Assessment of Soil Quality Variation under Different Land Use Practices using Principal Component Analysis in Nigeria's Derived Savannah

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Abstract
Soil quality assessment is essential for evaluating agroecosystem sustainability, monitoring soil degradation, and identifying effective land management practices. This study assessed the effects of different land use practices on soil quality in a derived savannah zone of Nigeria. Soil samples were collected from two depths (0–15 cm and 15–30 cm) across four land use types: arable land (AR), cashew plantation (CA), Gmelina plantation (GM), and grassland (GR). Variations in soil quality indicators among land uses and soil depths were analysed, and a minimum data set (MDS) of key indicators was selected using principal component analysis (PCA) to compute the soil quality index (SQI). Results showed that gravel content, sand, silt, total porosity, water holding capacity, exchangeable acidity, and base saturation varied significantly ($P < 0.001$) with the interaction of land use and soil depth. Soil quality was categorized as intermediate ($0.55 < SQI < 0.70$) in AR and high ($SQI > 0.70$) in CA, GM, and GR. The SQI values were 0.581 for AR, 0.712 for CA, 0.820 for GR, and 0.923 for GM. The primary factors limiting soil quality in arable land were low exchangeable bases, organic matter depletion, and increased bulk density. These findings suggest that intensive agricultural activities reduce soil quality, while tree-based and grassland systems promote better soil conditions. Sustainable soil management practices, including proper fertiliser use, organic amendments, and conservation-oriented land use, are recommended to enhance soil quality and long-term productivity in the region.

Keywords: *Soil quality; Minimum data set (MDS); Land use type; Principal component analysis (PCA).*

Introduction
Soil is one of the most essential natural resources supporting agricultural and livestock activities, which are fundamental to global food security (Zhang *et al.,* 2007). Soil quality, defined as the capacity of soil to promote plant and animal productivity while maintaining or enhancing water and air quality, plays a vital role in achieving sustainable land management (Doran, 2002). Understanding soil quality is particularly important in developing countries, where both productivity and sustainability concerns are pressing. Soil quality assessment provides valuable insights for identifying areas of concern, detecting degradation trends, and designing rational soil use and improvement strategies (Bindraban *et al*., 2000; McGrath & Zhang, 2003; Mu *et al*., 2020).

Reliable evaluation of soil quality is essential for designing effective soil management practices that enhance productivity and environmental sustainability. Various methods are available for evaluating soil quality, including soil quality index (SQI) methods, fuzzy association rules, and the soil management assessment framework (Karlen *et al.,* 2008; Wienhold *et al.,* 2009; Xue *et al.,* 2010). Among these, SQI is the most commonly used method due to its simplicity, quantitative flexibility, and applicability. SQI methods can be categorized into three groups: additive index, weighted additive, and decision support vector (Andrews *et al*., 2002).

Soil quality assessment has become increasingly relevant in addressing global challenges such as population growth, climate change, and land degradation. Sustainable land management requires a comprehensive understanding of soil quality dynamics and their relationship with land use practices. Quantifying the extent and rate of soil quality variation under different land use types offers essential insights for developing targeted soil conservation and management strategies. Despite the importance of soil quality assessment in supporting sustainable land use decisions, there remains a paucity of quantitative studies examining soil quality variations across different land use systems within the derived savannah zone of Nigeria.

This study, therefore, aims to assess the impacts of different land use practices on soil quality in a derived savannah ecosystem of Nigeria. By examining soil quality under arable, cashew, Gmelina, and grassland systems, this study contributes to a deeper understanding of how land use practices influence soil quality and productivity. The findings are expected to inform the development of sustainable land management strategies, support efforts to mitigate soil degradation, and enhance long-term agricultural productivity in the region. Moreover, the results will provide valuable guidance for policymakers, land managers, and researchers engaged in soil conservation and sustainable land-use planning.

Materials and methods

Description of the Study Area: The study was conducted at the University of Ilorin, Kwara State, Nigeria. The area is located between latitudes 8°26′ and 8°29′ N and longitudes 4°38′ and 4°40′ E (Figure 1). Ecologically, it lies within a savannah ecotone—a transitional zone between the forest and savannah regions. Geologically, the site is part of the Precambrian Basement Complex of southwestern Nigeria, composed mainly of migmatite-gneiss complexes, quartzites, and granites (Obaje, 2009). The climate is tropical, with distinct wet and dry seasons. The hottest period usually occurs in March, while the coolest is in December. Mean maximum and minimum temperatures range from 28.9–35.8 °C and 19.5–23.5 °C, respectively. Rainfall follows a bimodal pattern, with peaks in June and September (Alao, 2012), and a mean annual total of approximately 1,252 ± 239 mm (Ejieji, 2004).

