



CHARACTERIZATION AND CLASSIFICATION OF CRESTAL SOILS IN BOKI, CROSS RIVER STATE – NIGERIA

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ABSTRACT

This study aimed to characterise and taxonomically classify crestal soils in the Boki Local Government Area, Cross River State, Nigeria, to generate reliable soil data to support sustainable land use and improve crop productivity. Six soil profiles were spatially sited on the crests of major agrarian communities in Boki. Various shades of reddish colours were distributed across profile depths, with dominant hues of 2.5YR and 5YR in the surface soils, while loamy textural classes were dominant there. Bulk density was below 1.7 Mg/m³ and total porosity was 35–70% at all depths. However, clay bulges were clearly observed in all profiles at depths exceeding 15 cm. Soil pH was below the recommended range of 5.5–6.5, while soil organic carbon was high, with most values exceeding 1.5%. Furthermore, exchangeable Ca²⁺, Mg²⁺ and cation exchange capacity (CEC) were moderate in the soils. By the USDA Soil Taxonomy System, the soils were classified as Typic Paleudults, which corresponded to Luvic Umbrisol (Eutric, Loamic), Haplic Acrisol (clayic, Ochric), and Haplic Acrisol (Loamic, Ochric). Soil organic C, total N, CEC, exchangeable Ca²⁺, and porosity were among the soil properties expressed by PC1, whereas organic C, total N, CEC, exchangeable Ca²⁺, Mg²⁺, clay, and bulk density consistently differed with soil depth in all six (6) crestal soils. Application of agricultural lime is recommended to improve soil pH and nutrient availability. This way, soil microbial activities are enhanced, organic materials are decomposed, and nutrients are available for crop uptake and enhanced production. Potassic fertilizers are recommended to boost soil K levels, while alley cropping, minimum tillage, and cover cropping will protect the immediate soil surface from surficial erosion.

Keywords: Soil fertility; Soil morphology; Tropical rainforest; Ultisols

INTRODUCTION

Inadequate information and knowledge about soil and land resources in Nigeria have hindered agricultural operations and affected food security. Therefore, soil characterization serves as pedological data mining for land evaluation and planning. This is of particular interest for crestal soils, which occupy the most stable landscape position. Pedological data, and by extension characterization, are critical to understanding the properties, processes, and genesis of soils, and are necessary for the classification and management of soils (Esu, 2010). This affirms that soil characterization and classification provide valuable information for agricultural land-use decisions and offer a universal language for soil prediction (Ofem *et al.*, 2025a). Such characterization studies are considered the first step to good land management for food security through soil surveys.

Recently, soil classification systems rely on quantitative soil properties (SSS, 2014b). They play a great role in soil-related knowledge organization at the local and regional levels, help in understanding the relationships among classified soil individuals, and aid in remembering the properties of classified soils. Most importantly, soil classification helps predict soil behaviour and productivity, inform land-use planning, and facilitate knowledge extrapolation (Esu, 2010; Ofem *et al.*, 2025a).

Previous studies have reported optimum ranges of total N, exchangeable Ca, Mg and base saturation (Kekong and Ndifon, 2020) for crop production. Similarly, Ofem *et al.* (2025a) reported that the exchangeable sites of the soils of Boki were dominated by exchangeable Ca^{2+} with a concentration below 6.0 cmol/kg. Furthermore, exchangeable Mg^{2+} , K^{+} and Na^{+} were less than 1.0 cmol/kg required for most tropical soils (Ofem *et al.* 2025a). These findings fall short of critical nutrients requirements for cocoa producing areas as Fasina and Adeyanju (2007), and Ibiremo *et al.* (2011) obtained 0.90 and 30.0 g/kg for total N and organic C, respectively, 5 - 8 soil pH (H_2O) units, 10 mg/kg of available P, and 0.30, 5.0 and 0.90 cmol/kg for exchangeable K, Ca and Mg, respectively. In similar soils in Etung, Cross River State, Ajiboye *et al.* (2015) reported low fertility, low pH (KCl) of 3.5 - 4.9 and low CEC of 1.67-10.75 cmol/kg.

Although Boki LGA is a major producer of cocoa and oil palm in Cross River State, detailed pedological information on its stable-crestal soils remains inadequate. These soils are stable,

exhibit inherent soil properties (Esu, 2010) and occupy the highest landscape position (FAO, 2006). Existing studies in Boki and nearby Etung LGA have reported low pH, low base cations, and low CEC (Ajiboye *et al.* 2015; Kekong and Ndifon, 2020; and Ofem *et al.* 2025a), but did not provide comprehensive profile characterization linked to specific landscape positions and taxonomic units required for precision agriculture. This gap limits farmers' and extension agents' ability to make informed decisions about soil management, liming, and crop suitability.

Consequently, this study was conducted to characterize and classify crestal soils in Boki based on their morphological, physical, and chemical properties, as well as environmental variables. This aims to generate reliable soil data to guide sustainable land use, improve crop productivity in the area, and complement earlier studies in the largely agrarian area.

MATERIALS AND METHODS

Study area

Boki LGA lies at latitude 5°51'0'' to 6°36'0''N, and longitude 8°46'0'' to 9°14'0''E, having local boundaries with Obudu to the north, Ogoja to the west, Ikom and Etung to the south, and with international territorial boundaries with the Cameroons to the East (*Fig. 1*). In the low-lying areas of Boki is recent alluvium, whereas in the upland is shale and limestone with sandstone intercalation, porphyritic granite and biotite hornblende granite, and hornblende granite gneiss. The soils in the area have previously been classified as Typic Paleudult and Humic Hapludult {Luvic Umbrisol (Eutric, Loamic) and Luvic Umbrisol (Eutric, Humic, Loamic)} (Ofem *et al.*, 2025a), and have earlier been described as regolith and weathered ferallitic soils (Egesi, 2021).

