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Original Article

Pedological characterization and classification of sandy soils along a toposequence in the tropical rainforest of Nigeria

OPEN ACCESS

Frank Chibuzor OKENMUO*[1,2]

[1]*Department of Environmental Management, Pan African University of Life & Earth Sciences Institute, University of Ibadan, Ibadan, Nigeria*

[2]*Department of Soil Science, Chukwuemeka Odumegwu Ojukwu University, Igbariam, Nigeria*

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A B S T R A C T

Soil profiles are essential for understanding soil variability and precise micro-management especially of farmers' fields. This study characterized the sandy soils occurring on a toposequence of Ojoto, Anambra State, Nigeria for appropriate conservation and management. Four profile pits were excavated along the toposequence, following the slope classes viz: hilltop, back-slope, foot-slope and toe-slope. Soil samples were collected from the soil profiles based on the pedogenetic horizons for morphological description, physicochemical properties and classification. The topsoil depths increased by 5 cm from the upper slope to the toe slope. Soil colour of the horizons mainly contrasted from strong brown (7.5YR 4/6) through yellowish red (5YR 5/8), with redness increasing with depth down the soil profiles. Soil structure contrasted from weak/fine granular to subangular blocky. Textural classes were mainly sandy (greater than 82 %) with little clay illuviation. Crestal positions are possibly more resistant to soil erosion due to greater amount of clay. The pH ranged from strongly to moderately acidic (pH 4.7-5.7 in KCl). The concentration of Organic matter (3.7-23.3 g kg^{-1}), available phosphorus (1-16 mg kg^{-1}), total nitrogen (0.2-1.3 g kg^{-1}), and ECEC (2.9-6.0 cmol kg^{-1}) were generally low. The base saturation status (72-89%) was generally high, while exchangeable calcium (0.1-0.6 cmol kg^{-1}), magnesium (0.2-0.6 cmol kg^{-1}) were low. The soils are classified as Typic Hapludox and correlated with Arenic Ferralsols. The initiation of fertilization and soil stabilization programmes in the area can replenish nutrient reserves and improve soil resistance to erosion.

K E Y W O R D S : *Catena, Land use, Red soils, Soil conservation, Soil depth.*

INTRODUCTION

The global threat to continued life dependence on soils is a direct result of a lack of understanding of its properties, processes, and dynamics, which is crucial for informing its sustainable use. Soil is formed from the interaction of factors such as parent material, climate, living organisms, relief and time (Sharma & Bhakri, 2019). As a result, variations in interactions between the active (climate and organisms) and passive (parent material, relief and time) factors, soil often exhibit natural variabilities. Relief is an important modifier associated with water, temperature, soil erosion, and micro-climate relations at local and regional scales. It influences depth, texture, biological activities and soil profile development from one area to another (Pidwirny, 2006). Even at fine-scale, topographic variations of landscapes (catena) have been reported to responsible for variation in soil properties (Okenmuo *et*

*Corresponding author: fcvokenmuo1@gmail.com

al., 2020; Ukabiala *et al.*, 2022). The term catena is an array of soil under same parent materials but dissimilar elevation characteristics, from the top to the bottom of a slope.

Many scientists in Nigeria have attempted to study soils based on the catenary sequences (Aweto & Enaruvbe, 2010; Samndi, 2012; Osujieke, 2017). Catenary-related variations in soil properties have relationships with soil texture, structure, depth, pH, organic carbon and total nitrogen, available phosphorus, total exchangeable bases, cation exchange capacity, micronutrients and land use. In Cumberland, Arnold (2005) found a significant link between parent material, landscape position, and soil slope. Hapludults thrived in areas where pedogenesis was evident, while Dystrudepts were prevalent in locations with limited pedogenesis. Similarly, heterogeneity in chemical properties and taxonomic units have been largely related to relief and hillslope position (Aweto & Enaruvbe, 2010; Deressa *et al.* 2018). Soil profiles along a catena can be remarkably different in morphological, physicochemical properties, classification and management requirements. The strong correlation between topography and soils in tropical belt of West Africa has long been reported (Moorman, 1981; Okunsami *et al*, 1985). The variations in the characteristics of soils along a catena provides a useful tool for soil mapping, erosion assessment and fertility conservation (Rehm & Grashey-Jansen, 2016; Osujieke, 2017). This study aimed to assess the variation of soil properties on a sand-texture-dominated catena, their classification and suggest appropriate landscape management.