Soil Sampling: Four land use types [arable land (AR), grassland (GR), Gmelina (GM) and cashew (CA)] were selected for this study. Surface soil samples were randomly collected from five points in three replicates from each land use type at two depths (0–15 cm and 15–30 cm). The samples from each land use at different depths were mixed to obtain a composite sample. Consequently, 24 composite samples were collected from the four land use types (4 land use types x 2 depths x 3 replications). Additional undisturbed soil core samples of known volume were collected from each land use type and sampling depths in three replications for bulk density determination.

Description of Land-Use History: Arable land (AR): The arable land in this study refers to an area previously cleared of natural forest cover through slash-and-burn techniques. It is currently utilized for the cultivation of food crops such as cassava (*Manihot esculenta*), cowpea (*Vigna unguiculata*), and maize (*Zea mays*). These crops are actively grown and harvested, contributing to both local agricultural production and household sustenance. Cashew Plantation (CA): The cashew plot represents land that transitioned from prior cultivation of maize and cassava to the establishment of a cashew (*Anacardium occidentale*) plantation. Cashew trees were deliberately planted to replace the earlier crops, reflecting a strategic shift towards perennial cash crop cultivation. This transition underscores the growing economic significance and potential profitability of cashew production in the region. Gmelina Plantation (GM): Similar to the arable land, the Gmelina plot was created by clearing the natural forest through slash-and-burn practices. However, instead of food crops, *Gmelina arborea* trees were intentionally established on this land. The cultivation of Gmelina reflects a deliberate effort to promote fast-growing tree species valued for timber production, reforestation, and commercial purposes, highlighting the multifunctional role of this land-use type.

Grassland (GR): The grassland area is characterized by an abundance of short grass and a relatively low density of trees. It is a distinct land type with minimal tree cover, primarily dominated by grasses. This land type typically experiences limited tree growth due to environmental factors such as soil conditions, climate, and natural ecological processes. The grassland environment supports grass-dominated ecosystems and represents a distinct land-use class within the study area. The disturbed composite soil samples collected from each land use type were air-dried, mixed well and passed through a 2 mm sieve for the analysis of selected soil physical and chemical properties. The soil samples were analyzed for specific physical and chemical indicators. Soil textural fractions were analyzed using the Bouyoucos hydrometer method (Mwendwa, 2022). Bulk density was measured by the core method (Jabro & Mikha, 2021). The soil's total porosity was estimated from the bulk density data at an assumed particle density of 2.65 g cm^{-3}. Saturated hydraulic conductivity was measured on the core samples by the constant head (Usowicz & Lipiec, 2021).