Based on the Köppen climate classification, the area is tropical moist, with temperatures exceeding 18 °C year-round and precipitation exceeding 1500 mm/year. The rainfall in Boki is bimodal, with a range of 1200–3000 mm and an average of 2248.8 mm per year. Temperature varies from 22.56 to 31.95 °C, with a mean annual temperature of 26.9 °C (Sambo *et al.*, 2016). The vegetation is tropical rainforest, dominated by thick, tall, and luxuriant trees, covering more than half of the land area.

Soil profile selection and soil sampling

Field reconnaissance visits were conducted in five communities in Boki LGA, including Borum (BM), Okundi (OK1 and OK2), Biakwan (BK), Bamba (BA), and Kataba (KB). The visits were to verify the geology and identify crestal positions along toposequences using the digital elevation model, which defines the area's elevation ranges. The specific profile locations were therefore spotted using a German Etrex (2000) geographical positioning system meter. These areas have previously been mapped by the Nigerian Geological Survey Agency and shown to be underlain by shale and limestone with sandstone intercalations, porphyritic granite and biotite-hornblende granite, and hornblende-granite gneiss (Fig. 1).

Soil profile pits were randomly sunk on the crests of the identified toposequences in the various communities. Six representative soil profiles (BM, OK1, OK2, BK, BA, and KB) were therefore studied on the crests of major agrarian communities in Boki LGA. This aligns with the reports of Esu (2010) on the conditions for siting profile pits on a landscape unit. The report recommends a minimum of two (2) profile pits per position. However, for near-absolute representation, the current study exceeded the recommendation of Esu (2010) by sitting six (6) profile pits.

Soil profiles were dug at specifications of 2 m (length) x 1.5 m (width) x 2 m (depth). Each soil profile pit was georeferenced using a geographical positioning system, and general site information for the pits was recorded, with the profile pits described using soil description sheets according to the guidelines of Schoeneberger *et al.* (2012).

Soil samples were collected from identified horizons based on natural boundaries, from bottom to top. Soil sampling was done using a hand trowel. The soil samples were air-dried, ground, and sieved through a 2.00 mm mesh. Undisturbed core samples were collected from the soil horizons to determine total and air-filled porosities, gravimetric water content, and bulk density.

Laboratory studies

Fine earth fraction (< 2.00 mm) was used for laboratory analyses in the Soil Science Laboratory at the University of Calabar. However, soil samples intended for organic C and total N determinations were further sieved through a 0.5 mm sieve. All soil analyses were carried out by the procedures outlined in the Soil Survey Staff (2014a).

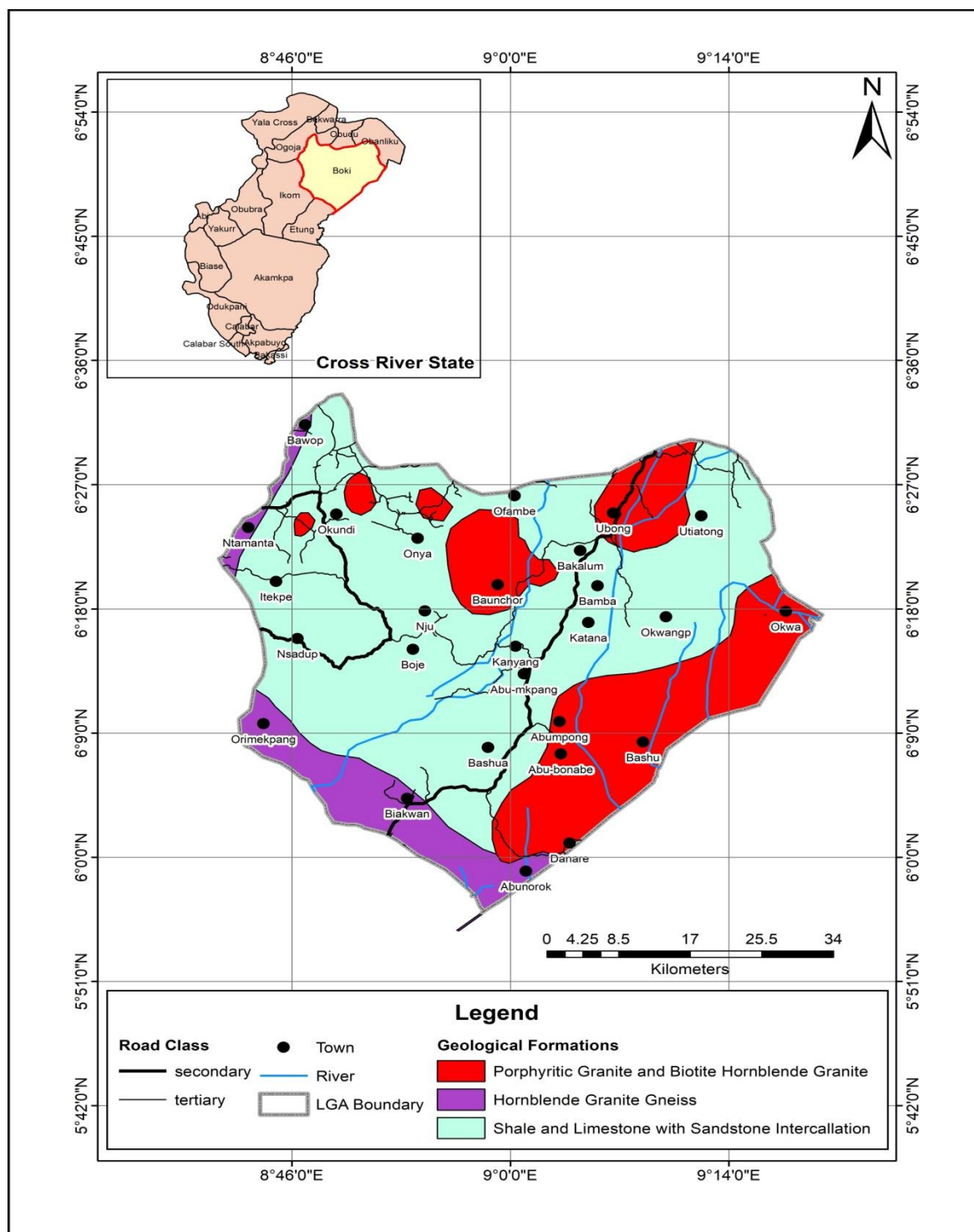


Figure 1: Geology of the study area

Source: GIS Unit, 2024

Particle size distribution was determined using the Bouyoucos hydrometer method with calgon as a dispersing agent. Soil moisture content was calculated as the mass of water in the soil expressed as a percentage of the fresh mass of the soil, whereas bulk density (Bd) was

determined by oven-drying undisturbed core soil samples at 105 °C to constant weight and dividing the oven-dry mass of the soil by the volume of the soil. Total porosity was expressed as $\{1 - (\text{bulk density}/\text{particle density})\} \times 100$, by using 2.65 Mg/m³ as particle density (Soil Survey Staff, 2014a). Consequently, air-filled porosity was estimated from the difference between total porosity and gravimetric water content.

