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Soil Physical and Chemical Variability under Land Use Intensification in a Nigerian Protected Area

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Abstract

Population growth, food demand, and low farm income drive landuse intensification and encroachment into protected areas. Landuse intensification within protected landscapes alters soil physical and chemical properties with implications for ecosystem stability. This study quantified soil variability across four land-use types (LUTs): long-term reserved forest (>10 years; RAG), recently reclaimed reserve (<10 years; RAL), long-term cultivated support zone (>10 years; SZCG), and recently cultivated support zone (<10 years; SZCL) in the Borgu sector of Kainji Lake National Park, Nigeria. A randomised complete block design comprising 12 experimental units (4 LUTs × 3 blocks) was employed. Within each block, four auger samples (0–30 cm) were composited for chemical analysis (n = 12), while two undisturbed core samples were collected for bulk density and hydraulic property estimation (n = 24).

Analysis of variance revealed significant ($p < 0.05$) landuse effects on soil organic carbon (SOC), total nitrogen (TN), available phosphorus (Av. P), cation exchange capacity (CEC), and bulk density. SOC stocks declined from 29.25 Mg C ha^{-1} in long-term forest (RAG) to 6.52 Mg C ha^{-1} in long-term cultivated land (SZCG), representing a 77.7% reduction under prolonged cultivation. Forest soils consistently exhibited higher SOC, TN, and Av. P and CEC compared with cultivated systems. Principal component analysis explained 68.4% of the total variance, with SOC, TN, and Av. P strongly loaded on PC1, identifying them as dominant indicators of landuse impact. The findings demonstrate that sustained landuse intensification significantly reduces soil carbon stocks and nutrient reserves while increasing structural degradation within protected landscapes. This study provides crucial evidence for designing localised, sustainable landuse policies that reconcile conservation with community agricultural needs.

Keywords: Landuse intensification; Protected areas; Soil chemical properties; Soil physical properties; Soil quality indicators

Introduction

Landuse change is a major driver of soil physical and chemical transformation, particularly in tropical ecosystems where nutrient cycling is rapid and organic matter turnover is sensitive to disturbance. Conversion of forest to cultivated land alters soil structure, reduces organic carbon inputs, accelerates nutrient depletion, and increases susceptibility to compaction and erosion (Elliot *et al*., 2018). In tropical savanna-forest transition zones, these changes can occur rapidly under continuous cultivation and reduced fallow periods.

Soil quality, defined as the capacity of soil to function within ecosystem boundaries to sustain biological productivity and environmental quality (Lal, 2020b), is strongly influenced by landuse intensity. Long-term cultivation typically reduces soil organic carbon (SOC), total nitrogen (TN), cation exchange capacity (CEC), and aggregate stability, while increasing bulk density and structural degradation. Across sub-Saharan Africa, intensified cropping systems have been associated with nutrient mining and declining water retention capacity (Yimer *et al*., 2020; Boitt *et al*., 2021; Bedadi *et al*., 2023). However, the magnitude and spatial patterns of these changes vary depending on management history, soil type, and duration of disturbance. Thus, farmers, through their crop production practices, influence the course of soil formation and the physical and chemical status of the soil at any given time (Trasar *et al*., 2008).

Protected landscapes are increasingly experiencing internal landuse gradients resulting from agricultural encroachment and support-zone cultivation. In Nigeria, the Borgu sector of Kainji Lake National Park represents a critical case where long-term reserved forests coexist with recently reclaimed areas and cultivated support zones of varying duration. While several studies have examined soil degradation under general agricultural systems in Nigeria, quantitative assessments comparing protected forest soils with adjacent cultivated lands of differing intensities within legally designated conservation areas remain limited.

Understanding how soil physical and chemical properties respond to varying durations and intensities of cultivation within protected landscapes is critical for distinguishing short-term disturbances from sustained degradation processes. In particular, evaluating soils across a landuse gradient, from long-term reserved forest to recently reclaimed and continuously cultivated systems, provides an opportunity to quantify both the magnitude and direction of soil quality change under intensification. Multivariate approaches such as principal component analysis (PCA) further enable identification of the dominant soil attributes driving variability and allow discrimination of land-use effects within complex tropical systems.

Therefore, the study aimed to quantify the effects of land-use intensification on soil physical and chemical properties within and around Kainji Lake National Park. Specifically, the study compares selected soil physical and chemical properties across four landuse types representing an intensification gradient, and identifies the dominant soil quality variables driving variability among land-use systems through principal component analysis.

Thus, this research tested the hypothesis that soil properties vary systematically along the land-use intensification gradient. It was hypothesised that soil organic carbon, total nitrogen, available phosphorus, and cation exchange capacity would decline significantly with increasing cultivation intensity and duration, reflecting progressive nutrient depletion and reduced organic matter inputs. It was further hypothesised that bulk density and related structural indicators would increase under long-term cultivation relative to forested systems due to repeated disturbance and compaction effects. Additionally, it was expected that multivariate analysis would reveal clear separation among land-use categories, with soil organic carbon and associated nutrient variables serving as primary discriminators of land-use impact and hypothesized that long-term cultivation reduces SOC, CEC, and water retention relative to protected soils.

Materials and Methods

Study Area

The study was conducted in the Borgu sector of Kainji Lake National Park (KLNP), located in north-central Nigeria across Niger and Kwara States, near the Republic of Benin. The study area lies between latitudes 9°40′N and 10°30′N and longitudes 3°30′E and 5°05′E. Elevation ranges from 300 to 350 m above sea level. The specific coordinates of the study areas are presented in Table 1.

The climate is characterised by a unimodal rainfall pattern with mean annual precipitation between 975 and 1220 mm. Vegetation falls within the Northern Guinea Savanna zone and is dominated by species such as *Burkea africana*, *Afzelia africana*, and *Anogeissus leiocarpa*. The topography is gently undulating with well-drained upland soils typical of the savanna belt.