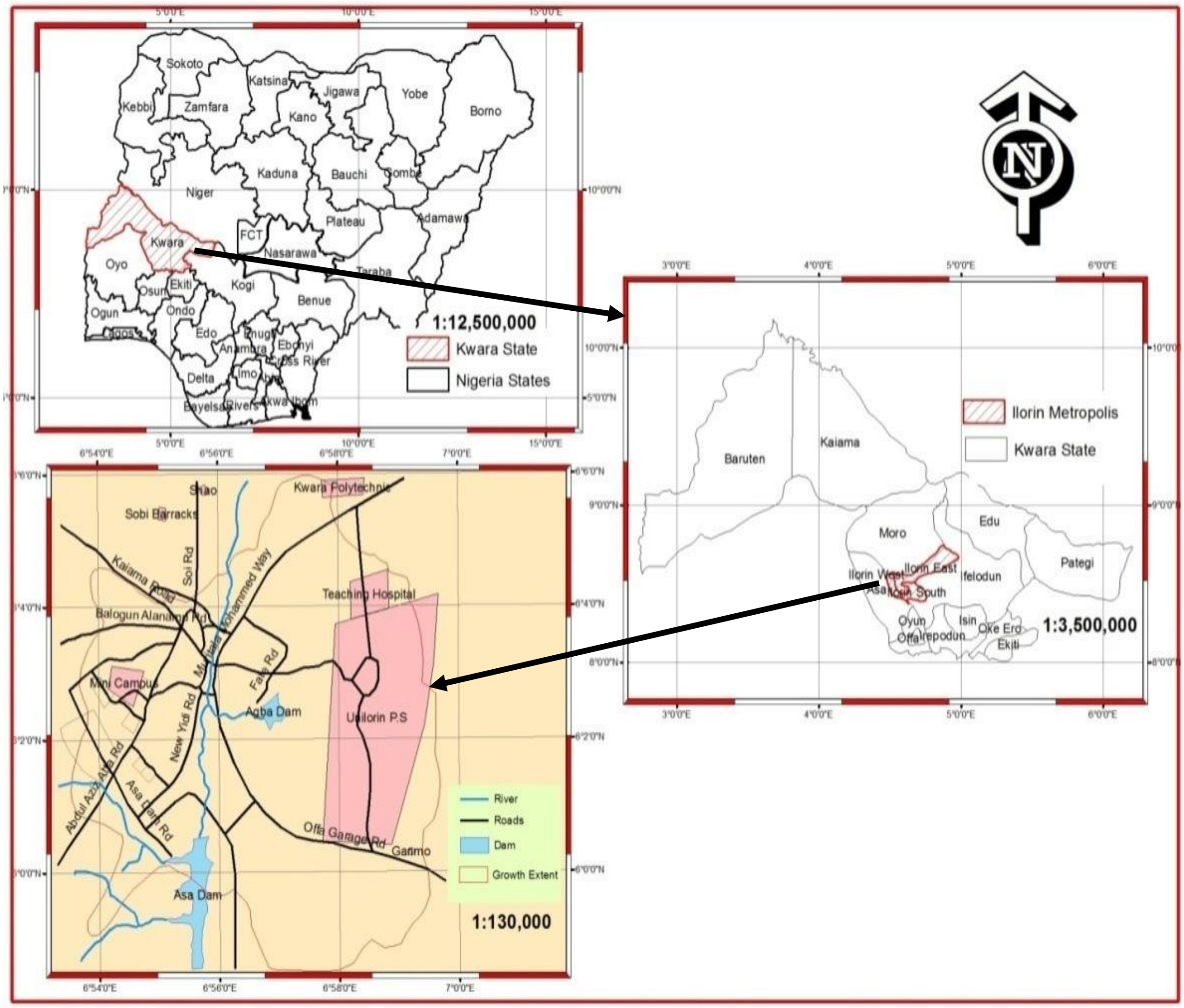

Figure 1: Map of Nigeria showing the location of the study area in Ilorin, Kwara State (source: Ajadi *et. al.,* 2016)

The soil water-holding capacities were determined using the core rings method. Soil pH was determined using a 1:2.5 soil-to-water ratio and then analyzed by a digital pH meter (Takamoto *et al.,* 2023). The total nitrogen content of the soil was determined by the Kjeldahl method (Kalambe, 2021), soil organic carbon was determined by a modified Walkley-Black wet oxidizing method (Alovisi *et al.,* 2024), and soil organic matter (SOM) was calculated by multiplying the percentage of organic carbon by a factor of 1.724. The available phosphorus (P) was determined by the Bray P1 method (Tsadilas *et al.,* 2022). Exchangeable acidity was determined by the KCl extraction method (Singh *et al*., 2023). The exchangeable bases (Ca, Mg, K, & Na) were extracted from the soil using the ammonium acetate method, and the extract was then analyzed for Ca^{2+} and Mg^{2+} by the use of an atomic absorption spectrophotometer, and the K^+ and Na^+ were determined by the use of a flame photometer (Jain & Taylor, 2023). The Cation Exchange Capacity (CEC) was calculated by the summation of exchangeable bases and exchangeable acids. Per cent base saturation was calculated by dividing the sum of the base-forming cations (Ca, Mg, Na, and K) by the CEC of the soil and multiplying by 100.

Soil Quality Index Calculation: A minimum dataset was developed to calculate the SQI. The mean data for each parameter were used. Development of the SQI followed three steps that were described by Andrews *et al.* (2002). **Selection of Indicators in the Minimum Data Set**: A minimum data set (MDS) of indicators was selected through a principal component analysis (PCA), according to the MDS indicator selection procedure described by Andrews *et al.* (2002). Components with eigenvalues ≥1 were considered. However, when more than one variable was retained under a particular PC, a multivariate correlation matrix was used to determine the correlation coefficients between the parameters. If the parameters were significantly correlated ($r > 0.60$, $p < 0.05$), then the one with the highest loading factor was retained in the MDS and all others were eliminated from the MDS to avoid redundancy. **Weight Assignment and Scoring**: Each PC explained a certain amount of variation in the dataset, which was divided by the total variation of all PCs selected for the MDS to get a certain weight value under a particular PC (Andrews *et al.,* 2002). The selected indicators were transformed using Liebig linear scoring. Indicators were ranked in ascending order for "more is better" and descending order for "less is better" in terms of soil functions (Liebig *et al*., 2001). Each "more is better" indicator was divided by the highest observed value in the group, such that the highest observed value received a score of 1. For 'less is better' indicators, the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received a score of 1. For some indicators, observations are scored as 'higher is better' up to a threshold value and as 'lower is better' above the threshold (Mazumdar *et al*., 2014). **Integration into an Index**: The third step involved the multiplication of transformed indicators by their weight. The results were summed to calculate the SQI (soil quality index).

$$SQI = \sum_{i=1}^{n} W_i S_i \qquad 1$$

Where SQI is the soil quality index, W_i is the weighting factor equal to the ratio of the variance of each PC to the total cumulative variance, and S_i is the scored value of each soil quality indicator.

The SQI was then divided into three grades according to Marzaioli *et al*. (2010): SQI < 0.55 was regarded as low soil quality, 0.55 < SQI < 0.70 was regarded as intermediate soil quality and SQI > 0.70 as high soil quality.

