enaruvbe, 2010). Topography affects the pattern of soil distribution over landscapes even when the soils are derived from the same parent material (Hu et al., 2019). The variation in soils along topography leads to very shallow and gravelly soils on hills or steep slopes due to the minimal rate of weathering and high removal of soil by erosion, whereas soil on gentle slopes allows ample infiltration of water and develops into deep profiles (Moeslund et al., 2013). Previous studies also reported the influence of topography on soil texture, organic carbon (OC) and cation exchange capacity (CEC) in soils of Africa (Awato and Enaruvbe, 2010; Tellen and Yerima, 2018). This study area is characterised by rolling topography, and soil properties will vary due to the factor of slope, which will play a vital role in influencing soil properties as one moves from the upper slope position down to the lower slope. There are complex relationships among topographic positions; land usage, and soil quality is usually site specific. Therefore, it is very important to understand the dynamics and distribution of soil properties, which are decisive factors in assessing land use and management for sustainability (Jimoh et al., 2020; Sadiq et al., 2021). For sustainable utilisation and proper management of soils, understanding their properties and their variation is very important. Gombe State has poor soil data required for providing management practices to attain food security. Previous studies (Ibrahim and Umar, 2012; Abba et al., 2016; Jimoh et al., 2019) have focused on the assessment of soil properties under varying land uses and management practices and their suitability for crop production. To the best of our knowledge, research on the impact of toposequences on soil quality is a novel area to combat the rapid rate of soil loss and decline in its fertility, thereby striving to ensure food security in developing countries. Therefore, knowledge of the characteristics of soils at different slope positions is required for effective land use management for crop production on a topographic landscape. Assessment of the relationships between slope classes and soil properties is of great significance in the Tula area due to its distinct variation in topography. This research hypothesises that there are no significant differences in soil properties and quality within the toposequence. The aim of this study is to assess the effect of toposequence on soil properties and quality in Tula, Gombe State, Nigeria.

MATERIAL AND METHODS

Study area

Tula is located in the Kaltungo Local Government Area of the Gombe State covering latitudes11°75′55″ to 19°34′48″ N and longitudes 11°59′34″ to 11°34′60″ E (Figure 1); within the plateau area with an elevation of