The potentiometric method was used to determine soil pH in a soil-to-water or salt ratio of 1:2.5 using a glass-electrode pH meter, while the Walkey and Black wet oxidation method was employed to determine organic carbon, using diphenolic amine as the indicator and potassium dichromate as the oxidizing agent (Allison, 1965). The macro Kjeldahl method was used to determine total nitrogen using the macro-Kjeldahl digestion-distillation apparatus, while the Bray 1 solution was used as the extractant for available phosphorus determination. Exchangeable bases were determined by leaching the soil sample with 1 *N* neutral NH₄OAc at a pH of 7.0. The titrimetric method was employed to analyze exchangeable bases (K, Ca, Mg, Na), whereas cation exchange capacity (CEC) was assessed using the NH₄OAc displacement method at pH 7.0. Furthermore, exchangeable Al³⁺ and H⁺ were determined by titration with 1 *M* KCl as the extracting agent. Base saturation was estimated by expressing the sum of exchangeable bases (Ca²⁺, Mg²⁺, K⁺ and Na⁺) as a percentage of CEC (IITA, 1979).

Statistical analysis

Data were subjected to descriptive statistics, including the mean, range, and coefficient of variation, to assess variability across the six crestal locations. Principal component analysis was also used to explore relationships among soil properties. One-Way ANOVA was conducted at $p < 0.05$ for each of the 6 profiles to assess whether soil properties differ with increasing depth in crestal soils. Statistical analysis was carried out using Python 3.11 with Pandas, NumPy, and scikit-learn packages.

RESULTS AND DISCUSSION

Morphological properties of the soils

Soil morphological properties are presented in Table 1. The soils showed dominance of Bt and Crt horizons in the subsurface at 15-200 cm. This implies that eluviation of fine clays

from the Ap horizon resulted in their deposition in the B and C horizons in the process of argilluviation. This suggests extended pedogenesis that has occurred over longer periods in the soils, extending to the C-horizons, with indications of more intense argillation in the KB-profile. The findings in the current study align with those of Nwaka (1990) and Ayolagha (2001), who reported that soil development can be deduced from kinds and sequences of horizons in soil colour matrix in the surface soils ranged from dark reddish brown (5YR 3/3; 2.5YR 3/3) to reddish brown (2.5YR 4/3), very dark grey (5YR 3/1), dark brown (7.5YR 3/3) and dark grey (5YR 4/1), with yellowish red (5YR 5/6) and dark red (2.5YR 3/6) to red and reddish yellow (5YR 6/6) in the subsurface soils. Reddish colours and their variations indicate the presence of Fe_2O_3 and oxidized soil conditions, as evidenced in the study area. Silva-Neto (2008) and Tardi and Nahon (1985) attributed the reddish colours in some soils to rapid precipitation of iron oxides occasioned by high pH, which favours the precipitation of ferrihydrites. According to Esu (2010), reddish yellow indicates a transition from unhydrated Fe oxide in well-drained soil to hydrated Fe oxide under somewhat moister conditions. Mottle colours in the soils were not due to a high water table but to seasonal fluctuations in water, and ranged from common, medium-distinct pink (5YR 8/4) to red (10R 4/8).

Biological properties of the soils

The presence of ants, worms and termites across depths in the soils is an indication that soil mixing, otherwise called faunal pedoturbation, was a probable reason for the presence of transition horizons. Also, animal burrowing in and out of the soils encouraged aeration, water percolation and soil aggregate formation. Few charcoal particles were seen in some horizons, with only a few Fe_2O_3 nodules observed in OK2. Also, common clay cutans on ped faces were observed in the subsurface soils of OK2. The presence of cutans further suggests subsurface argillation and soil maturity (Esu, 2010).

Physical properties of the soils

Soil physical properties are presented in Table 2, while Table 3 shows the properties that differ with depth for crestal soils, highlighting the main depth-related differences.