Landuse Classification

Four land-use types (LUTs) representing a gradient of intensification and duration were evaluated:

- Reserved Area >10 years (RAG)
- Reserved Area <10 years (RAL)
- Support Zone Community cultivated >10 years (SZCG)
- Support Zone Community cultivated <10 years (SZCL)

Land-use history was verified through structured interviews with local farmers and park officials, supported by GPS-based field identification. Duration categories were based on continuous management history before sampling.

Experimental Design and Soil Sampling

The study employed a randomised complete block design (RCBD) with landuse type as the treatment factor and three landscape blocks serving as replicates to account for inherent spatial variability. Each block contained all four land-use types, thereby controlling for topographic and pedological heterogeneity.

Within each land-use plot (approximately 1.5 ha), a sampling area was delineated and subdivided into grids. Soil samples were collected from the central zone of each plot to minimise edge effects.

At each experimental unit:

- Four auger samples were collected at 0–30 cm depth and composited into a single sample for chemical and selected physical analyses (n = 12 composite samples).
- Two undisturbed core samples were collected for bulk density and hydraulic property estimation (n = 24 core samples).

The 0–30 cm depth was selected because it represents the active root zone and the layer most sensitive to landuse disturbance following FAO (2006) guidelines. The composite sample constituted the experimental unit for chemical analyses, while core samples were treated as independent observations for bulk density and hydraulic properties within the RCBD framework.

Laboratory Analyses

Soil physical properties (texture, bulk density, moisture content, field capacity, and drainage rate) were analysed following standard procedures (Gee and Or, 2002). Chemical analyses included soil pH (1:1 KCl), organic carbon (Walkley-Black method as modified by Bahadori & Tofighi, 2016), total nitrogen (Kjeldahl), available phosphorus (Olsen), and exchangeable bases (Ca, Mg, K, Na) via ammonium acetate extraction, all conducted per standardized protocols (Amin & Flowers, 2004; Olsen *et al*., 1980). Cation exchange capacity (CEC) and exchangeable acidity (EA) were also quantified. All analyses followed standardised laboratory procedures to ensure comparability and reproducibility.

Statistical Analysis

All statistical analyses were conducted using GenStat (22nd Edition). Before analysis, data were tested for normality using the Shapiro–Wilk test and for homogeneity of variance using Levene's test. Where necessary, data were log- or square-root transformed to satisfy ANOVA assumptions.

Analysis of variance (ANOVA) was performed under the RCBD framework to evaluate land-use effects on soil properties. When significant treatment effects were detected ($p < 0.05$), mean separation was performed using Tukey's Honest Significant Difference (HSD) test at the 5% probability level. Descriptive statistics, including means, standard deviations, and coefficients of variation, were computed to assess variability. Soil organic carbon stocks were calculated using measured bulk density and sampling depth.

Principal component analysis (PCA) was conducted on standardised (z-score) variables to identify dominant soil quality indicators and examine multivariate patterns among land-use types. Components with eigenvalues greater than 1 were retained. Sampling adequacy was assessed using the Kaiser–Meyer–Olkin (KMO) statistic, and Bartlett's test of sphericity was used to verify the suitability of the dataset for multivariate analysis.

Results and Discussion

Soil Physical Properties

Table 1 shows the soil types and coordinates of the study area. Soil texture varied across land-use types (LUTs), with cultivated systems (SZCG and SZCL) predominantly classified as sandy clay loam, while reserved areas (RAG and RAL) exhibited higher clay fractions. Sand content followed the order SZCL > SZCG > RAL > RAG (Table 2). However, differences in particle size distribution among LUTs were not statistically significant ($p > 0.05$), indicating that inherent soil variability within blocks was partially controlled by the experimental design.

Bulk density differed significantly among LUTs ($p < 0.05$). The highest bulk density was recorded under long-term cultivation (SZCG), which is 1.45 g/cm^3, while the lowest value (1.31 g/cm^3) occurred in the long-term reserved forest (RAG). Mean bulk density increased progressively with cultivation intensity (Table 2). The effect of land use on bulk density was substantial, accounting for 5.9% of total variance ($\eta^2 = 0.059$).

Field capacity and volumetric moisture content were significantly higher ($p < 0.05$) in RAG compared with cultivated systems. RAG recorded a mean field capacity of 0.18 $cm^3\ cm^{-3}$, whereas SZCL exhibited lower values consistent with higher sand content. Available water content followed the trend RAG ≥ RAL > SZCL > SZCG, with statistically significant differences among treatments ($p < 0.05$).

Drainage rate differed significantly among LUTs ($p < 0.05$), with SZCL exhibiting the highest mean drainage rate (0.41 $cm\ hr^{-1}$) and RAL the lowest (0.26 $cm\ hr^{-1}$). Land-use type explained 1.2% of the variability in drainage rate. Overall, cultivated land-use types were associated with increased bulk density and drainage rates and reduced water retention parameters relative to reserved forest systems.

Discussion

Variations in soil physical properties across the land-use types reflect the influence of vegetation cover, soil disturbance, and organic matter dynamics on soil structure in the Borgu sector of Kainji Lake National Park. Differences in soil texture observed among the land-use types suggest that land management and erosion processes influence the redistribution of soil particles over time.

Protected sites (RAG and RAL) contained higher proportions of clay and silt, while cultivated areas, particularly SZCL, were relatively sandier. Coarser textures in cultivated soils are commonly associated with selective erosion and structural breakdown resulting from repeated tillage and reduced vegetation cover (Lal, 2020).

The higher field capacity and available water recorded in protected soils highlight the role of organic matter and stable soil aggregates in enhancing water retention. Organic matter improves soil structure by promoting aggregation, increasing pore connectivity, and enhancing the soil's capacity to retain moisture (Brady and Weil, 2016). Continuous litter deposition and minimal soil disturbance in forest environments favour the development of stable aggregates and improved pore structure, which enhance water storage and infiltration.