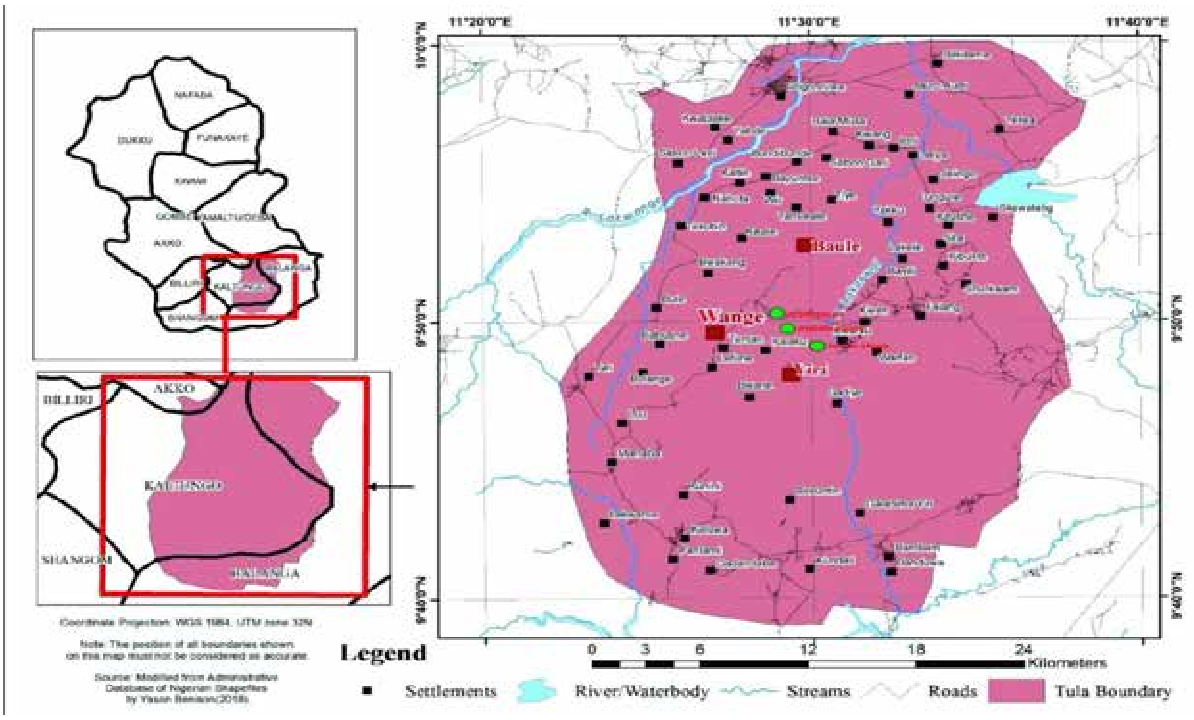

Figure 1. Map of the study area showing the sample points

645 m above sea level. The climate of the study area according to the Köppen climatic classification is within the AW type of climate. It is seasonally wet and dry, having an average annual rainfall regime ranging from 850 to 1200 mm over a period of three decades (Yusuf and Yahaya 2017). The rainfall is concentrated in the months of May and October, with a single maximum in July/August (Balzerek et al., 2003). The soils are developed on crystalline basement complex bedrock. Sedimentary formation underlies most of the area during the Late Cretaceous period, which has influenced the topography of the area. The soils and vegetation in Tula differ from those of surrounding areas due to the nature of the topography. The vegetation of the study area comprises a light close canopy, with spindling of under shrubs and sparse growth of grasses to a more open grass lessee's height as a result of the presence of scattered rocks around the area. Some of the major tree species in the study area include *Acacia* spp., *Anogeisus leiocarpus, Entanda africana, Prosopsi safricana, Vitex doniana, Vitaleria paradoxum, Khaya senegalensis,* and *Parkiabi globosa*.

An undulating terrain was selected for the purpose of assessing the impact of topography on soil properties and quality in the study area. The upper, middle and lower slopes were marked using the ranging poles at intervals of 30 m along each slope class. Each slope class was subdivided into two (2), making a total of six (6) subclasses. Soil samples were collected from 0–15 cm and 15 – 30 cm in the six (6) subclasses, making a total of twelve (12) soil samples. The soil samples collected from each slope class at 0 – 15 cm were mixed thoroughly together as well as those at 15–30 cm to obtain a composite sample. Thus a total of six (6) samples were taken for laboratory analysis.

Soil quality was assessed based on the soil quality index by Parr et al. (1992). Soil quality indicators selected as the minimum data set include soil functions such as support for plant growth, i.e., gravel contents, bulk density (BD), soil reaction (pH), total nitrogen (TN), and available phosphorus (Avail P). Organic carbon (OC) is an indicator of biological activity in the soil. Indicator ratings were divided into three groups: more is better were applied to TN, Avail P and OC, while less is better were applied to bulk density, gravel content, and exchangeable sodium percentage (ESP), and optimum is better was applied to pH (Andrews and Carroll, 2001). Soil quality was assessed using the Parr et al. (1992) equation:

$$SQ = f\,(SP, P, E, H, ER, BD, FQ, MI) \qquad (1)$$

where:
SQ = soil quality, SP = soil properties, P = potential productivity, E = environmental factors, H = health (human/animal), ER = erodibility, BD = biodiversity, FQ = food quality and MI = management input.

A score scale of 1 to 3 was used in the assessment of parameters in the model, where 1 is the best and 3 is the worst condition. However, P, E, H, ER, FQ and MI were each scored 1.0 because the field used had being optimally managed to satisfy optimal environmental conditions for sustainability, health factors for human and livestock optimal food quality obtained, biodiversity and input management (Odunze et al., 2019).