Statistical Analysis: Land use types and soil depth were used as independent variables (factors), and the soil parameters as dependent variables. Statistical differences between the values for the various parameters of land use type and soil depth were tested by two-way analysis of variance (ANOVA) using GenStat software. Duncan's Multiple Range Test (DMRT) was used for mean separation when the analysis of variance showed statistically significant differences ($p < 0.05$). The Principal Component Analysis (PCA) was performed using SPSS software, and Microsoft Excel was used to calculate the soil quality index (SQI).

Results and Discussion

The soil textural fractions of sand, silt, and clay significantly ($p < 0.05$) varied with land use types (Table 1) and the interaction effect was significant ($p < 0.001$) for sand and silt fractions (Table 2). Significantly higher sand content was recorded in grassland, while the highest silt content was in soils under Gmelina and arable. In the studied soil, the clay fraction was less than 100 g kg^{-1} across all land use types and soil depths. Concerning land use types, however, the mean clay fraction was significantly ($p < 0.05$) lower (50.40 g kg^{-1}) under Gmelina, although not significant, but the clay fraction increased with increasing depth, and this might indicate possible clay translocation from the top layer to the layer below (Chesworth 2008). The increase in clay fraction with increasing depth and the lowest overall mean proportion of clay fraction compared to the sand and silt fractions concurs with the findings of Yimer *et al.* (2006). The gravel content was significantly ($p < 0.001$) affected by the land use, soil depth and interaction among them. On average, the highest (271.00 g kg^{-1}) gravel content was recorded in grassland at 15-30 cm, while the lowest (42.30 g kg^{-1}) was recorded at 15 – 30 cm in arable land. It increases with depth in all the land use except for the arable land, which decreases with depth.

Table 1: Main effects of land use and soil depth on physical soil quality indicators

Treatment	Gravel (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Total Porosity (%)	WHC (%)	BD (g cm^{-3})	Ksat (cm/s)
Land use (L)								
Arable	58.90d	869.60c	70.00a	60.40a	42.16c	36.16c	1.54a	0.0045d
Cashew	97.20c	879.60b	50.00b	70.40a	48.69a	43.30b	1.36a	0.0170a
Gmelina	144.50b	879.60b	70.00a	50.40b	44.09b	47.56a	1.48a	0.0065c
Grassland	266.20a	899.60a	30.00c	70.40a	39.70d	30.51d	1.59a	0.0130b
SED	0.920	0.534	0.534	0.534	0.534	0.534	NS	0.0014
Soil depth (D)								
0-15 cm	123.90b	884.60a	55.00a	60.40a	46.66a	43.29a	1.41a	0.0105a
15-30 cm	159.60a	879.60a	55.00a	65.80a	40.66b	35.47b	1.57a	0.0100a
SED	0.651	NS	NS	NS	0.377	0.377	NS	NS
Interaction								
L*D	**	**	**	NS	**	**	NS	NS

NS: Not significant at $P \leq 0.05$, **: significant at $P < 0.001$. WHC: Water-holding capacity, Ksat: saturated hydraulic conductivity, BD: bulk density.

Table 2: Interaction effects of land use and soil depth (cm) on soil physical properties
WHC: Water-holding capacity

Land use type	Sand (g kg^{-1})		Silt (g kg^{-1})		Gravel (g kg^{-1})		WHC (%)		Total porosity (%)	
	Soil depth (cm)		Soil depth (cm)		Soil depth (cm)		Soil depth (cm)		Soil depth (cm)	
	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
Arable	889.60b	849.60c	60.00c	80.00b	75.60d	42.30e	35.61c	36.71c	44.66c	39.67e
Cashew	849.60c	909.60a	80.00b	20.00e	83.50d	111.00c	54.53a	32.06d	51.35b	46.02c
Gmelina	909.60a	849.60c	40.00d	100.00a	75.00d	213.90b	53.21a	41.92b	53.75a	34.43g
Grassland	889.60b	909.60a	40.00d	20.00e	261.50a	271.00a	29.81e	31.21d	36.86f	42.53d
SED	0.755		0.755		1.302		0.755		0.755	