MATERIALS AND METHODS

Description of the study area

The study area is Ojoto located in Anambra State, Southeastern Nigeria (Figure 1). The area falls within the tropical climate (Koppen's Awi climate) with an annual rainfall of about 1500 mm – 3000 mm and characterized by two distinct conditions i.e. the dry and wet months. (Nigerian Meteorological Agency, 2013; Anambra State Nigerian Erosion and Watershed Management Project, 2017). The mean temperature is about 32ºC during the hottest months of February to April. The area is drained by the Idemili River and other smaller streams. The geological formation is the Ogwashi-Asaba Formation (Miocene series) described by (Onu & Ibezim, 2004) and the general elevation ranges from 73 - 83.5 m above sea level. In terms of geomorphology, undulating and depressed landscapes are common feature. The soil is predominantly reddish sand with low cohesion. Due to the rapid population growth and urbanization, intense pressure is on land resources. Hence the former crop rotation and bush fallow systems have been replaced with continuous cropping.

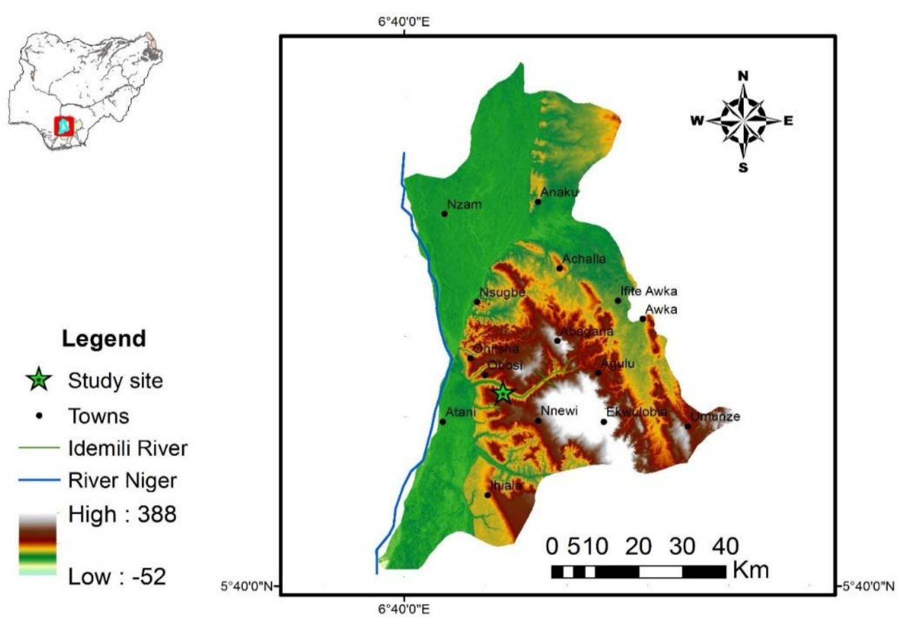

Figure 1: Location of the study area

METHODOLOGY

A hillslope was demarcated into four zones based on the differences in the elevation, colour of top soils and vegetation patterns. The hillslope terminated in a dry gullied valley. One profile pit was sited in each zone and georeferenced using a Geographical Positioning System (GPS) (GARMIN GPSMAP 64SC). The characteristics of the positions are shown in Table 1. The surrounding site and the morphology of the profiles were described based on the Field Soil Description Guide (FAO, 2006). The profiles were sampled from the lower horizons upwards, bagged and transported to the laboratory. The samples were subsequently air dried, sieved and subjected to physico-chemical analysis.

Table 1: Positions and characteristics of sites

Landscape position	Latitude	Longitude	Elevation	Land Use
Hilltop	6°04'31.64" N.	006°52' 16.48"E.	83.5 meters a.s.l.	Arable cropping
Back-slope	6°04'32.69" N	006°52'15.22" E	79 meters a.s.l.	Grassland
Foot-slope	06°4.33.8" N.	006°52'14.0" E.	75 meters a.s.l.	Grassland
Toe-slope	6°4' 34.92"N.	006°52'12.87" E.	72 meters a.s.l.	Mixed land use