Therefore,
SQ = f (SP) was used to assess the quality of soils (2)

Laboratory analyses

The sampled soils were air-dried, crushed and sieved through a 2 mm sieve, and less than 2 mm fractions were used for laboratory analysis. The particle size distribution was determined by the hydrometer method (Gee and Bauder, 1979). Bulk density was determined using the core method (Blake and Hartge, 1986). Soil pH was measured in water and 0.01 M $CaCl_2$ (1:2.5 w/v) using a glass electrode pH meter. Organic carbon was determined by the dichromate wet oxidation method of Walkley and Black (Nelson and Sommers, 1982). Available P was determined using the Bray 1 method (Agbenin, 1995). TN was determined by the Kjeldahl method (Agbenin, 1995). Exchangeable bases (calcium, magnesium, potassium and sodium) in the soil were determined using ammonium acetate extract. Sodium and K in the extract were determined using a flame photometer, whereas Ca and Mg were determined using an atomic absorption spectrometer. The effective cation exchange capacity (ECEC) was determined by the summation method (Agbenin, 1995). Base saturation was calculated as a percentage of the sum of total exchangeable bases divided by effective cation exchange capacity, and electrical conductivity (ECe) was determined by the Wheatstone bridge method (Agbenin, 1995).

Data analysis

The data collected were subjected to analysis of variance (ANOVA) to assess variation in soil properties along the toposequence. Duncan's multiple range test was used for mean separation at the 0.05 level of significance in the Statistical Package for Social Science (SPSS) software, version 23.

Table 1. Mean Soil Properties along Tula Topography

Parameters	Gravel	Sand	Silt	Clay	BD	pH	pH	ECe	OC
Locations	%	------------g kg^{-1}------------			Mg cm^{-3}	(water)	($CaCl_2$)	dS m^{-3}	mg kg^{-1}
US	46.10	82.5	6.6	11.00	1.02	6.56b	6.29ab	0.20	13.62
MS	47.20	83.5	6.5	10.00	1.12	6.73ab	6.23b	0.16	8.85
LS	47.20	85.5	8.0	6.50	1.19	6.97a	6.49a	0.27	10.50
P-value	0.99	0.052	0.696	0.181	0.33	0.02	0.05	0.41	0.37
LOS	NS	NS	NS	NS	NS	*	*	NS	NS
SE+	3.18	0.6	0.68	1.04	0.04	0.07	0.06	0.07	2.90
Depth									
Surface	42.10	83.00	8.33	8.00	1.06	6.74	6.35	0.22a	12.78a
Subsoils	51.00	84.00	5.66	10.33	1.15	6.77	6.32	0.20b	9.19b
P-value	0.153	0.69	0.15	0.36	0.09	0.07	0.12	0.01	0.01
LOS	NS	NS	NS	NS	NS	NS	NS	**	*
SE+	36.37	1.33	0.74	2.02	0.08	0.09	0.06	0.03	1.11

Means followed by different letter(s) are significant at the 5% level of probability
BD = Bulk density, ECe = electrical conductivity, OC = Organic carbon, US = upper slope, MS = middle slope, LS = lower slope, LOS = level of significance, NS = not significant, * = $p < 0.05$, ** = $p < 0.01$, SE = standard error

RESULTS

Physical properties

Gravel content increased down the toposequence. Subsoils were higher in gravel content than surface soils (Table 1). Sand dominated the soil particle size in the study area. The values of sand and silt increase down the toposequence, similar to the gravel content pattern of distribution, while clay content shows an irregular distribution as values increase from the crest to the middle slope but decrease from the middle to the lower slope. Subsoils were higher in clay content than surface soils. The soil texture varied from loamy sandy on the upper slope to sand on the middle and lower slopes. There was no significant difference in bulk density across the slope classes (Table 1).