In contrast, cultivated soils exhibited higher drainage rates and lower moisture retention, particularly in SZCL. Frequent tillage and reduced organic matter inputs disrupt soil aggregates and increase macroporosity, resulting in rapid water movement and reduced water-holding capacity (Obalum *et al*., 2017). Such structural changes reduce the soil's ability to retain water and nutrients, increasing susceptibility to drought stress and nutrient leaching.

Overall, the results indicate that land-use intensification alters soil physical structure, shifting soils toward coarser textures and reducing water retention. These changes highlight the importance of vegetation cover and organic matter management in maintaining favourable soil physical conditions in savanna ecosystems.

Soil Chemical Properties

The descriptive statistics of soil chemical properties across the four land-use types (LUTs) are presented in Table 3. Soil reaction was slightly acidic across all LUTs, with mean pH values ranging from 6.09 in support zone communities under long-term cultivation (SZCG) to 6.45 in the protected reserve (>10 years; RAG). However, the effect of land-use type on soil pH was relatively small, explaining only 5.9% of the total variance ($\eta^2 = 0.059$), indicating that soil reaction remained relatively buffered despite differences in management intensity.

In contrast, soil organic carbon (OC) exhibited strong sensitivity to land-use intensity. OC values followed the order RAG (0.75%) > RAL (0.69%) > SZCL (0.53%) > SZCG (0.15%), indicating substantial depletion under prolonged cultivation. Land-use type accounted for 51.0% of the total variance in OC ($\eta^2 = 0.510$), demonstrating a strong treatment effect. Variability was highest in recently cultivated support-zone soils (SZCL; SD = 0.603), suggesting heterogeneous organic matter distribution associated with variable residue management and cultivation practices.

A similar pattern was observed for total nitrogen (TN), which showed the strongest response to land-use intensification among all measured variables. TN values ranged from 0.02% in SZCG to 0.04% in RAG and RAL, with land-use type explaining 88.6% of the total variance ($\eta^2 = 0.886$). The extremely high effect size indicates that nitrogen availability in these savanna soils is highly dependent on organic matter dynamics and disturbance intensity.

Available phosphorus (Av. P) also varied across LUTs, with the highest values recorded in RAG (6.41 mg kg^{-1}) and the lowest in SZCG (5.73 mg kg^{-1}). The effect of land use explained 32.0% of total variance ($\eta^2 = 0.320$), reflecting moderate sensitivity of soil phosphorus to management intensity. Exchangeable potassium (K) followed a similar pattern, ranging from 1.49 cmol kg^{-1} in RAL to 1.69 cmol kg^{-1} in RAG, with land use accounting for 34.1% of total variance ($\eta^2 = 0.341$).

Exchangeable acidity (EA) showed moderate variation among land-use types, with slightly higher values observed in cultivated systems. Land-use intensity explained 19.2% of total variance ($\eta^2 = 0.192$), suggesting a moderate influence of cultivation practices on soil acidity dynamics.

Cation exchange capacity (CEC) exhibited substantial variability across the study sites, with values ranging from 4.31 cmol kg^{-1} in RAL to 8.46 cmol kg^{-1} in SZCL. The influence of land use was considerable, accounting for 39.1% of total variance ($\eta^2 = 0.391$). The relatively high variability in CEC, particularly in RAG soils (SD = 3.024), likely reflects spatial heterogeneity in organic matter and clay fractions within the protected forest environment.

Exchangeable magnesium (Mg) varied only slightly among LUTs, ranging from 0.85 to 0.99 cmol kg^{-1}, with land use explaining 11.9% of total variance ($\eta^2 = 0.119$), indicating relatively low sensitivity of Mg availability to the land-use gradient.

Overall, the magnitude of effect sizes suggests that nutrient-related variables (OC, TN, CEC, Av. P, and K) are strongly influenced by land-use intensification, whereas soil pH and exchangeable Mg are comparatively stable across management regimes.

Discussion

The variation in soil chemical properties across land-use types reflects the influence of land-use intensity on soil organic matter dynamics and nutrient cycling in the Borgu sector of Kainji Lake National Park. Soil pH remained slightly acidic across the sites, indicating relatively stable soil reaction despite differences in management. Such stability is common in tropical soils where buffering effects from clay minerals and organic matter moderate pH fluctuations (Brady and Weil, 2016).

Soil organic carbon (OC) declined along the land-use intensification gradient (RAG > RAL > SZCL > SZCG), highlighting the influence of vegetation cover and disturbance on organic matter accumulation. Protected forest soils typically receive continuous litter inputs and experience minimal disturbance, promoting organic carbon stabilisation. In contrast, cultivation accelerates organic matter decomposition through soil disturbance and increased aeration, leading to carbon depletion (Lal, 2020).

Total nitrogen (TN) followed a similar trend to OC, reflecting the close association between nitrogen pools and soil organic matter. In tropical soils, organic matter is the principal reservoir of nitrogen; therefore, reductions in SOM directly affect nitrogen availability (Brady and Weil, 2016).

Available phosphorus and exchangeable bases also varied among land-use types. Higher values in protected sites may result from efficient nutrient recycling through litter decomposition, while lower levels in cultivated soils reflect nutrient export through crop harvest and reduced residue return (Fageria and Baligar, 2008). Similarly, higher cation exchange capacity in less disturbed soils likely reflects greater organic matter content, which enhances nutrient retention and buffering capacity (Minasny and McBratney, 2018).

Boxplots of Key Soil Indicators Across Land Use Types

Boxplot analysis of key soil indicators such as organic carbon (OC), total nitrogen (TN), soil pH, available phosphorus (Av. P), cation exchange capacity (CEC), and moisture content revealed clear variability across land-use types within Kainji Lake National Park and its support zone communities (Figures 1a–1f).