Table 1: Morphological properties of the soils

Horizon	Depth (cm)	Munsell (moist)	colour	Mottles	Texture	Structure	Consistence	Boundary	Other characteristics
BK: N0491433, E0671864, 115 m above sea level									
Ap	0-30	Reddish brown (2.5YR 4/4)		-	SiL	1m gr	wss; mfi.	Cw	Many coarse pores; many roots of fine size.
Bt	30-58	Red (10R 4/8)		-	L	1m sbk	wss; mfr.	Gw	Common fine medium pores; and few common roots.
BC	58-109	Dark red (7.5R 3/8)		-	SiL	1m abk	wns; mvfr.	Cw	Few very fine pores.
Crt	109-200	Red (7.5R 4/8)		-	SiL	2m abk	ws; mfi.		
BA: N0513514, E0696737; 155m above sea level									
Ap	0-15	Reddish brown (2.5YR 4/3)		-	SL	2m Cr	wss; mvfri.	Cs	Common medium pores, many fine medium roots, ants and worms.
Bt	15-68	Dark red (2.5YR 3/6)		-	L	2m sbk	ws; mfri.	Gw	Few common fine medium pores; few fine roots
Crt1	68-145	Dark red (2.5YR 3/6)		-	CL	2m sbk	ws; mfi.	Gw	Few fine pores;
Crt2	145-200	Red (2.5YR 4/6)		-	CL	2m sbk	ws; mfi		Few fine pores
OK2: N0477707, E0712029; 199m above sea level									
Ap	0-30	Very dark grey (5YR 3/1)		-	SL	1m gr	wns; mvfri.	Cs	Many medium/coarse pores, few roots, many ants and termites.
Bt	30-100	Yellowish red (5YR 4/6)		c.m.d (Red) 10R 4/8)	CL	1m sbk	wss; mfri	Cw	Few pores; few roots; few Fe and Fe ₂ O ₃ nodules; few ants.
CB	100-135	Yellowish red (5R 4/6)		m.c.p. (Red) (2.5 YR4/8)	L	2m sbk	ws; mfi.	Gw	Few medium pores and roots, Fe ₂ O ₃ nodules, clay cutans on peds.
Crt	135-200	Reddish yellowish (5YR 6/6)		m.c.d. (Red) (2.5 YR4/8)	CL	2m sbk	ws; mfi.		Few very fine pores, few roots, Fe concretions, clay cutans on peds.
OK1: N0477691, E0711367; 141 m above sea level									
Ap	0-18	Dark reddish brown (2.5YR 3/3)		-	L	1m gr	wss; mvfri.	Cs	Many coarse pores and many roots; and ants holes seen
Bt	18-77	Red (2.5YR 4/8)		-	C	2m sbk	ws; mfi	Gs	Common medium pores; common medium roots and few ant holes.
BC	77-144	Red (2.5YR 4/8)			CL	2m sbk	ws; mfi.	Gw	Few fine pores; few medium root size
Crt	144-200	Red (2.5YR 4/8)		c.m.d (pink) (5 YR 8/4)	Sil	2m sbk	ws; mfi.		Few very fine pores; and few medium size roots.

BMM: NO485789, E07094301; 137m above sea level									
Ap	0-15	Dark reddish brown (5YR 3/8)	-	SL	1m gr	wss; mvfr.	Cs	Common many medium coarse pores; many medium and coarse roots; many termites, ants and worms.	
BC	15-100	Red (10R 4/6)	-	CL	2m Sbk	wss; mfr.	Cs	Many medium pores; common medium roots; Fe, and ants seen.	
Bt	100-130	Red (2.5YR 4/8)	-	CL	2m sbk	wss; mfr.	Cs	Few concretes seen and few ants sighted.	
Crt	130-200	Red (2.5YR 4/8)		SiCL	2m sbk	wss; mfr.	-	-	
KB: N0498178, E0691360; 152 m above sea level									
Ap	0-15	Dark grey (5YR 4/1)		SL	1m gr.	Wss; mfr.	Cs	Many fine medium pores; many roots and many ant holes.	
Bt	15-58	Yellowish red (5YR 4/6)		C	2m sbk	Ws, mfi.	Gw	Common fine medium pores and roots and few ant holes.	
BC	58-125	Reddish yellow (5YR 6/8)	(Red) 4/8)	CL	2m abk	Wvs; wvfi	Gs	Few fine medium pores; few fine roots, termites and ant holes seen.	
Crt	125-200	Reddish yellow (5YR 4/6)	(Red) (10R 4/8)	SiL	2m abk	Wvs, wvfi		Few fine pores; roots gravel seen.	

Mottles: cmd= common, medium, distinct; mcp= moderate, coarse, prominent; mcd= moderate, coarse, distinct; Texture= Si, L = loam, S = sand, C = clay; structure: 1,2,3 = weak, moderate, m, c = medium, coarse; gr, cr, sbk = granular, crumbly and sub-angular blocky; Consistence: w = wet, m = moist, ss = slightly sticky, fr = friable, fi = firm, v = very; Boundary: cs = clear smooth, cw = clear wavy, gw = gradual wavy; gi = gradual irregular, ASL: above sea level

Soil moisture content had ranges of 2.5 - 32.6 and 9.3 - 24.7 % in the surface and subsurface soils, respectively. The high percentage of soil moisture content exceeding 20% in most horizons will favour the availability of nutrients to plant roots and their growth, but may affect soil aeration and oxygen availability (Esu, 2010; Ofem *et al.*, 2021). Plants are likely to proliferate shallow roots in response to high soil moisture to take advantage of the solubility of nutrients in water. Coefficient of variability of moisture content between the surface soils was 55.5 % and described as high on the scale of Wilding (1985). At lower water tension, soils have more moisture, which requires less energy for plant uptake. Soil moisture content is essential for irrigation schedules (Shock and Wang, 2011), and it is often affected by crop type, soil texture, climate and method of irrigation (Shock and Wang, 2011; Tamburino *et al.*, 2020). This way, different crops are adapted to different climates.

Bulk density of 0.84 - 1.40 in the surface soils increased regularly with soil depth to 1.3 - 1.67 Mg/m³ in the subsurface soils. The soils may be slightly threatened by optimal air and water movement in some subsurface soils where values slightly exceed 1.6 Mg/m³ (Esu, 2010; Ofem *et al.*, 2021). Similar findings were obtained by Ajiboye *et al.* (2015), who reported that the cocoa-growing soils of Etung had a range of 0.91-1.84 Mg/m³, with the surface horizons having lower bulk density. Consequently, horizons with bulk density <1.3 Mg/m³ indicate a porous soil condition (Esu, 2010), while 1.1 – 1.4 Mg/m³ is optimum for cultivated loams (Donahue *et al.*, 1983). Bulk density varied moderately between the surface soils with a CV of 16.2%. The proliferation of adventitious roots is sensitive to an increase in soil bulk density (Nunes *et al.* 2016). Bulk density differed significantly ($p < 0.05$) with soil depth across all studied soil profiles except in BK (Table 3).