Chemical properties

Soils on the lower slope were significantly ($p < 0.05$) higher in soil pH than other slope classes. The soil pH value was relatively low in the surface soil and higher in

Table 2. Ranking of Mean Soil Properties along Tula Topography

Parameters	TN	AP	Ca	Mg	K	Na	H+Al	ECEC	BS
Locations	g/kg	mg/kg	--------------------- cmol(+)kg^{-1}-----------------------						%
US	0.74	58.84	5.00	9.11a	0.20	0.38	0.7a	16.35	89.8b
MS	0.56	34.70	6.36	7.85b	0.12	0.42	0.4b	15.65	94.2a
LS	0.88	102.20	3.81	8.25a	0.22	0.43	0.8a	13.90	91.4ab
Pvalue	0.76	0.17	0.28	0.04	0.18	0.54	0.03	0.24	0.05
LOS	NS	NS	NS	*	NS	NS	*	NS	*
SE+	0.41	26.54	1.29	0.26	0.04	0.04	0.08	1.15	1.37
Depth									
Surface	0.98a	69.76a	5.43a	8.29	0.19a	0.40	0.67	15.7a	91.25
Subsoils	0.46b	60.72b	4.67b	8.52	0.16b	0.41	0.60	14.9b	92.35
Pvalue	0.00	0.00	0.01	0.07	0.02	0.24	0.32	0.00	0.42
LOS	***	***	**	NS	*	NS	NS	***	NS
SE+	0.09	6.67	0.67	0.27	0.03	0.02	0.09	0.63	2.00

Means followed by different letter(s) are significant at the 5% level of probability, TN = total nitrogen, AP = available phosphorus, Ca = calcium, K = potassium, Na = sodium, H+Al = acidity, ECEC = effective cation exchange capacity, BS = base saturation, US = upper slope, MS = middle slope, LS = lower slope, LOS = level of significance, NS = not significant, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, SE = standard error the subsoil (Table 1). The soil pH in $CaCl_2$ was generally lower than the pH in water in the study area. Electrical conductivity values were higher in the lower slope position, followed by the upper slope, while the middle slope recorded the lowest value. Surface soils were significantly ($p < 0.05$) higher in ECe than subsoils. Soil organic carbon (OC) was irregularly distributed along the toposequence, and surface soils were significantly ($p < 0.05$) higher than subsoils (Table 1). The mean total nitrogen values in the lower slope recorded the highest value relative to other slope classes (Table 2). Surface soils were significantly ($p < 0.01$) higher in TN than subsoils. Available phosphorus (Avail P) on the lower slope recorded the highest values, followed by upper slope and middle slope, with the lowest values similar to OC and TN (Table 2). Exchangeable Mg on the upper slope recorded the highest values when compared to other slope classes (Table 2). Subsoils were higher in exchangeable Mg than surface soils. Surface soils had significantly ($p < 0.001$) higher calcium concentrations than subsoils. Further, surface soils had significantly ($p < 0.05$) higher potassium contents than subsoils. The effective cation exchange capacity (ECEC) value decreases from the upper slope down to the lower slope. Surface soils were significantly ($p < 0.05$) higher in ECEC than subsoils. The percentage base saturation (PBS) for the middle and lower slope soils were significantly ($p < 0.05$) higher than that for the upper slope classes. The PBS values increased with soil depth, as subsoils were higher than surface soils.

Soil quality

The soil quality results showed that soils on the upper slope recorded a score of 17, followed by soils on the lower slope with 22, and soils on the middle slope with