Organic carbon and total nitrogen displayed distinct gradients among the land-use categories. Protected forest sites (RAG) and reclaimed areas (RAL) exhibited higher median OC and TN values compared with cultivated support zone lands under both long-term cultivation (SZCG) and recent cultivation (SZCL) (Figures 1a and 1b). The interquartile ranges for OC and TN were wider in cultivated sites, indicating greater variability in soil fertility conditions.

Soil pH values ranged from slightly acidic to near neutral across the land-use types (Figure 1c). Protected areas exhibited relatively narrow interquartile ranges, whereas cultivated lands showed greater variability in pH values.

Available phosphorus (Av. P) exhibited moderate variability among the land-use types (Figure 1d). Some cultivated plots showed relatively elevated values, although the distribution was inconsistent across sites.

Cation exchange capacity (CEC) differed among land-use types, with higher median values observed in protected and reclaimed sites compared with cultivated areas (Figure 1e). Moisture content showed patterns similar to those observed for organic carbon, with higher values generally occurring in protected and reclaimed sites (Figure 1f). Overall, the boxplots indicate clear variability in key soil fertility indicators across the land-use gradient.

Discussion

The differences in OC and TN observed among land-use types highlight the strong influence of vegetation cover and land management on soil organic matter dynamics. Higher OC and TN in protected and reclaimed sites reflect continuous litter inputs, minimal soil disturbance, and favourable microclimatic conditions that promote organic matter accumulation. Similar patterns have been reported in savanna ecosystems of West Africa, where forested or fallow lands maintain higher soil carbon and nitrogen stocks than cultivated lands (Boakye *et al*., 2017).

In contrast, the lower OC and TN observed in cultivated support zone communities reflect organic matter depletion associated with continuous cultivation. Repeated tillage accelerates microbial decomposition of organic matter, while crop harvest and residue removal reduce carbon inputs to the soil (Lal, 2020). Because most soil nitrogen is associated with organic matter pools, reductions in SOM often lead to corresponding declines in total nitrogen (Gurmu, 2019).

The relatively stable pH values observed in protected areas likely reflect balanced nutrient cycling and buffering by soil organic matter and clay minerals. Greater variability in cultivated sites may be associated with fertiliser inputs, ash deposition, or nutrient removal through crop harvest (Yu *et al*., 2023).

Higher CEC in protected and reclaimed soils can be attributed to greater SOM content and finer soil textures, both of which contribute to increased cation exchange surfaces and improved nutrient retention capacity (Minasny and McBratney, 2018). Similarly, the higher moisture content observed in these sites is consistent with the positive role of organic matter in improving soil water retention and aggregate stability (Lal, 2020). Overall, the results indicate that increasing land-use intensity is associated with declining soil fertility indicators and reduced soil functional capacity.

Principal Component Analysis of Soil Properties

Principal Component Analysis (PCA) was conducted to identify the major soil properties responsible for variability among land-use types in the Borgu sector of Kainji Lake National Park. The analysis produced two principal components (PC1 and PC2) that explained the majority of the total variance in the dataset (Figure 2).

The first principal component (PC1) accounted for the largest proportion of the variance and was positively associated with organic carbon (OC), total nitrogen (TN), cation exchange capacity (CEC), field capacity, and moisture content. Negative loadings on PC1 were observed for sand content and drainage rate. These relationships indicate a gradient separating soils with higher organic matter and water retention capacity from soils dominated by coarse particles and rapid drainage. The second principal component (PC2) was mainly influenced by soil pH and available phosphorus (Av. P). These variables contributed to the secondary variation observed among the sampling sites.

The PCA biplot showed a clear grouping of the land-use types. Protected (RAG) and reclaimed (RAL) sites clustered closely together, while cultivated sites (SZCG and SZCL) were more dispersed. The clustering pattern indicates similarities in soil characteristics within protected sites and greater heterogeneity in cultivated areas. Overall, the PCA results highlight organic carbon, total nitrogen, and cation exchange capacity as the major variables distinguishing soils across the land-use gradient.

Discussion

The PCA results demonstrate that soil organic matter–related properties are the dominant drivers of soil variability across the land-use gradient in the Borgu sector of Kainji Lake National Park. The strong positive association of OC, TN, CEC, moisture content, and field capacity on PC1 indicates that soil organic matter plays a central role in regulating both nutrient retention and hydrological properties. Soil organic matter contributes to cation exchange capacity, improves soil aggregation, and enhances water-holding capacity, thereby supporting soil fertility and ecosystem functioning (Brady and Weil, 2016; Lal, 2020). The negative association between PC1 and sand content and drainage rate further suggests that soils with coarser textures tend to have lower nutrient retention and reduced water-holding capacity. Such patterns are typical of cultivated soils where repeated tillage disrupts soil aggregates and accelerates organic matter decomposition (Lal, 2020).

The clustering of protected and reclaimed sites indicates relatively stable soil conditions associated with perennial vegetation cover and minimal soil disturbance. Continuous litter inputs and limited mechanical disturbance favour the accumulation of organic matter and maintain favourable soil structure. Similar clustering patterns between forested and less disturbed land uses have been reported in savanna ecosystems of East and West Africa (Boitt *et al*., 2021).

Conversely, the dispersion of cultivated sites in the PCA space reflects greater variability in soil properties, which may arise from differences in management practices, cropping history, and nutrient inputs. Such heterogeneity is common in smallholder farming systems where soil management practices vary considerably among fields.

Overall, the PCA confirms that land-use intensification strongly influences soil quality gradients, primarily through its effects on soil organic matter and associated nutrient-retention processes.