Total soil porosity ranged from 47.2 to 68.3% in the surface soils, with a steady decrease with increasing soil depth to 37-50.9% in the subsurface soils, and a CV of only 13.5%. The soils were rated high for total porosity on the scale of Brady (1974), with values exceeding 50%. The soils are porous (Paglia, 1988; Ofem *et al.*, 2021), with a high potential for nutrient leaching. High porosity may be a reason for the reddish colouration of the soil. However, most total porosity values in subsurface soils were less than 50%. In related studies by Fetter (1998) and Rieu and Sposito (1991), reports have it that when total porosity is greater than 45.50 %, the soils are considered good for agriculture.

Table 2: Physical properties of the soils

Soil profiles	Soil depth Cm	% Moisture content	BD Mg/m ³	%TP	%MaP	% Clay	% Silt	% Sand	Textural class
BK	0-30	21.4	1.40	47.2	25.8	18.8	54.0	27.2	SiL
	30-58	14.4	1.55	41.5	27.1	26.8	42.0	31.2	L
	58-109	16.9	1.42	46.4	29.5	14.8	56.0	29.2	SiL
	109-200	16.0	1.56	41.1	25.1	16.8	64.0	19.2	SiL
BA	0-15	2.5	1.40	47.2	44.7	12.8	26.0	61.2	SL
	15-68	12.7	1.49	43.8	31.1	26.8	36.0	37.2	L
	68-145	23.5	1.41	46.8	23.3	28.8	38.0	33.2	CL
	145-200	16.9	1.39	47.5	30.6	28.8	46.0	33.2	CL
OK2	0-30	17.5	1.18	55.5	38.0	14.8	20.0	65.2	SL
	30-100	16.9	1.67	37.0	20.1	38.8	40.0	21.2	CL
	100-135	21.0	1.34	49.4	28.4	24.8	44.0	31.2	L
	135-200	21.0	1.38	47.9	26.9	26.8	40.0	33.2	CL
OK1	0-18	32.6	0.84	68.3	35.7	22.8	30.0	47.2	L
	18-77	19.0	1.45	45.3	26.3	44.8	34.0	21.2	C
	77-144	22.6	1.42	46.4	23.8	28.8	48.0	23.2	CL
	144-200	24.4	1.40	47.2	22.8	18.8	68.0	13.2	SiL
BMM	0-15	20.5	1.23	53.6	33.1	10.8	22.0	67.2	SL
	15-100	12.6	1.48	44.2	31.6	28.8	28.0	43.2	CL
	100-130	22.2	1.40	47.2	25.0	32.8	46.0	21.2	CL
	130-200	24.7	1.48	44.2	19.5	28.8	54.0	17.2	SiCL
KB	0-15	12.5	1.29	51.3	38.8	16.8	26.0	57.2	SL
	15-58	9.3	1.39	47.5	38.2	42.8	28.0	29.2	C
	58-125	18.8	1.38	47.9	29.1	38.8	36.0	25.2	CL
	125-200	18.5	1.30	50.9	32.4	18.8	62.0	19.2	SiL
Range Surface		2.5-32.6	0.84- 1.40	47.2- 68.3	25.8- 44.7	10.8- 22.8	20.0- 32.0	47.2-67.2	
Mean surface		17.8	1.22	53.9	36.0	16.1	29.7	54.2	
CV Surface (%)		55.5	16.20	13.5	17.0	26.4	41.9	28.4	
Range Subsurface		9.3-24.7	1.30- 1.67	37.0 - 50.9	19.5- 38.2	18.8- 44.8	26.0- 68.0	13.2-45.2	
Mean Surface		18.4	1.44	45.7	27.3	28.7	45.0	26.8	

BD = Bulk density, TP = Total porosity, MaP = Macro Porosity. Textural class: Si = Silt, L = Loam, C = Clay, S = Sand. CV= Coefficient of variation, < 15 % = low, 15 – 35 % = moderate, >35 % = high, (Wilding, 1985)4

Table 3: **Physical soil properties differing with soil depth in the crest**

Soil profiles	% Moisture content	BD Mg/m ³	%TP	%MaP	% Clay	% Silt	% Sand
BK	NS	NS	NS	NS	*	NS	*
BA	NS	*	NS	*	*	NS	NS
OK2	NS	*	*	NS	*	*	*
OK1	NS	*	*	*	*	*	*
BMM	NS	*	*	*	*	*	*
KB	NS	*	*	NS	*	*	*

NS = Not significant, * = Significant at $p < 0.5$, BD = Bulk density, TP = Total porosity, MaP = Macro porosity
Total porosity differed significantly ($p < 0.05$) with soil depth across all the studied soil profiles except in BK and BA (Table 3).

Macro -porosity decreased from 25.8 - 44.7 in the surface soils to 19.5 - 38.2 % in the subsurface soils with a moderate CV of 17 %. Macro porosity differed significantly ($p < 0.05$) with soil depth across BA, OK1 and BMM profile pits (Table 3). Studies by Silva (2004) stated that for continuous plant growth in agriculture and food production, the critical air-filled porosity should be 10%. This suggests good air porosity that allows for good aeration, water movement and solubility of nutrients. According to the ratings of Engalaar and Yoneyama (2004), when air-filled porosity decreases to 10% or less, the soil oxygen diffusion rate is inhibited. This results in root injury and an inability to function optimally, harming plant growth (Grichko and Glick, 2001; Voorhees *et al.*, 1975).

Clay amount was below 25 % in the surface soils and below 45 % in the subsurface soils. Clay was moderately variable in the surface soils, with a CV of 26.4%. However, clay bulges were clearly observed between 15 and 60 cm in profile depth. The high clay content, particularly in the subsurface soils, implies that the soils are well-developed and have been exposed to prolonged pedogenesis. Similar clay bulges have been reported by Ofem and Esu (2015) and Ajiboye *et al.* (2015) in parts of Cross River State. According to Birkeland (1984), larger soil particles weather physically to smaller particle sizes like silt and clay with soil age. Additionally, Cowie (1968) and Thompson (1981) reported that total silt and clay in soil profiles show straight-line relationships with soil age, while Weerden *et al.* (2010) opined that the amount of clay is responsible for pore-size distribution. In all studied crestal soils, the amount of clay differed significantly ($p < 0.05$) with soil depth (Table 3). This

underscores the importance of clay movement with soil depth in the genesis of the soils under study.