Table 3. Soil Quality Ranking Index by Parr

Parameter	Units	Upper slope	Middle slope	Lower slope
Gravel	%	46.10 (1)	47.20 (2)	47.20 (2)
Bulk Density	Mg/kg	1.02 (1)	1.12 (2)	1.18 (3)
pH H_2O		6.56 (3)	6.73 (2)	6.97 (1)
OC	mg/kg	13.62 (1)	8.85 (3)	10.49 (2)
Avail. P	mg/kg	58.84 (2)	34.69 (3)	102.2 (1)
TN	g/kg	0.74 (2)	0.56 (3)	0.87 (1)
Ca	mg/kg	5.00 (2)	6.36 (1)	3.81 (3)
Mg	mg/kg	9.11 (1)	7.85 (3)	8.25 (2)
ESP	%	2.29 (1)	2.68 (2)	3.06 (3)
K	mg/kg	0.19 (2)	0.12 (3)	0.22 (1)
ECEC	mg/kg	16.35 (1)	15.65 (2)	13.9 (3)
Total/Rank		**17/1**	**26/3**	**22/2**

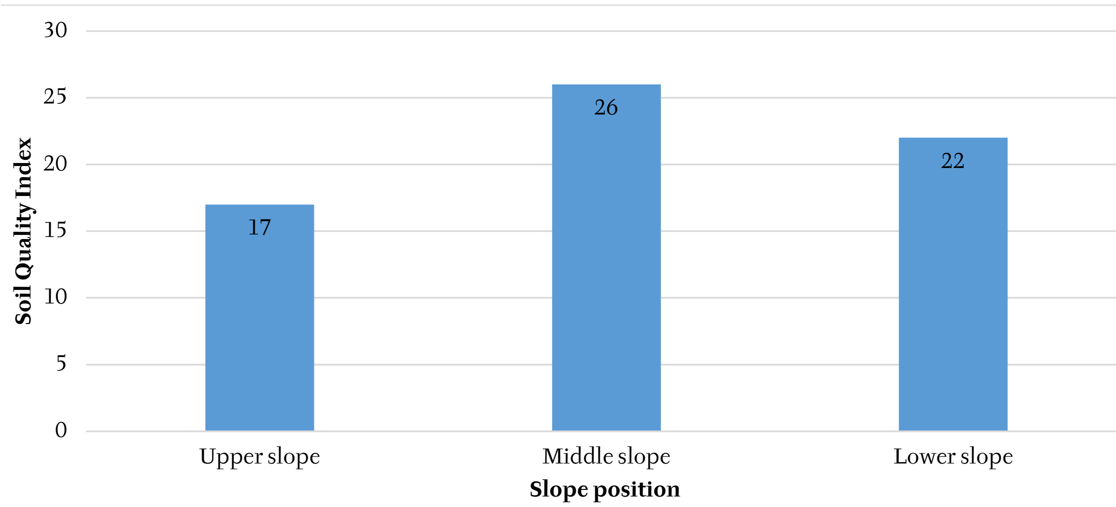

Figure 2. Variation in the soil quality index along the toposequence in Tula.
Note: the lower the quality index is, the better the soil quality

26 (Table 3 and Figure 2). In Par's soil quality evaluation, the lower the quality index is, the better the soil quality.

DISCUSSION

Soil physical properties

The high sand content, which dominates the particle size fractions of the soils, could be attributed to sedimentary formation of the underlying geology and its high quartz content (Wilson, 2010). This corroborated Jimoh et al. (2019), who also reported high sand content in soils of Gombe. Bulk density values were rated medium and were less than 1.60 mg cm^{-3} and will support root growth and development (Odunze and Kureh, 2009). Bulk density, which increased down the topography, supports the result of Hu et al. (2019), who also reported higher BD in soils of flat valley positions. The higher BD in the lower slope could be attributed to the higher silt content due to the transportation of fine materials from the upper slope, tramping and continuous cultivation (Odunze et al., 2019).