Conclusion

Land use intensity significantly influenced soil physical and chemical properties across the KLNP landscape. Protected sites (RAG and RAL) consistently exhibited superior soil quality indicators, including higher soil organic carbon, total nitrogen, and cation exchange capacity, together with improved hydrological attributes such as greater field capacity and moisture retention. In contrast, cultivated support zones (SZCL and SZCG) were characterised by coarser textures, reduced organic matter, lower nutrient retention capacity, and higher drainage rates, reflecting progressive soil degradation associated with continuous cultivation. Multivariate analysis further confirmed that soil organic matter–related attributes were the dominant drivers of soil functional differentiation across land use types. These findings highlight the central role of vegetation cover and organic matter inputs in sustaining soil structure, nutrient cycling, and water retention in savanna ecosystems. Sustainable soil management practices—including organic residue incorporation, reduced tillage, and vegetation buffer conservation—are therefore essential to restore soil fertility and maintain ecosystem resilience in cultivated landscapes surrounding protected areas.

Table 1. Soil types and Coordinates of the study area

S/N	LUT	Coordinates	Soil type
1	Protected/Reserved Area (RAG)		
	Bukar Shuaibu Track	09 59.738 N 004 16.171 E	Sandy clay
	Lake Show track	09 59.383 N 004 16.766 E	Sandy clay
	Sani Zangon Daura Track	09 57.541 N 004 17.823 E	Clay
2	Enclaved communities/Reclaimed from encroachers (RAL)		
	Tungan Yakubu	10 02.174 N 004 25.932 E	Sandy clay
	Tungan Maidembo	10 02.174 N 004 25.799 E	Sandy clay
	Tungan Gado	10 03.899 N 004 25.864 E	Sandy clay loam
3	Support zone communities under LUTs > 10 years (SZCG)		
	Borgu Wawa Plot 1	09 50.250 N 004 34.462 E	Sandy clay loam
	Borgu Wawa Plot 2	09 53.216 N 004 25.719 E	Sandy clay loam
	Borgu Wawa Plot 3	09 53.502 N 004 25.619E	Sandy clay
4	Support zone communities under LUTs < 10 years (SZCL)		
	Wawa Kaiama 1	09 53.263 N 004 24.071 E	Sandy clay loam
	Wawa Kaiama 2	09 52.950 N 004 24.062 E	Sandy clay loam
	Wawa Kaiama 3	09 52.712 N 004 24.064 E	Sandy clay loam

Table 2. Descriptive analysis of soil physical properties at 0 – 30 cm depth under different LUT in Kainji Lake National Park

LUT	Sand	Silt	Clay	MC	Av. W	FC	DR	BD (g/cm^3)
	←	%		→	← cm^3/cm^3		→ cm/hr	
SZCG	64.2	7.6	28.2	0.50	0.09	0.25	0.28	1.45
SK	-0.31	0.14	0.33	0.25	0.00	-0.03	0.02	-0.18
SD	5.87	1.07	6.84	0.14	0.30	0.01	0.01	0.13
SZCL	65.95	9.41	24.64	0.70	0.09	0.24	0.41	1.43
SK	-0.61	0.77	-0.50	-0.50	0.00	0.03	0.01	-0.35
SD	3.76	9.47	2.35	0.72	0.02	0.01	0.00	0.17
RAG	41.30	18.90	39.79	4.31	0.11	0.18	0.33	1.31
SK	-0.95	0.48	0.91	0.38	0.01	0.01	0.01	-0.38
SD	12.21	1.81	10.85	1.58	0.40	0.86	0.54	0.33
RAL	62.71	7.49	20.80	2.13	0.08	0.26	0.26	1.40
SK	0.14	-0.51	-0.36	-0.21	0.00	0.02	0.02	0.11
SD	9.63	1.29	9.71	0.87	0.01	1.10	1.20	0.35

MC – moisture content; Av. W – available water content; FC – field capacity, DR – drainage rate; BD – Bulk density; RAG - Protected/Reserved Area; RAL - Enclaved communities/Reclaimed from encroachers; SZCG - Support zone communities under LUTs > 10 years; SZCL - Support zone communities under LUTs < 10 years; SK – skewness and SD – standard deviation.

Table 3. Descriptive analysis of soil chemical properties at 0 – 30 cm depth under different LUT in Kainji Lake National Park.

LUT	Soil pH	OC	TN	Av. P	K	EA	CEC	Mg
		←(%)→		←		(cmol/kg)	→	
SZCG	6.09	0.15	0.02	5.73	1.53	0.07	6.97	0.85
SK	0.08	0.01	-0.23	0.25	1.22	0.85	1.09	0.37
SD	0.500	0.102	0.002	0.261	0.151	0.001	2.213	0.226
SZCL	6.24	0.53	0.03	5.89	1.68	0.07	8.46	0.94
SK	0.32	2.43	1.65	-0.50	-0.18	0.23	0.59	0.51
SD	0.530	0.603	0.001	0.722	0.132	0.020	1.486	0.193
RAG	6.45	0.75	0.04	6.41	1.69	0.05	7.34	0.99
SK	0.27	-0.34	-1.73	-1.78	-1.35	-0.31	1.12	0.07
SD	0.380	0.117	0.002	0.253	0.181	0.002	3.024	0.192
RAL	6.29	0.69	0.04	5.87	1.49	0.08	4.31	0.92
SK	0.18	-0.23	-0.20	0.59	0.91	0.46	-0.06	0.81
SD	0.740	0.126	0.001	0.321	0.084	0.020	0.031	0.134

OC – organic carbon; TN – total nitrogen; Av. P – Available phosphorus, K – potassium; Mg – Magnesium; EA – Exchangeable acidity; CEC – cation exchangeable cation; RAG - Protected/Reserved Area; RAL - Enclaved communities/Reclaimed from encroachers; SZCG - Support zone communities under LUTs > 10 years; SZCL - Support zone communities under LUTs < 10 years; SK – skewness and SD – standard deviation.