Sand content showed clear dominance, with values in the surface soils exceeding 25% and decreasing regularly with soil depth. Although the sand content is high, it falls short of the silt content in some horizons. This suggests that the sand-sized particles may have been weathered to finer particles of silt and clay over time (Birkeland, 1984). Soils with finer particles like clay and silt have larger surface areas and a greater capacity for cation adsorption on the soil exchange complex. However, the somewhat high amount of sand in the soil may contribute to the leaching of exchangeable bases. Sand content had a moderate CV of 28.4% across the studied profiles and varied significantly with soil depth, except in the BA profile pit.

Soil chemical properties

Soil chemical properties are presented in Table 4, while Table 5 presents chemical soil properties that differ with depth for cretal soils. Soil pH varied irregularly with soil depth, with ranges of 4.9–5.5 and 4.7–5.5 pH units in the surface and subsurface soils. Coefficient of variation of 4 % across the surface soils qualified the soils as having low pH variability on the scale of Wilding (1985). At all depths, pH (KCl) was lower than pH (H₂O) by about 1 pH unit. These values were rated as very strongly to strongly acidic on the scale of Holland *et al.* (1989). This suggests that exchangeable Al³⁺ and H⁺ are present in the soil solution to affect plant growth. In a similar study by Kekong and Ndifon (2020), the pH of Boki cocoa-growing soils ranged from 4.9 to 5.1, whereas Ofem and Esu (2015) reported a pH of 4.3–5.2 (H₂O). Such ranges could result from heavy rainfall and soil weathering. According to Udo *et al.* (2009), a pH of 4.5–5.5 indicates a significant amount of exchangeable Al³⁺ in the soil solution that is likely to affect crop production.

Soil organic carbon showed a regular decrease from 1.44–3.11 % in the surface soils, with a moderate CV of 33.7 % among the surface cretal soils. The organic carbon content is high on Holland *et al.*'s (1989) scale, with values exceeding 1.5%. High organic carbon may be due to leaf fall in the densely forested area of Boki, as well as delayed mineralization relative to humification (Haynes, 2005). This could show that the soils contain either umbric or mollic epipedon as values of organic carbon in the upper 15 cm were higher than 0.6 % (Esu,

2010). The current study aligns with the results obtained by Ajiboye *et al.* (2015), who reported that soil organic carbon in Etung ranged from 0.04% in the subsurface horizons to 3.5% in the surface horizons. Soil organic carbon differed significantly ($p < 0.05$) with soil depth across all studied crestal profile pits (Table 5). This steep depth-wise variation could be due to surface deposition of organic materials.

Total N was below 0.30 % in the soils with a high CV of 35 % across surface soils on the scale of Wilding (1985) but decreased regularly with soil depth and qualified as low on the scale of Holland *et al.* (1989). This decrease could result from inhibited bacterial activity and an unfavourable pH for the decomposition of soil organic matter and the release of N (Agbede, 2009). The results in the current study are dissimilar to the findings of Kekong and Udie (2020) in Boki, who, however, reported that total nitrogen content in Boki soils was 0.9 %, attributing the low values to continued nutrients mining by plants. Total N differed significantly ($p < 0.05$) with soil depth across all studied crestal profile pits (Table 5).

Available phosphorus distribution aligned with organic carbon and ranged from 1.5 to 13.5 mg/kg in the surface soils with high CV of 64.4 %. Available P decreased irregularly as soil depth increased. Such irregularity may be due to soil pH fluctuation with depth (Agbede, 2009). The soils were rated low to medium in available P (Holland *et al.*, 1989) as values were found to be below 20 mg/kg. Available P differed significantly ($p < 0.05$) with soil depth in KB, while values in other crestal profiles did not vary significantly (Table 5). Exchangeable Ca ranged from 2.8 to 7.8 cmol/kg, while Mg ranged from 0.4 to 1.4 cmol/kg in the surface soils. Both exchangeable bases differed significantly with soil depth in the crestal soils. However, exchangeable Mg^{2+} did not differ with soil depth in OK1. Exchangeable Ca^{2+} and Mg^{2+} had CVs of 32.1 and 49.4 %, and qualified as moderate and high on the scale of Wilding *et al.* (1985).

Though Ca and Mg dominated the soil's exchange complex as reported in Ofem *et al.* (2025^{a,b,c}) and Ofem *et al.* (2024^a) for tropical soils, the values of exchangeable Ca and Mg were low to moderate on the scale of Holland *et al.* (1989). Such rating may be due to leaching occasioned by the high rainfall amount in the area, sandy textures as well as steep slopes in high elevations. Despite the low to moderate rating of the soils for Ca and Mg, they have been largely utilized for cocoa production (Ajiboye *et al.* 2015) and reported as moderately to highly suitable for cocoa production (Ojie *et al.*, 2024; Ofem *et al.*, 2024b).