Chemical properties

The soil pH value was rated slightly acidic in the surface soil and neutral in the subsoil. Higher pH values in subsoils could be attributed to leaching of basic cations (Sadiq et al., 2021). The lower slope that recorded the highest mean pH value corroborated Seifu et al. (2020), who also reported higher soil pH at lower elevations and attributed it to the accumulation of basic cations at landscape positions. The lower soil pH at the upper slope could be due to soil erosion, intensive cultivation, and free open grazing pressure. Soil electrical conductivity was rated low across the toposequence as values were less than 4 dS m^{-1}. The low value of ECe in the middle slope could be attributed to active erosion, which tends to carry away soil materials from the upper and middle slopes down to the lower slope. The higher ECe values on the lower slope could be attributed to the erosion, transportation and deposition of salts from the upper and middle slopes. Similarly, higher ECe values in lower slope positions in soils of Ethiopia were reported by Seifu et al. (2020). The higher ECe in surface soils than in subsoils could be attributed to the accumulation of salts brought to the surface by the capillary movement of water as a result of evaporation and subsequent deposition of salts on the soil surface (Jimoh et al., 2020). Soil organic carbon in the upper and lower slopes were both rated medium as their values were higher than 10 g/kg, while the middle slope was rated low as less than 10 g/kg. The low content of organic carbon in the middle slope could be attributed to the steep slope terrain of the site, which supported the erosion of soils in the surface, resulting in the loss of organic carbon. The values of organic carbon reported in all slope classes were higher than the 7.0 $g \cdot kg^{-1}$ reported by Jimoh et al. (2019) in soils under date plantation in Gombe. The low content of OC in the soils could be due to bush burning, continuous cultivation and overgrazing, which destroy organic materials that would have contributed to soil organic matter. The higher OC in the upper and lower slopes corroborated Hu et al. (2019) and Seifu et al. (2020), who also reported higher OC in the lower slope position, which was attributed to the erosion process that transported organic humus and fine particles from the upper slope with runoff water and accumulated at the lower slope. The low value of total nitrogen could be ascribed to the influence of continuous cultivation, crop residue removal, bush burning and low levels of N fertiliser application (Elias and Agegnehu, 2020). Hu et al. (2019) and Seifu et al. (2020) also reported higher TN in lower slope positions and were attributed to the erosion process that transports organic humus, a major source of nitrogen. Organic carbon in the soils was reported to contribute 95% of the TN content in the soils (Walworth, 2013). Similarly, the higher TN value on the lower slope could be attributed to the low-temperature conditions, which decreased the volatilisation of TN. The low content of TN on the middle slope was attributed to soil erosion, continuous cultivation, plant uptake, and volatilisation (Tolessa and Senbeta, 2018). The slope classes were all rated very high in available phosphorus, and the values were higher than those reported by previous authors (Abba et al., 2016; Jimoh et al., 2019) in their studies at different locations in Gombe State. The higher value of phosphorus in the lower slope could be attributed to erosion and deposition of organic materials from the upper slope and its mineralisation to release more available phosphorus. The higher available phosphorus in the surface soils than in the subsoils could be attributed to the low organic matter in the subsoils. Similarly, Sadiq et al. (2021) also reported that available phosphorus decreased with depth following the organic matter distribution. The decrease in the available phosphorus with depth may be attributed to high contents of sesquioxides, which fix the phosphorus and the acidic nature of the soils (Akpan-Idiok et al., 2013). Seifu et al. (2020) also reported a significant ($p < 0.05$) variation in available phosphorus within topographic position soils of a toposequence in Ethiopia. Exchangeable Mg dominated the exchange site and was rated very high. The dominance of exchangeable magnesium contradicts previous studies by Abba et al. (2016) and Jimoh et al. (2019), who reported the dominance of calcium in soils of Gombe State. The predominance of Mg may be due to the presence of magnesium-bearing parent material in the area. However, the accumulation of Mg in the exchange complex is worrisome, as a high content of Mg may cause deterioration of the soil structure, lower water intake and affect both chemical and biological properties (Garcia-Ocampo, 2003). The higher content of exchangeable Mg in the upper and lower slopes could be attributed to the low erosion of basic cations due to the stable topography compared to the slope terrain of the middle slope, which favours erosion. The lower Ca content in the lower slope position corroborates Oku et al. (2010), who also reported lower Ca values in the lower slope in soils of southeastern Nigeria. The non-significant difference in Na could be attributed to similar parent material. The higher K content in the lower slope could be attributed to the transportation and deposition of soluble K from the upper slope. The higher potassium content in surface soils relative to subsoils could be due to the higher organic carbon in surface soils, which is a reservoir of soil nutrients. Abba et al. (2016) also reported a medium value of K in soils of Gombe, whereas Jimoh et al. (2020) reported that K content in the upper slope increases with depth. They attributed this trend to the leaching of basic cations, while the middle and valley bottom values, which showed a decrease in K content with depth, were attributed to nutrient mining by crop removal and continuous cultivation. The effective cation exchange capacity of the soils was rated high across the toposequence. The high value of ECEC suggests a dominance of 2:1 clay minerals over sesquioxides and kaolinite clay minerals (Chidowe et al., 2014) in the soils. The decrease in ECEC with soil depth could be attributed to nutrient uptake by plants and the decrease in OC with soil depth. Organic carbon is a major reservoir of plant nutrients. Percentage base saturation was rated high as values were greater than 90% in middle and lower slope but medium in upper slope. This corroborates with Jimoh et al. (2019), who also reported higher PBS (> 90%) in soils of Date palm plantation in Gombe.