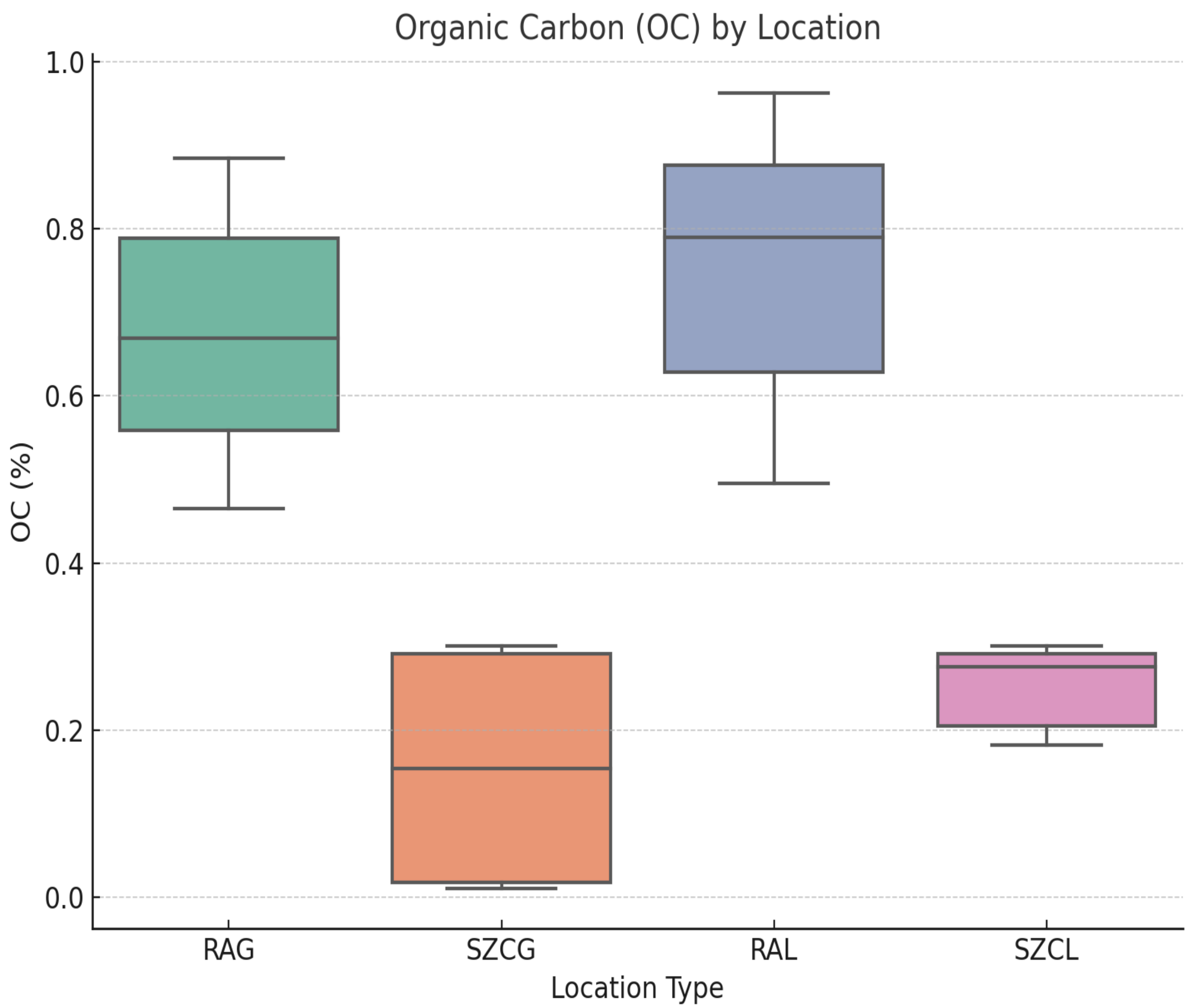

Figure 1a: Boxplot of organic carbon (OC, %) across four land use types in Kainji Lake National Park and adjacent support zones.

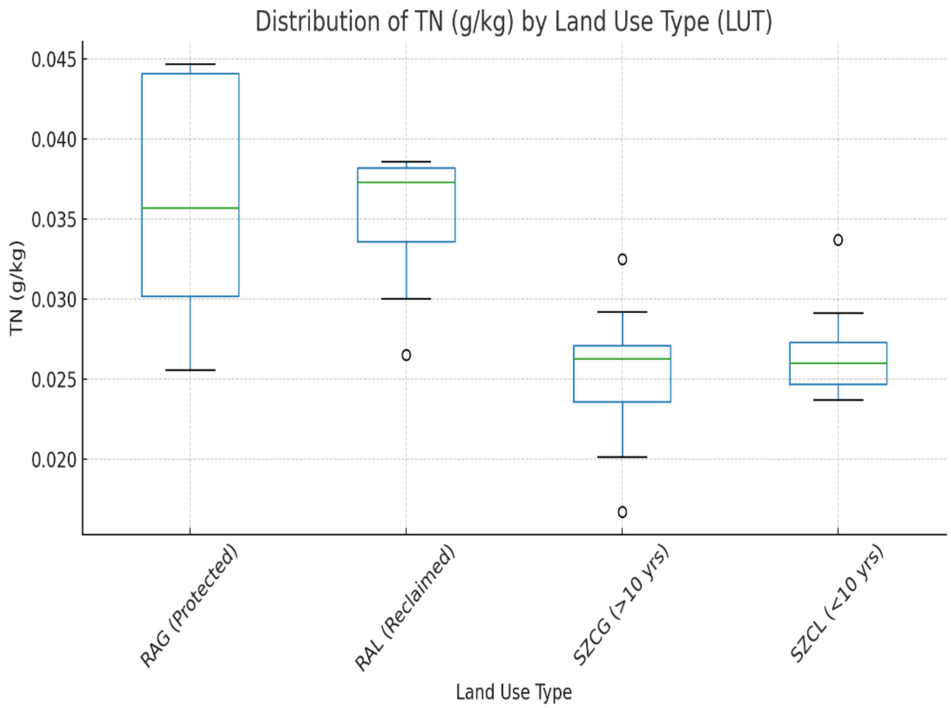

Figure 1b: Boxplot of total nitrogen (TN, g kg^{-1}) across four land use types in Kainji Lake National Park and adjacent support zones.