Table 4: Chemical properties of the soils

Profile pit	Soil depth Cm	pH		% Org C	%T.N	Avail. P mg kg ⁻¹	Ca ²⁺ cmol kg ⁻¹	Mg ²⁺ cmol kg ⁻¹	K ⁺ cmol kg ⁻¹	Na ⁺ cmol kg ⁻¹	Al ³⁺ cmol kg ⁻¹	H ⁺ cmol kg ⁻¹	CEC	%BS
		H ₂ O	KCl											
BK	0-30	5.5	4.7	2.13	0.18	6.75	5.6	1.4	0.11	0.09	0.00	1.00	20.0	36
	30-58	5.5	4.4	1.89	0.16	5.87	4.6	0.8	0.11	0.10	0.00	1.04	18.0	31
	58-109	5.2	4.4	0.32	0.02	3.37	3.0	0.6	0.10	0.08	0.76	0.40	14.0	27
	109-200	5.0	4.4	0.24	0.01	5.12	2.8	0.4	0.09	0.07	0.52	1.04	12.0	28
BA	0-15	5.4	4.4	1.64	0.14	1.50	5.6	0.4	0.11	0.09	0.00	0.72	19.0	33
	15-68	5.0	4.4	0.76	0.06	1.50	4.4	0.2	0.09	0.07	0.40	0.70	16.0	30
	68-145	5.4	4.5	0.50	0.04	2.75	4.0	0.4	0.11	0.09	0.46	0.72	16.0	29
	145-200	5.3	4.0	0.20	0.01	1.25	3.8	0.4	0.10	0.08	1.00	0.48	12.0	37
OK2	0-30	5.2	4.4	1.34	0.11	8.25	4.4	0.8	0.10	0.08	0.00	0.96	17.0	32
	30-100	5.0	4.3	0.58	0.04	5.25	3.0	0.6	0.09	0.07	1.16	0.76	13.0	29
	100-135	5.0	4.2	0.42	0.03	4.50	4.0	0.6	0.09	0.08	0.64	1.82	14.0	34
	135-200	5.1	4.1	0.17	0.01	4.50	3.0	0.4	0.10	0.08	1.52	1.28	16.0	22
OK1	0-18	5.1	4.3	3.11	0.27	7.37	2.8	0.8	0.08	0.06	0.52	0.94	11.0	34
	18-77	4.7	4.3	0.66	0.05	5.37	2.8	0.4	0.09	0.07	0.80	0.80	12.0	28
	77-144	4.9	4.3	0.46	0.03	5.62	2.8	0.4	0.12	0.09	0.00	1.00	14.0	24
	144-200	5.2	4.2	0.44	0.03	7.87	2.8	0.4	0.11	0.08	0.36	1.00	15.0	23
BMM	0-15	4.9	4.3	2.59	0.22	2.62	7.8	1.4	0.08	0.07	0.08	0.64	18.0	52
	15-100	5.1	4.5	0.42	0.03	2.75	4.2	0.4	0.10	0.08	0.00	0.72	11.0	43
	100-130	5.4	4.5	0.24	0.01	2.25	4.0	0.2	0.10	0.09	0.40	0.44	16.0	27
	130-200	5.5	4.4	0.30	0.02	2.12	3.8	0.2	0.10	0.09	0.40	0.44	11.0	38
KB	0-15	5.1	4.3	1.44	0.12	13.5	4.6	0.4	0.11	0.09	0.00	0.70	18.0	29
	15-58	5.0	4.2	0.76	0.06	4.12	2.8	0.4	0.10	0.08	1.92	0.16	14.0	24
	58-125	4.9	4.2	0.32	0.02	3.62	2.8	0.4	0.12	0.10	1.08	1.16	11.0	31
	125-200	5.3	4.2	0.28	0.01	4.75	2.6	0.2	0.10	0.08	1.64	0.72	10.0	30
Statistics	Range Sur	4.7-5.5	4.3-4.7	1.34-3.11	0.11-0.27	1.5-13.5	2.8-7.8	0.4-1.4	0.08-0.11	0.06-0.09	0.0-0.52	0.64-1.0	11-20	32-52
	Mean Sur	5.2	4.4	2.04	0.17	6.70	5.1	0.9	0.10	0.08	0.10	0.83	17.2	36
	CV Sur (%)	4.0	3.4	33.70	35.00	64.40	32.1	49.4	13.90	16.40	202.5	16.80	17.1	22
	Range Sub	4.7-5.5	4.0-4.5	0.17-1.89	0.01-0.16	1.25-7.87	2.6-4.6	0.2-0.8	0.09-0.12	0.07-0.10	0.0-1.92	0.16-1.82	10-18	22-43
	Mean Sub	5.1	4.3	0.50	0.04	4.03	3.4	0.4	0.10	0.08	0.73	0.82	13.6	30

NB: Org C = Organic carbon, T. N. = Total nitrogen, avail. P = available P, CEC = cation exchange capacity, BS= Base saturation

CV= Coefficient of variation, < 15 % = low, 15 – 35 % = moderate, >35 % = high, (Wilding, 1985)

Table 5: Chemical soil properties differing with soil depth in the crest

Profile pit	pH (H ₂ O)	pH(KCl)	% Org C	%T.N	Avail. P	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	Al ³⁺	H ⁺	CEC	%BS
BK	NS	NS	*	*	NS	*	*	NS	NS	*	*	*	NS
BA	NS	NS	*	*	NS	*	*	NS	NS	*	*	NS	NS
OK2	NS	NS	*	*	NS	*	*	NS	NS	*	*	*	NS
OK1	NS	NS	*	*	NS	*	NS	NS	NS	NS	NS	*	NS
BMM	NS	NS	*	*	NS	*	*	NS	NS	NS	NS	*	*
KB	NS	NS	*	*	*	*	*	NS	NS	*	NS	*	NS

NS = Not significant, * = Significant at $p < 0.05$, Org C = Organic carbon, T. N. = Total nitrogen, Avail. P = available P, CEC = cation exchange capacity, BS= Base saturation

Exchangeable potassium and sodium were below 0.2 cmol/kg in all the studied soils and found within the range of low on the scale of Holland *et al.* (1989). The soils are also not likely to be sodic and harmful to plants roots as exchangeable Na⁺ values were less than 1.0 cmol/kg (Olasoji *et al.* 2022; Uwitonze *et al.* 2016).

Moderate concentrations of exchangeable Al³⁺ and H⁺ which were largely below 1.0 cmol/kg corroborate the soil pH level and do not pose threats to plants due to Al toxicity (Ajiboye *et al.*, 2015). This is because values are below 20 % on the soil exchange complex. As Al³⁺ are released during acidification or weathering processes, they become more accessible on cation exchange sites; in solution or simply on exposed surfaces. This identifies Al toxicity as a major limiting factor in plant growth in acid, highly weathered tropical soils (Ofem *et al.*, 2025a). Higher values of exchangeable H⁺ compared to Al³⁺ as was the case in most of the studied soils suggest that the hydrolytic reaction of Al³⁺ had proceeded at a faster rate leading to the formation of H⁺.