The mean bulk density did not show any significant differences for land use types, soil depth and their interactions ($p > 0.05$). The mean soil bulk density across the different land use types ranges from 1.36 g cm^{-3} in cashew to 1.59 g cm^{-3} in grassland. The relatively higher bulk density observed under grassland (1.59 g cm^{-3}) and arable land (1.54 g cm^{-3}) compared with cashew (1.36 g cm^{-3}) and Gmelina (1.48 g cm^{-3}) suggests possible compaction resulting from human and animal activities, as well as reduced organic matter input. Conversely, the relatively lower bulk density recorded under cashew and Gmelina could be attributed to the continuous addition of organic residues from leaf litter on the soil surface, which enhances soil aggregation and porosity (Negasa *et al.,* 2017). The total porosity and water-holding capacity showed significant variation with land use types, soil depths ($p < 0.05$) and their interaction effect ($p < 0.001$). The total porosity is inversely proportional to the bulk density; it increases with a decrease in bulk density. The highest (53.75%) and the lowest (34.43%) total porosity were recorded in Gmelina at 0 -15 and 15 – 30 cm, respectively. The highest (54.53%) and lowest (29.81%) values of water-holding capacity were recorded at 15 – 30 cm in cashew and grassland, respectively. The lower total porosity in arable and grassland indicates relatively high bulk density, while the lowest value of water-holding capacity recorded in soil under grassland might be because of high gravel content. The water-holding capacity increased with depth, and this might indicate organic matter whose large surface area attracted and retained the charged surfaces of water molecules (Chikamnele *et al.,* 2017). The Ksat was significantly ($p < 0.05$) affected by land use, whereas soil depth and its interaction with land use were insignificant ($p > 0.05$). It was significantly higher in cashew, followed by grassland, while the lower value was recorded in arable land. The lowest (0.0045 cm s^{-1}) Ksat value in arable land might be because of the relatively high bulk density, while the highest (0.0170 cm s^{-1}) value recorded in cashew was because of the high total porosity. This result was in line with the findings of Zimmerman *et al.* (2006), who observed that a decrease in Ksat was proportional to land use intensity.

The soil pH-H_2O and pH-KCl were significantly (p < 0.05) affected by land use type, while pH-KCl was significantly (p < 0.05) affected by land use type and soil depth (Table 3). According to the soil pH ratings of Hazelton and Murphy (2007), the soils under the cashew and Gmelina were found to be slightly acidic, while those in arable and grassland were neutral. The neutral soil reaction in arable might be because of liming, while in grassland, it could be attributed to the limited removal of basic cations through erosion and leaching. The higher value of pH-H_2O than pH-KCl showed that the soil has a net negative charge and can retain basic cations (Afu *et al.,* 2017). OC and TN contents were significantly (p < 0.05) affected by land use, but they showed insignificant values for the soil depth and interaction effect of land use and soil depth (p > 0.05, Table 3). The mean values of both OC and TN were higher in the grassland. Thus, following the rating of TN by Uquetan *et al.* (2017), the mean total nitrogen content of the soil was moderate in Gmelina and arable, but high in cashew and grassland. The relatively higher mean value of TN in soil under arable land compared to Gmelina might be because of nitrogenous fertilizer application. An increase in the level of OC in the soils of cashew and grassland could have been the result of an accumulation of plant residues in the upper few centimetres of soil depth and their lower rate of decomposition and disturbances (Khresat *et al*., 2008). Conversely, the decline in OC contents in the arable land could be attributed to the effect of continuous cultivation that aggravates organic matter oxidation and insufficient inputs of organic substrates from the farming system due to residue removal and zero crop rotation**.** The C: N did not show significant differences between land use, depth and their interactions (Table 3). Similar studies (Khresat *et al.,* 2008; Moges *et al.,* 2013) also reported that C: N did not show a significant variation in land use. The mean C: N varied from 2.19 - 3.48; these values are lower in soils under arable than in cashew and Gmelina, but the lowest value was recorded in grassland. The lower value of arable land may be due to the combination of lower carbon inputs into the soil after crop plants are harvested, losses in carbon due to bush burning, aggregate disruption arising from tillage and accelerated erosion (Abe *et al.,* 2010).

The amount of AP was significantly (p < 0.05) affected by land use, whereas soil depth and its interaction with land use were insignificant (p > 0.05). The AP was significantly higher in Gmelina and arable land, and it varied from 2.76 – 3.37 mg kg^{-1}. In general, the amount of AP in the studied area is low as per the ratings of Uquetan et al. (2017). The low AP in the studied areas could be because of low content in the parent material and sorption of this nutrient on the mineral surface (Brady & Weil, 2013). The decrease in AP with depth could be attributed to the increment in clay content with depth that might have caused phosphorus fixation. The exchangeable acidity was significantly (p < 0.001) affected by the interaction between land use and soil depth (Tables 3 and 4). The highest (0.42 cmol kg^{-1}) exchangeable acidity was recorded in grassland while the lowest (0.24 cmol kg^{-1}) was in cashew and Gmelina at soil depth 15-30 cm, their variation is not considered to be a limitation to arable crop production because values were below 1.00 cmol kg^{-1} considered to be critical levels for soils to have acidity problem according to Muhammed *et al.* (2016).

Exchangeable Na was dominant in the exchange sites of the soil colloidal materials (Table 3). Ca and Na increase with soil depth, while Mg and K decrease with soil depth. They were all significantly (p < 0.05) affected by land use. Gmelina had the highest content of exchangeable Ca, Mg, and Na, while grassland had the highest exchangeable K. Generally, the concentration of exchangeable Mg was higher (sufficient) than the critical level of 0.5 cmol kg^{-1} soil as suggested by Uquetan *et al*. (2017); a concentration less than this value would require an application of magnesium limestone accordingly. The higher concentration of exchangeable K and Mg in the top surface layer than in the lower soil layer (Table 3) suggests that vegetation pumps bases such as K, Ca and Mg from the subsoil to the topsoil (Yimer *et al*., 2008).