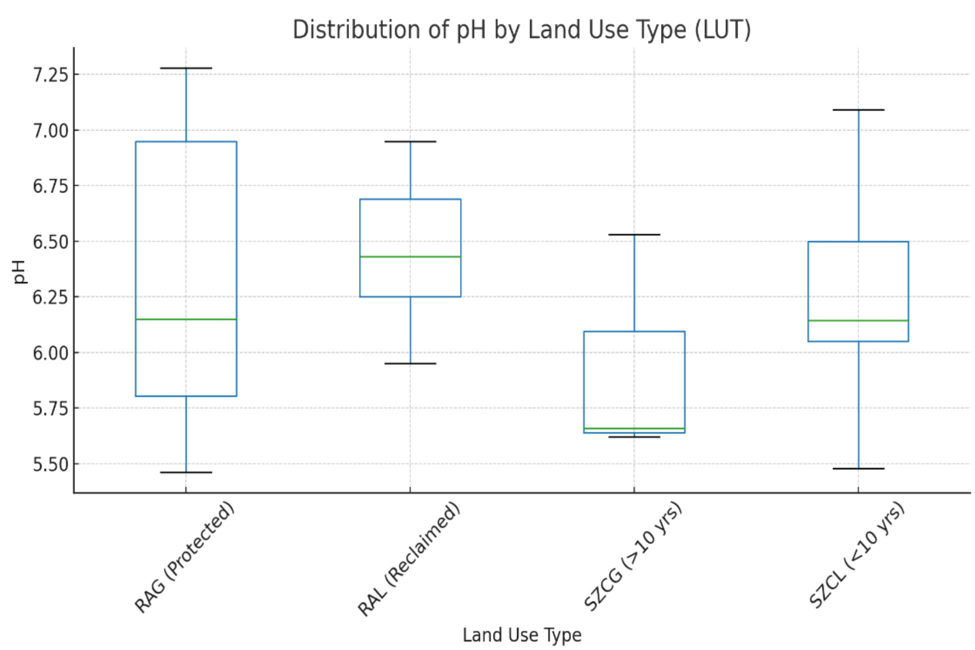

Figure 1c: Boxplot of soil pH across four land use types in Kainji Lake National Park and adjacent support zones.

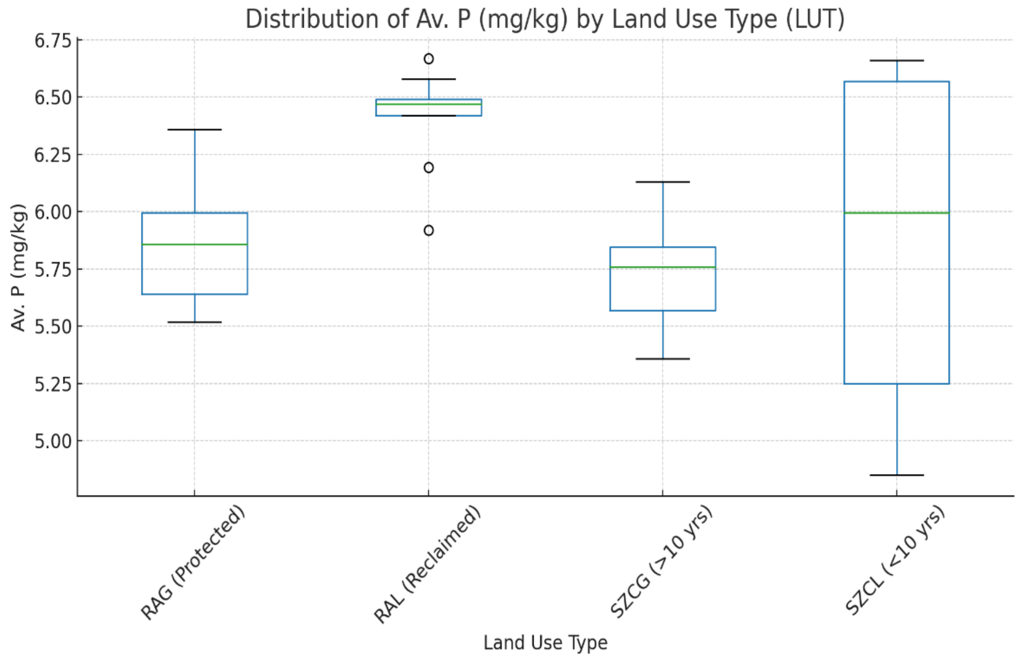

Figure 1d: Boxplot of available Phosphorus (mg kg⁻¹) across four land use types in Kainji Lake National Park and adjacent support zones.