Cation exchange capacity had ranges of 10 – 20 in the surface soils and appeared to decrease to 10 – 18 cmol/kg in the subsurface soils. Since most values fell within 12 – 20 cmol/kg, the soils are rated as moderate in CEC on the scale of Holland *et al.* (1989). It differed significantly with soil depth except in OK1, and had moderate CV of 17.1 % across the surface soils of profile pits and qualified as moderate on the scale of Wilding (1985). The moderate level of CEC seems to have aligned with the moderate to high SOC, while its distribution significantly varied with soil

depth followed clay amount. However, the leaching of exchangeable bases and weathering processes due to high rainfall in the area have impacted on the soils CEC.

Base saturation of the soils was largely below 40 % irrespective of soil depth, and found within the low to moderate rating on the scale of Holland *et al*, (1989). This is an indication that basic nutrients may not have occurred in available forms in soil solution for plant uptake or the soils may have been highly weathered and lost its basic cations to leaching. Base saturation decreased at the argillic B horizons reaching values below 50 %. A possible indication that the soils are ultisols (Esu, 2010).

Interpretation of principal component analysis of the surface soils

In order to know the principal contributors to soil variation as reported by the coefficient of variation, principal component (PC) analysis extracted three principal components accounting for 87.3 % of total variance (Table 6). PC1 was positively associated with soil fertility, defined by organic C, total N, CEC, exchangeable Ca^{2+} and porosity and negatively loaded by bulk density. Soil properties having positive loading are positively correlated, whereas negative loadings as in the case of bulk density suggests an inverse relationship. PC2 was positively loaded by sand and Al^{3+} , and negatively loaded by silt, clay and pH suggesting soil textural and acidity influence. PC3 was associated with available P and soil moisture. Properties classified in PC1 are more influential and contribute more to the variation of soils. This suggests that fertility and textural differences are the major sources of variation among crestral soils in Boki LGA.

Table 6: Principal components correlation with variables

PC	Soil properties	Eigenvalue	% Variance	Cumulative %
PC1	Org C, TN, CEC, Ca, %TP	9.42	47.1	47.1
PC2	Sand, Al^{3+} , pH, Silt	4.51	22.5	69.6
PC3	Available P and % moisture content	3.53	17.7	87.3

PC = Principal component, Org. C = organic carbon, TN = Total nitrogen, CEC = Cation exchange capacity, TP = Total porosity, Ca = calcium

Taxonomic classification of the soils

The studied soils had argillic horizons beginning at depths of 30, 15, and 18 cm, with base saturation (NH₄OAc at pH 7.0) below 35% in the Bt horizons, and qualify as Ultisols by the USDA system (SSS, 2014b). Udic soil moisture regime, which characterizes the soils, qualifies them as Udults. With increasing soil depth, the soils do not have a clay decrease of 20% or more from the maximum clay content and qualify as Paleudults in the great group and as Typic Paleudults in the subgroup category. By the World Reference Base for Soil Resources system (World Reference Base, 2014), BK and OK2 have > 0.6 % SOC, umbric epipedon (> 25 cm thick, < 50 % base saturation by NH₄OAc) and qualify as Umbrisol, whereas other soils with thickness < 20 cm, ochric epipedon and with argic horizons (< 100 cm), low base saturation (< 50 % NH₄OAc) qualified as Acrisols. With argic horizon starting < 100 cm from the mineral soil surface, CEC by NH₄OAc of > 24 cmol/kg clay within 150 cm of the mineral soil surface, and exchangeable Al < exchangeable (Ca + Mg + K + Na) throughout the depth, the Umbrisols qualify in the Luvic Principal qualifier. Clay loam and loam textural classes with thicknesses ≥ 30 cm within the first 100 cm of mineral soil surface further qualify the soils for the Loamic Supplementary qualifier. Also, at a 20– 50 cm depth of the mineral soil surface, exchangeable (Ca + Mg + K + Na) > exchangeable Al at all depths of the profile qualifies the soils for the Eutric supplementary qualifier. Therefore, BK and OK2 soils qualify as Luvic Umbrisol (Eutric, Loamic). Acrisols are characterized by the Haplic as the principal qualifier, with a range of supplementary qualifiers. For example, OK1 and KB have clayic, while BA and BM have loamic supplementary qualifiers due to the clay and clay loam textural classes, respectively. However, OK1, KB, BA and BMM have an ochric supplementary qualifier. Therefore, OK1 and KB are classified as Haplic Acrisol (clayic, Ochric, while BA and BMM were classified as Haplic Acrisol (Loamic, Ochric).

SUMMARY AND CONCLUSION

The study aimed to characterize and taxonomically classify the soils of Boki Local Government Area based on the morphological, physical, and chemical properties of six crestal soil profiles. The soils were predominantly reddish throughout the profile, while bulk density and soil porosity encouraged the proliferation of plant roots at all depths. The contents of silt and sand were quite

similar, dominating the soils at various times and resulting in silt loam, sandy loam, or loam in the surface soils. However, clay bulges occurred in all profiles at depths exceeding 15 cm. Soil pH was below the optimum 5.5–6.5 pH units, and soil organic carbon was high, with most values exceeding 1.5%. Furthermore, exchangeable Ca, Mg and cation exchange capacity were low to moderate. Organic C, total N, CEC, exchangeable Ca²⁺ and porosity were among the soil properties expressed by PC1, whereas organic C, total N, CEC, exchangeable Ca²⁺, Mg²⁺, clay, and bulk density consistently differed with soil depth in all six (6) crestal soils.

The soils qualified as Typic Paleudults in the USDA system. In the World Reference Base for Soil Resources system, the soils were classified as Luvic Umbrisol (Eutric, Loamic), Haplic Acrisol (clayic, Ochric) and Haplic Acrisol (Loamic, Ochric).

The application of agricultural lime is recommended to raise soil pH to 5.5–6.5 and increase nutrient availability. This way, soil biological activities will be enhanced for enhanced crop production. Considering the low exchangeable K⁺ in the soils, potassic fertilizers are recommended to boost K levels while practicing conservation farming such as alley cropping, minimum tillage, and cover cropping.

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