Table 3: Main effects of land use and soil depth on soil chemical properties

Treatment	**pH H_2O**	**pH KCl**	**cmol kg^{-1}**						**PBS (%)**	**OC (%)**	**Total N (%)**	**C: N**	**Avail. P (mg kg^{-1})**
			Exchangeable bases				Exch. Acidity	CEC					
			Ca	Mg	Na	K							
Land use (L)													
Arable	7.10a	5.35a	0.67c	0.95a	3.65a	0.27b	0.35a	5.61b	93.92bc	1.14b	0.38c	3.09	2.96a
Cashew	6.33b	5.01ab	0.70c	0.68b	1.23b	0.16d	0.30b	5.57b	90.22c	1.56a	0.62b	3.39	2.85ab
Gmelina	6.43ab	4.73b	1.27a	0.96a	3.96a	0.23c	0.30b	9.00a	95.52a	1.17ab	0.34c	3.48	3.37a
Grassland	6.94a	5.33a	0.91b	0.88a	3.41ab	0.34a	0.35a	5.89b	94.02b	1.76a	0.81a	2.19	2.76b
SED	0.266	0.266	0.104	0.104	0.266	0.015	0.023	0.437	0.437	0.266	0.104	NS	0.266
Soil depth (D)													
0-15 cm	6.70a	5.32a	0.88b	0.92	2.89	0.26a	0.32	7.02a	73.09b	1.43	0.50	3.49	3.07
15-30 cm	6.70a	4.88b	0.90a	0.81	3.23	0.24b	0.33	6.01b	83.38a	1.39	0.58	2.58	2.89
SED	NS	0.188	0.074	NS	NS	0.010	NS	0.309	0.309	NS	NS	NS	NS
Interaction													
L*D	NS	NS	NS	NS	NS	NS	**	*	**	NS	NS	NS	NS

Exch: exchangeable, Ca: calcium, Mg: magnesium, K: potassium, N: nitrogen, OC: organic carbon, PBS: percentage base saturation, CEC: cation exchange capacity, NS: non-significant *: significant at $p < 0.05$, **: highly significant at $p < 0.001$.

Table 4: Interaction effects of land use and soil depth (cm) on soil chemical properties

Land use type	Exch. Acidity (cmol kg^{-1})		CEC (cmol kg^{-1})		Percentage Base saturation (%)	
	Soil depth (cm)		Soil depth (cm)		Soil depth (cm)	
	0-15	15-30	0-15	15-30	0-15	15-30
Arable	0.28b	0.41a	5.83c	5.39c	95.20b	92.65c
Cashew	0.36a	0.24b	5.79c	5.35c	88.39e	92.05d
Gmelina	0.35ab	0.24b	10.43a	7.56b	94.35c	96.69a
Grassland	0.28b	0.42a	6.04c	5.74c	95.31b	92.73d
	0.033		0.755		0.148	

However, the contents of both exchangeable Ca and Na increased with soil depth. The increasing trend of exchangeable Ca and Na with soil depth could be associated with an increase in clay particles in the subsurface than the surface soils, as evidenced by the current study. The clay mineral components of soil have negatively charged sites on their surfaces, which adsorb and hold positively charged ions (cations) by electrostatic force (Matocha 2006). CEC and Percentage Base Saturation (PBS) of the soils in the study area were significantly ($p < 0.01$) affected by land use, soil depth and their interaction effects (Tables 3 & 4). The mean CEC was below 10 cmol kg^{-1} across the land use types, and it declined by 15.28% with soil depth. The highest value (10.43 cmol kg^{-1}) was recorded in Gmelina at 0 -15 cm, while the lowest value (5.35 cmol kg^{-1}) was recorded in cashew at 15 -30 cm. The low CEC of the soil could be attributed to the fact that soil in this area is strongly weathered, has little or no content of weathered materials in sand and silt fractions and has predominantly kaolinite in its clay fraction (Korieocha *et al.,* 2010). Percentage base saturation (PBS) is frequently used as an indication of the fertility status of soil (Chesworth, 2008). The highest (96.69%) and lowest (88.39%) PBS were recorded in Gmelina and cashew at 15 – 30 and 0 – 15 cm, respectively. Therefore, as PBS was above 80% in all cases, the soils have high fertility potential (Hazelton & Murphy, 2007). The high PBS indicates that the basic nutrient occurs in available form despite the low CEC reserve in the soil (Akpan-Idiok, 2012). The results of the Principal Component Analysis (PCA) are presented in Tables 5 and 6. It showed that eight PCs had eigenvalues> 1, which cumulatively explained 97% (PC1 = 28.92%, PC2 = 21.09%, PC3 = 13.32%, PC4 = 9.023%, PC5 = 8.09%, PC6 = 6.65%, PC7 = 5.16%, PC8 = 4.80%) of the total variation in the data set. The Eigenvalue decreased from PC 1 to PC 8. Similarly, the variance explained decreased from PC1 to PC8. The highly weighted factor loadings are defined as having absolute values within 10% of the highest factor loading. When more than one variable is retained under a single PC, the Pearson correlation test was used to examine the correlation among indicators to reduce redundancy.