Soil analysis

Particle size distribution of the soils was determined using the hydrometer method as described by Gee & Or (2002) using sodium hexametaphosphate (calgon solution) as dispersant. Soil textural classes were read from the textural triangle (WRB, 2014). The soil pH was determined using 0.1N KCl solution. After stirring for 30 minutes, the pH was read off using the Hanna electrical pH meter (Mclean, 1982). The electrical conductivity was determined using the electrical conductivity meter. Exchangeable acidity was extracted by 1 M KCl solution and determined titrimetrically (Bertsch & Bloom, 1996). Total nitrogen was determined by Micro-Kjeldahl method using $CuSO_4/Na_2SO_4$ catalyst mixture in a digestion flask and afterwards distilled and titrated with 0.05N HCl (Bremmer & Mulvaney, 1982). Available phosphorus was determined using Bray-2 extraction method as described by Page *et al*.(1982). Soil organic carbon (SOC) was determined using the modified Walkley-Black wet digestion and combustion method described by Nelson & Sommers (1982). Organic matter (OM) was calculated by multiplying the value for organic carbon by the "Van Bemmelen factor" (1.724) (Allison, 1982). Exchangeable cations (Ca, Mg, Na, K were extracted by 1M ammonuim acetate (NH_4OAc) solution at pH 7.0 (Thomas, 1982). Afterwards, Exchangeable Ca and Mg in leachate were determined by Atomic Absorption Spectroscopy (AAS) technique while Na and K were determined by flame photometry. Effective Cation Exchange Capacity (ECEC) was determined by the summation of the exchangeable bases (Ca, Mg, K, and Na) and exchangeable acidities (H and Al). Base saturation (BS) (Eq. 1) was calculated as the summation of exchangeable bases and dividing by the respective CEC and multiplying the quotient by 100.

$$BS = \frac{TEB}{CEC} \times \frac{100}{1} \quad (1)$$

Where TEB = Total exchangeable bases, CEC = Cation exchange capacity.

Soil Classification

The nutrient ratings by Esu (1991) and the Federal Fertilizer Department (2012) were used to rate the analytical chemical parameters (Table 2). All profiles were classified according to the U.S. Soil Taxanomy (Soil Survey Staff, 2014) and correlated with the FAO WRB System (2014).

RESULTS AND DISCUSSION

Morphology and Genesis of the soils

The slope was undulating (8%) and all the profiles were well drained. The morphological properties of the soils are presented in Table 3. The soils are generally moderately deep to deep, with topsoil depth of 10-30 cm. Topsoil depths increased by 5 cm from OJO-1 (hilltop) to OJO-4 (toe-slope). This is a reflection of erosion and deposition occurring down the catena and consequently leaving behind light and thinner soils upslope. This partly agrees with Moore *et al.* (1993) who observed that horizons thicker than 25 cm were mostly confined to the hilltop and toe-slope positions of an eroding landscape. The soil solum (A and B horizon) development generally had greater age down slope, this has been attributed to acrition down slope (Akamigbo & Asadu, 1986). The solum thickness is expected in the humid tropics compared to drier regions. The moist color (Munsell) indicated variation in soil colour matrix from 2.5YR to 7.5YR. The topsoil ranged from reddish brown at OJO-4 (5YR 5/4) and OJO-1 (2.5YR 4/4) to strong brown at OJO-2 and OJO-3 (7.5YR /6).

Table 2: Critical limits for interpreting fertility levels of soil analytical parameters

Parameter	Very low	Low	Moderate	High	Very high
Ca^{2+} (cmol kg^{-1})	<2.0	2.0-5.0	5.0-10.0	10.0-20.0	>20.0
Mg^{2+} (cmol kg^{-1})	<0.3	0.3-1.0	1.0-3.0	3.0-8.0	>8.0
K^{+} (cmol kg^{-1})	0.12-0.2	0.21-0.3	0.31-0.6	0.61-0.73	>0.74
Na^{+} (cmol kg^{-1})	<0.1	0.1-0.3	0.3-0.7	0.7-2.0	>2.0
CEC (cmol kg^{-1})	<6.0	6.0-12.0	12.0-25.0	25.0-40.0	>40.0
Org. C (g kg^{-1})	<4.0	4.0-10	10-14	14-20	>20
Avail. P (mg kg^{-1})	<3.0	3.0-7.0	7.0-20.0	>20.0	
BS (%)	<20	20-40	40-60	60-80	80-100
ESP (%)	<0.1	0.1-2.0	2.0-8.0	8.0-15	>15
TN (g kg^{-1})	0.3-0.5	0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.4
pH (H_2O)					
Strongly acid	5.0-5.5				
Moderately acid	5.6-6.0				
Slightly acid	6.1-6.5				
Neutral	6.6-7.2				
Slightly alkaline	7.3-7.8				