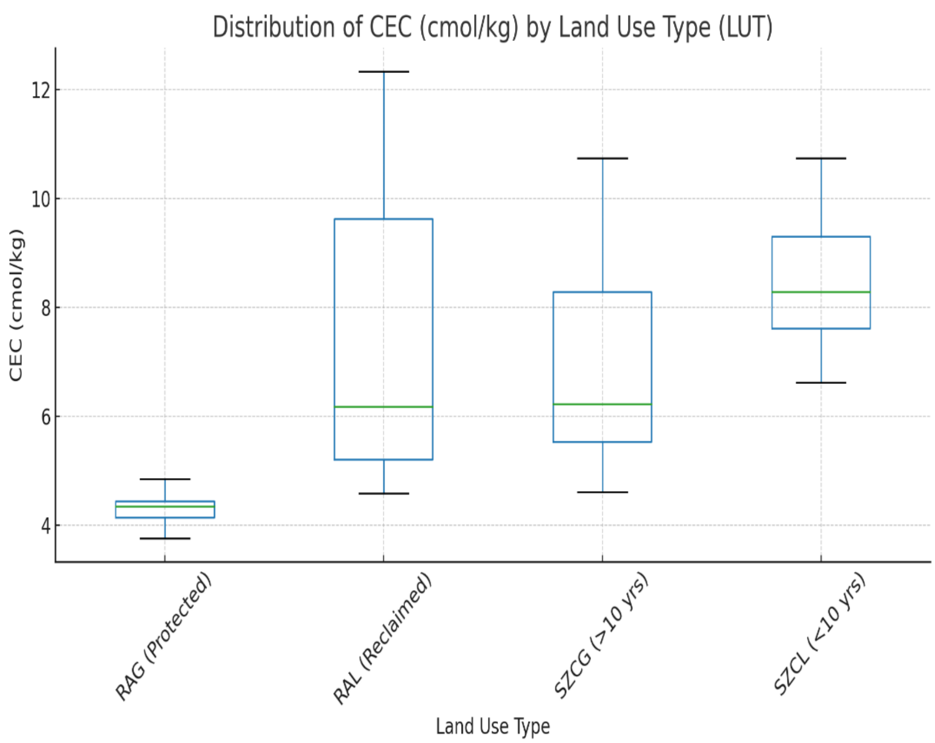

Figure 1e: Boxplot of cation exchange capacity (CEC, cmol kg⁻¹) across four land use types in Kainji Lake National Park and adjacent support zones.

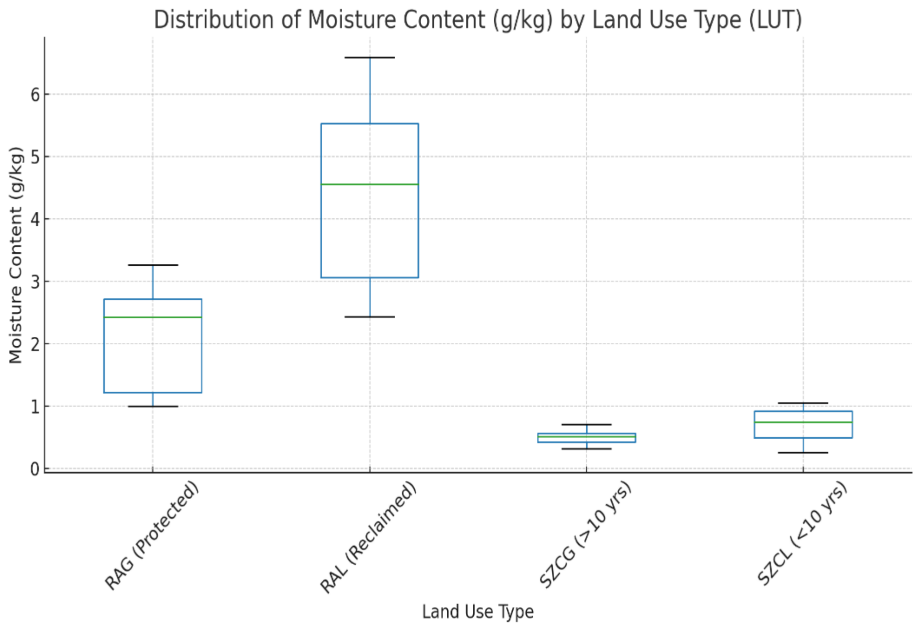

Figure 1f: Boxplot of moisture content (g kg^{-1}) across four land use types in Kainji Lake National Park and adjacent support zones.

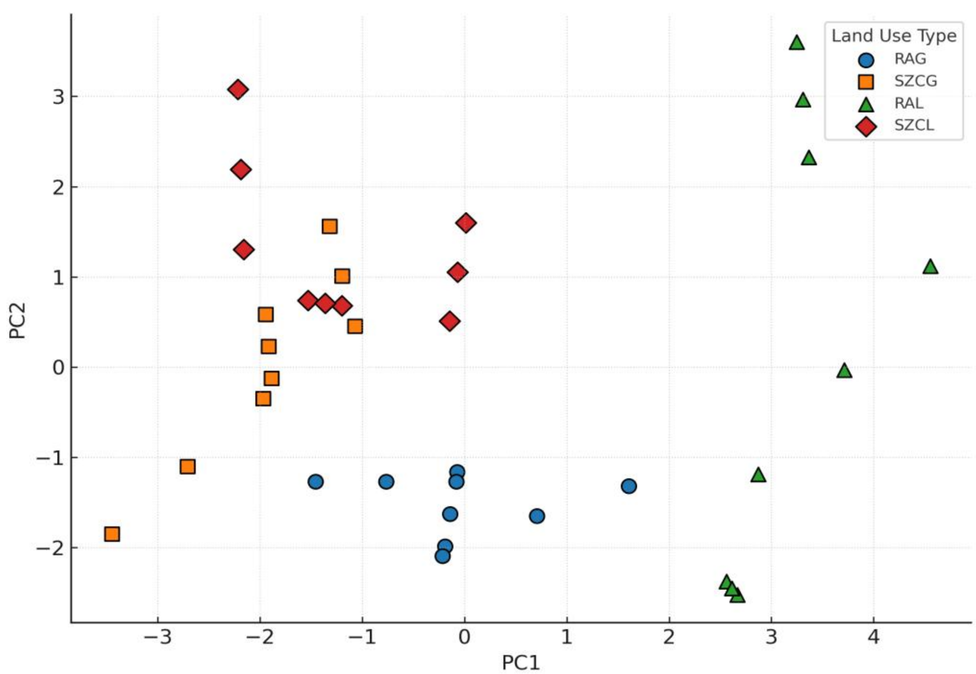

Figure 2: Principal Component Analysis (PCA) biplot showing the distribution of soil samples across land use types in and around Kainji Lake National Park.

The first two principal components (PC1 and PC2) explain the majority of variance among 13 soil properties, including OC, TN, pH, CEC, and texture fractions.

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