Table 5: Results of Eigenvalues of principal component analysis

PC	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**
Eigenvalues	6.651	4.851	3.063	2.076	1.861	1.530	1.186	1.103
%variance	28.917	21.093	13.316	9.025	8.091	6.654	5.158	4.795
Cumulative	28.917	50.010	63.326	72.351	80.442	87.096	92.254	97.049
PC Weight	0.296	0.217	0.137	0.093	0.083	0.069	0.053	0.049

Table 6: Results of the Eigenvectors for the principal components

Eigenvectors	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
TEB	0.964	0.045	0.051	0.013	-0.044	0.172	0.142	-0.066
Exch. Na	0.957	0.015	0.057	-0.105	-0.080	0.116	-0.019	0.084
CEC	0.954	0.043	0.085	0.004	-0.053	0.215	0.137	-0.077
PBS	0.922	-0.108	-0.169	0.144	-0.159	-0.171	0.106	-0.115
Exch. Mg	0.632	0.092	0.040	0.415	0.085	0.142	-0.580	-0.035
PH-H_2O	0.584	0.463	0.229	-0.401	0.122	-0.305	-0.244	0.207
Ksat	-0.556	0.245	-0.425	0.210	0.479	-0.129	0.061	0.262
Exch. K	0.555	0.455	-0.199	-0.293	-0.382	0.215	-0.013	0.266
OM	-0.284	0.865	0.269	0.073	0.025	0.132	0.134	0.172
OC	-0.130	0.857	0.387	0.084	0.081	-0.016	0.104	0.183
TN	-0.226	0.837	-0.238	0.166	0.264	0.227	-0.151	0.037
Clay	-0.278	0.714	0.054	-0.326	0.327	-0.088	0.081	-0.398
PH-KCl	0.105	0.687	0.545	-0.079	-0.201	-0.174	-0.300	0.173
WHC	-0.217	-0.358	0.706	0.318	0.232	0.360	0.121	0.083
C:N	-0.158	-0.332	0.607	-0.285	-0.226	-0.116	0.478	0.286
T Porosity	-0.568	0.045	0.587	0.453	-0.258	0.121	-0.017	-0.118
AVAIL. P	0.543	0.067	0.566	0.380	0.102	-0.421	0.070	0.124
Gravel	0.360	0.471	-0.565	0.024	0.170	0.077	0.481	0.221
Exch. Ca	0.564	-0.061	-0.042	0.610	0.392	0.327	0.151	0.112
Silt	0.340	-0.444	0.418	-0.348	0.608	0.088	-0.046	-0.024
Sand	-0.010	0.504	-0.118	0.504	-0.555	-0.184	0.190	-0.297
Exch. acidity	-0.206	0.286	0.195	-0.368	-0.217	0.778	-0.008	-0.172
Bulk Density	0.395	0.421	0.295	-0.108	0.337	-0.185	0.219	-0.581

Bold face indicate the highly weighted (within 10% of the highest) parameters in each PC. OM, organic matter; WHC, water-holding capacity; exch, exchangeable; Ca, calcium; Mg, magnesium; K, potassium; Ksat, saturated hydraulic conductivity; TN, total nitrogen; OC, organic carbon; OM, organic matter; PBS, percentage base saturation; TEB, total exchangeable bases.

Eigen vectors for the PC1 were directly related to the "exchange capacity of the soil", which explained up to 28.92% of the total variation; it had a positive loading for TEB, sodium (Na), CEC and PBS. PC2 was identified as an "organic matter component" It explained another 21.09% of the total variation and had positive loadings for OM, OC and TN. PC3 explained 13.32% of the total variance and had positive loading for WHC, PC4 explained 9.023% of the total variance and had positive loading for exchangeable Ca, PC5 explained 8.09% of the total variation and it had positive loading for silt and negative loading for sand, while PC 6, 7 and 8 had positive loading for exchangeable acidity, negative loading for exchangeable Mg and bulk density respectively. All four Eigenvectors in PC1 were significantly correlated ($r > 0.60$, $p < 0.01$) (Table 7). Since TEB had the highest factor loading, it was retained, and all other Eigenvectors in that PC were discarded. Similarly, in PC 2 and 5, the Eigenvectors were significantly correlated ($r > 0.60$, $p < 0.01$), and organic matter and silt fraction had the highest factor loading in both PCs, respectively, and they were selected as the preferred variables for retention in both PCs. Hence, TEB, OM, WHC, silt, bulk density, exchangeable Ca, Mg and acidity were selected to calculate SQI. Weighting factors were developed based on the percentage variation explained by the eight PCs (Table 4), resulting in a final normalized PCA-based SQI equation.