Source: Enwezor et al. (1989), Federal Fertilizer Department (2012)

The degree of redness generally increased down the profiles of OJO-1 and OJO-4, varying from strong brown to reddish at OJO-3 but was consistently strong brown at OJO-2 (Table 3). The reddish brown (7.5YR to 5YR) and deep red (5YR to 2.5YR) or the redder colours are caused by the occurence of ferrihydrite and hematite respectively. Dark and brown colours at the topsoils and some horizon in the subsoils reflect the influence of decomposed organic matter and magnetite soil profiles at the lower slopes. This observation corroborates findings of Akamigbo & Asadu (1986) along some toposequence in Anambra state. The profiles had structures that varied from weak fine granular (1g) to moderate medium sub angular blocky structure (2msbk). The structure of the soil had low cohesive strength as a result of little clay contents.

Particle size distribution of soils on Ojoto toposequence

The particle size distributions of the soils are shown in Figure 2. The sand content was generally higher than 82% in all profiles except OJO-1 where the value was 77.2% and 79.2% at C1 and C2 horizon respectively. The high percentage of sand in all the profiles indicate high infiltration and low water holding capacities of the soils and the possibility of moisture stress in the absence of irrigation systems. Clay content was highest in OJO-1 (AB and B) horizon, indicating a slightly higher resistance to soil erodibility. This also explains the loamy sands top soils of all the profiles with the exception of OJO-4. Ahn (1970); Akamigbo & Asadu (1986) have earlier reported that more clay occurs at the upper slopes of a catena. However, OJO-4 profile graded from sandy texture at the surface to loamy sand subsurface. This may indicate the lateral removal of clay by surface runoff. The inconsistent percentages of sand silt and clay in the soil profiles relates to the absence of clay migration (Deressa *et al*., 2018). However, the sandy nature of the soil is related to its formation being sandy lithology of the Bende-Ameki Formation (Onu & Ibezim 2004).

Chemical properties of soils on Ojoto toposequence

The chemical properties of the studied soils are presented in Table 4 and the ratings were based on the nutrient ratings by Enwezor *et al*. (1989) and the Federal Fertilizer Department (2012). The pH values ranged from strongly to moderately acidic, with 5.3 - 5.6 at the Ap horizon and 4.7 - 5.7 at the subsurface horizon. The low pH of the soil is attributable to the leaching of appreciable amounts of exchangeable bases caused by high precipitation, erosion of nutrient holding topsoil and the inability of the sandy parent material to retain basic cations. Electrical conductivity is a measure of soil quality used to estimate the amount of soluble material (cations and anions). Its values ranged from 30 - 51 dS m^{-1} at the topsoil decreased at the following horizon and increased again at the C–horizon. Organic matter contents, soil texture and leaching of nutrients down the profile may be contributing to the variations in EC values. Based on Brady and Weil (2016), the soils are not saline since their values are less than 4000 dS m^{-1}. However, the increasing salinity may be due to irrigation practices observed in the area. The total N values were generally very low to moderately low, ranging from 0.4 – 1.3 g kg^{-1} at the surface while at the subsoil, values ranged from 0.2 – 1.3 g kg^{-1}. The intense cultivation of the area, burning and low input of organic matter may explain the low total N especially at the top soil. Available P in the soils was very low to moderate. The value ranged from 5 - 12 mg kg^{-1} at the surface and 1 - 16 mg kg^{-1} at the subsurface horizons.