Soil quality

Generally, soil on the upper slope had no major limitation. This suggests that soils under the upper slope were of high quality for sustainable crop production. The major limitation of soils under the lower slope was slightly high bulk density, low calcium and ECEC content and high ESP content, thus classified as moderate in quality, whereas the major limitation of soils in the middle slope position was low in organic carbon, available phosphorus, total nitrogen, exchangeable magnesium and potassium, thus classified as lowest in quality. The soil developed on the upper slope had moderate gravel and bulk density values and the highest soil organic carbon, exchangeable magnesium and effective cation exchange capacity (ECEC) values compared to the other slope classes and had the lowest score, indicating higher quality and rated SQ1. Lower slope soils had optimal soil pH conditions, and the highest total nitrogen, available phosphorus and exchangeable potassium were moderate in quality and rated SQ2 with a medium aggregate score. Soils on the middle slope position were only higher in exchangeable calcium, moderate gravel, bulk density, pH, and exchangeable sodium percentage (ESP) and low in other soil properties and recorded the highest aggregate score, indicating low quality and rated SQ3. This shows that soil quality varies along the toposequence. Odunze et al. (2019) also reported variation in soil quality, as soils on lower slopes were of higher quality than other slope positions in soils of Afaka forest. The low soil quality observed on the middle slope could be attributed to continuous erosion and cultivation on the steep slope, which resulted in the depletion of soil nutrients over time.

CONCLUSION

The aim of this study was to assess the effect of toposequence on soil properties and quality in Tula, Kaltungo L.G.A Gombe State. The results showed that soils on the upper and middle slopes were loam sandy, whereas lower slope soils were sandy. The soil bulk density within the toposequence was moderate with no hindrance to plant root growth. The lower slope had greater organic content and soil nutrients, making them more fertile, followed by the upper slope, whereas the middle slope had the least amount of soil nutrients. The soils in the upper slope were higher in quality with no major limitation, soils in the lower slope were moderate in quality due to low ECEC content and high ESP, and soils in the middle slope were lowest in quality due to low soil nutrients. Therefore, the soil properties and quality varied along the toposequence as a result of the rolling topography and will require specific management practices.

RECOMMENDATIONS

a) Farmers are advised to apply more organic manure and crop residue as well as practice terrace farming on steep slope areas (middle slope) rather than on gentle slope sites (upper and lower slope).

b) Soil fertility management should focus on lowering the leaching of basic nutrients from soils through mulching, cover crop planting, crop rotation, and zero-tillage adoptions to boost soil fertility on a long-term basis along the whole toposequence to achieve food security.

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CONFLICT OF INTEREST

The author declared no conflict of interest with respect to research, authorship and publication of this article.

ETHICAL COMPLIANCE

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

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