PCA-SQI = 0.298*TEB + 0.217*OM + 0.137*WHC + 0.093*Exch.Ca + 0.083*Silt + EA*0.069 + Exch.Mg*0.053 + BD*0.049.

The variables were transformed using Liebig linear scoring functions, after deciding the shape of the anticipated response ("more is better" or "less is better"), the limits or threshold values were identified for each indicator. A "more is better" scoring function was applied to TEB, OM, WHC, exchangeable Ca, and Mg. A "less is better" scoring function was applied to exchangeable acidity and bulk density because their high content or value has an inhibitory effect on plant growth; a "more is better" scoring function was applied to silt because it was below the threshold value.

The SQI was determined by summing the weighted score of each parameter (Table 8). The calculated SQIs were in the following order GM(0.923) > GR(0.820) > CA(0.712) > AR(0.581). The soils under Gmelina, grassland, and OM, organic matter; OC, organic carbon; TN, total nitrogen; PBS, percentage base saturation; Exch, exchangeable; Na, sodium; TEB, total exchangeable bases ** Correlation is significant at $p < 0.01$ level. Cashew had high (>70) soil quality, while arable had intermediate soil quality. This reveals that the soils under Gmelina, grassland and cashew are better off in terms of soil functioning and soil health. The relatively higher soil quality index for grassland shows that the roots contribute organic matter through their extended roots below the surface, which are not easily decomposed (Guo & Gifford, 2002). On the other hand, arable land scored an intermediate SQI value, which indicates the need for judicious control of soil quality in the land use type (Nakajima *et al*. 2015). The variation in soil quality among different land-use types underscores the importance of implementing site-specific soil management interventions. Enhancing soil quality in arable systems requires the adoption of integrated soil fertility management (ISFM) approaches that combine organic and conservation-based practices. Key strategies include the incorporation of organic amendments, mulching, reduced or minimum tillage, and the use of cover crops to maintain soil organic matter and nutrient balance. In addition, promoting agroforestry systems offers multiple co-benefits, including increased organic matter inputs, improved soil structure and moisture retention, and enhanced nutrient cycling. Such practices contribute to long-term soil health and resilience, thereby supporting sustainable agricultural productivity and environmental stability.

Table 7: Correlation matrix for highly weighted variables under PCs with high factor loading

Variables	Exch. Na	TEB	CEC	PBS
Pearson's correlation				
PC1 Variables				
Exch. Na	1	.992**	.992**	.874**
TEB	.992**	1	.999**	.876**
CEC	.992**	.999**	1	.856**
PBS	.874**	.876**	.856**	1
PC2 Variables	OM	OC	TN	
OM	1	.915**	.914**	
OC	.915**	1	1.000**	
TN	.914**	1.000**	1	
PC5 Variables	Sand	Silt		
Sand	1	-.938**		
Silt	-.938**	1		

Table 8: Weighted scores of soil quality parameters

Land Use	TEB	OM	WHC	Exch. Ca	Silt	EA	Exch. Mg	BD	SQI
Arable	0.049	0.140	0.104	0.049	0.083	0.059	0.052	0.043	0.581
Cashew	0.128	0.193	0.125	0.051	0.059	0.069	0.038	0.049	0.712
Gmelina	0.298	0.145	0.137	0.093	0.083	0.069	0.053	0.045	0.923
Grassland	0.263	0.217	0.088	0.067	0.036	0.059	0.049	0.042	0.820

TEB, total exchangeable bases; OM, organic matter; WHC, Water-holding capacity; BD, bulk density; Exch, exchangeable; Ca, calcium; Mg, EA, exchangeable acidity; SQI, soil quality index.

Conclusion

This study demonstrated that land use practices have a strong influence on soil quality in the derived savannah of Nigeria. Variations in organic matter, water holding capacity, silt content, bulk density, exchangeable bases, and acidity were key determinants of the soil quality index (SQI). The SQI values revealed that arable land exhibited intermediate soil quality (0.55 < SQI < 0.70), while cashew, Gmelina, and grassland systems maintained high soil quality (SQI > 0.70). The relatively low SQI observed in arable land was primarily associated with organic matter depletion, reduced exchangeable bases, and increased bulk density due to intensive cultivation. These findings indicate that tree-based and grassland systems enhance soil structure, nutrient retention, and biological activity, thereby maintaining better overall soil quality than continuously cultivated arable systems. The observed relationships suggest that sustainable land management strategies promoting organic matter restoration, reduced tillage, and balanced nutrient inputs are essential for maintaining soil quality in arable lands.

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