Table 3: Morphological properties Ojoto toposequence

Horizon designation	Depth (cm)	Colour		Structure	HB		Other features
		Nt	Standard name		D	T	
			OJO-1 (Summit)				
Ap	0-10	2.5YR 4/4	Reddish brown	1g			1fr, A
AB	11-30	5YR 5/6	Yellowish red	1g	Clear	Smooth	1fr, A
B	31-45	5YR 4/6	Yellowish red	1g	Clear	Smooth	2fr, A
B2	46-80	5YR 5/6	Yellowish red	1g	Clear	Smooth	3fr
C1	81-110	5YR 5/8	Yellowish red	1g	Clear	Smooth	1fr, A
C2	111-200	5YR 6/6	Reddish brown	1g	Clear	Smooth	1fr
			OJO-2 (Shoulder-slope)				
Ap	0-15	7.5YR 4/6	Strong brown	1g			3fr
B	16-40	7.5 4/6	Strong brown	1g	Abrupt	Smooth	3fr
B2	41-70	7.5YR 4/6	Strong brown	1g	Gradual	Wavy	1fr
C1	71-130	7.5YR 5/6	Strong brown	1g	Clear	Smooth	1fr
C2	130-150	7.5YR 5/6	Strong brown	1g	Clear	Smooth	1fr
			OJO-3 (Back-slope)				
Ap	0-25	7.5YR 4/6	Strong brown	1g			1fr, A
B1	26-60	5YR 4/6	Yellowish red	1g	Clear	Smooth	3fr, A
B2	61-90	7.5YR 5/8	Strong brown	2msbk	Clear	Smooth	
C1	91-140	5YR 5/6	Yellowish red	1g	Clear	Smooth	A
C2	140-200	7.5YR 5/6	Strong brown	1g	Clear	Smooth	A
			OJO-4 (Toe-slope)				
Ap	0-30	5YR 5/4	Reddish brown	2msbk			3fr, A
B1	31-80	7.5YR 4/6	Brown	2msbk	Gradual	Wavy	1fr, A
B2	81-120	5YR 5/6	Yellowish red	2msbk	Gradual	Wavy	1fr, A
C	121-140	5YR 5/6	Yellowish red	2msbk	Clear	Smooth	1fr
C2	141-200	5YR 5/6	Yellowish red	-	Clear	Smooth	1fr; B

HB=Horizon boundary, D= Distinct, T= Topography, Nt= Notations, 1g= Weak fine granular, 2msbk= Moderate medium sub angular blocky, 1fr= few fine roots, 2fr= medium fine roots, 3fr= many fine roots, A= Artefacts, B= Biological activities

A slight drop in available P values at the B-horizon and further increases down the soil profiles may be associated with Mn, Al and Fe which occur in higher concentrations in strong acidic conditions to react with phosphorus ions to become insoluble. The organic matter content was very low to moderate, ranging from 6.0 – 23.0 g kg^{-1} at the topsoil, 3.7 – 23.3 g kg^{-1} at the subsoil. The values were higher in the subsoil compared to the topsoil except OJO-1. This may be due to the rapid oxidation of organic matter at prevailing high temperatures and rapid removal of organic matter in pronounced leaching and eroded environments.

The exchangeable Ca values were generally low in the subsoil, ranging from 0.0 - 0.1 cmol kg^{-1}, while the topsoil ranged from 0.1 - 0.6 cmol kg^{-1}. The exchangeable Mg values were similarly low in the soil, following a trend of decrease down the profile as Ca. Its values ranged from 0.2 - 0.6 cmol kg^{-1} at the top and 0.0 - 0.2 cmol kg^{-1} at the subsoils. The slightly increase down the slope may be attributed to the lateral translocation of cations in solutions downslope (Akamigbo & Asadu, 1986). The decrease of Ca and Mg down the profile in most soil profiles is related to erosion and biocycling. The value of exchangeable Na and K were generally high. The exchangeable K values were rated moderate to high (FDD, 2012). At the surface, it ranged from 0.4 - 0.8 cmol kg^{-1} while the subsoil it ranged from 0.5 – 1.0 cmol kg^{-1}. The values of exchangeable K were observed to increase down the profile except in OJO-1 where the increase was irregular. The value of Na for the surface horizon ranged from 1.9 - 3.1 cmol kg^{-1} at the topsoil and 1.7 – 4.6 cmol kg^{-1} at the subsurface horizons. The values of the exchangeable Na generally decrease from hilltop to toe slope. The nature of the parent material may be responsible for the low value of Ca and Mg and the high value of K and Na. Leaching and erosion may further contribute to the different values observed. Human activities such as irrigation and fertilization may contribute to high exchangeable Na observed with ESP above 15% indicating that the soils are sodic. The total exchangeable acidity was generally low (0.44 – 1.04 cmol kg^{-1}). However, the values tended to increase at the subsoil up to 1cmol kg^{-1} obtained at B horizon (OJO-1) and C1 horizon (OJO-2). The ECEC of the soil were generally low and increase substantively in the B and C horizon of OJO-1, OJO-2 and OJO-4.

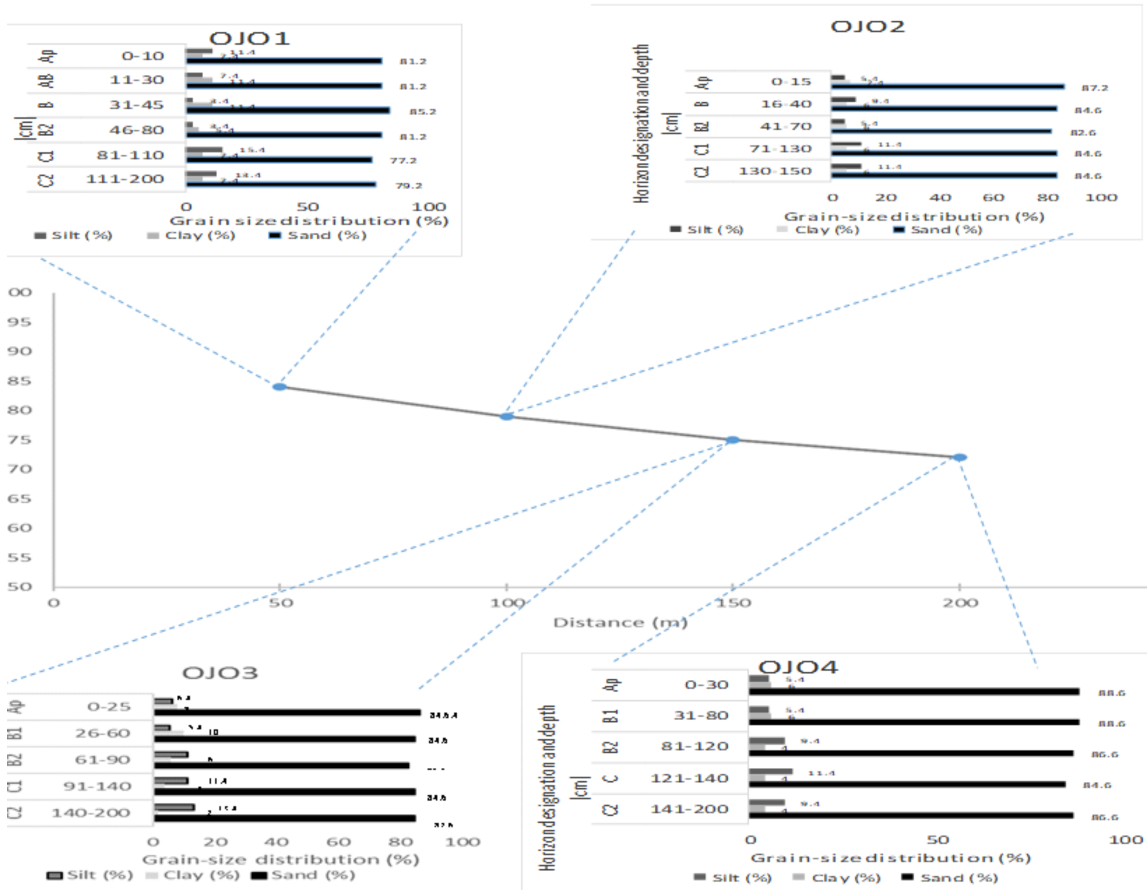

Figure 2: Slope, soil profile and particle size relationships at Ojoto catena

The topsoil value was low, ranging from 3.0 - 5.5 cmol kg^{-1}, while the subsurface ranged from 2.9 - 6.0 cmol kg^{-1}. The soil's low ECEC values indicate the dominance of mineral components over organic matter. This signifies the low fertility of the parent material, while the lower values in the topsoil likely result from erosion-induced changes due to clay loss. The base saturation value of the toposequence ranged from 84-85% in the topsoil and 72-89% in the subsoil. These values fluctuate across all profiles, but a noticeable decrease followed by an increase down the profile is evident (Table 4). It is evident that the influence of organic matter in this soil is not as significant as the lithology of the parent material.

Soil Classification

The soil of Ojoto was classified as Oxisols at the order level due to slight horizonation, the concentration of kaolin, quartz and free oxides, presence of oxic subsurface horizon (very low activity of the clay fraction and ECEC of 12 cmol (+) or lesser per kg clay). A Udic moisture regime qualified the soil to the Udox suborder and Hapludox at the great group level. In the subgroup, the soils are Typic Hapludox. Under the FAO WRB (2014), the soils correlated with the Ferralsols due to the ferralic horizon (absence of clay illuviation, yellowish-red colour and slight variation in colour and particle size distribution). They correlate as Arenic Ferralsols (Ochric, sombric) in WRB (FAO, 2015).

Table 4: Chemical Properties of Soils on Ojoto catena

Soil profile	H.D	Depth	pH (KCl)	EC (umho cm^{-3})	T. N (%)	Av. P (mg kg^{-1})	OM	Ex Bases (cmol kg^{-1})				Ex Acidity (cmol kg^{-1})		ECEC (cmol kg^{-1})	BS
								Ca	Mg	K	Na	H	Al		
OJO-1	Ap	0-10	5.28	51	0.13	4.61	2.23	0.57	0.09	0.82	3.09	0.88	-	5.45	84
	AB	11-30	5.33	20	0.13	2.87	2.16	0.06	0.04	0.55	4.57	0.8	-	6.02	87
	B	31-45	5.26	23	0.06	1.77	0.90	0.05	0.04	0.72	3.57	1.04	-	5.42	81
	B2	46-80	5.3	17	0.07	13.44	1.20	0.07	0.08	0.67	4.39	0.64	-	5.85	89
	C1	81-110	4.66	274	0.10	4.48	1.66	0.06	0.07	0.96	4	0.72	-	5.81	88
	C2	111-200	5.25	9	0.02	12.88	0.37	0.06	0.06	0.87	1.7	0.64	-	3.33	81
OJO-2	Ap	0-15	5.6	42	0.04	11.76	0.70	0.18	0.13	0.49	2.22	0.56	-	3.58	84
	B	16-40	5.34	21	0.11	2.56	1.76	0.05	0.04	0.51	3.09	0.72	-	4.41	84
	B2	41-70	5.71	16	0.14	5.42	2.33	0.07	0.05	0.57	2.78	0.88	-	4.35	80
	C1	71-130	5.59	17	0.09	6.72	1.56	0.03	0.03	0.69	1.91	1.04	-	3.7	72
	C2	130-150	5.48	23	0.08	11.78	1.30	0.03	0.04	0.72	1.72	0.64	-	3.15	80
OJO-3	Ap	0-25	5.63	55	0.04	6.78	0.73	0.13	0.12	0.54	2.65	0.64	-	4.08	84
	B1	26-60	5.57	28	0.11	1.31	1.83	0.03	0.04	0.61	1.39	0.82	-	2.89	72
	B2	61-90	5.63	14	0.13	3.24	2.22	0.03	0.04	0.59	2.22	0.88	-	3.76	77
	C1	91-140	5.65	11	0.09	9.83	1.56	0.03	0.04	0.79	1.78	0.88	-	3.52	75
	C2	140-200	5.68	578	0.06	15.99	1.07	0.04	0.05	0.63	2.26	0.64	0.12	3.74	80
OJO-4	Ap	0-30	5.57	30	0.04	8.38	0.60	0.09	0.1	0.44	1.87	0.45	-	2.95	85
	B1	31-80	5.43	19	1.11	2.7	1.90	0.05	0.08	0.49	2.22	0.96	-	3.8	75
	B2	81-120	5.31	15	1.12	7.72	1.78	0.03	0.05	0.59	2.9	0.64	0.25	4.46	80
	C1	121-140	5.49	14	0.09	14.06	1.56	0.04	0.04	0.56	2.61	0.56	-	3.81	85
	C2	141-200	5.66	20	0.07	13.06	1.23	0.02	0.04	0.69	2.09	0.44	-	3.28	87

CONCLUSION AND RECOMMENDATION

The soils in the study area are generally sandy, deep, and well-drained, making them relatively easy to cultivate. However, the high proportion of inactive sandy particles contributes to low nutrient levels and increases the risk of gully erosion. With an undulating slope of about 8%, there is a high likelihood of physical degradation, particularly soil erosion, which could significantly reduce crop yields in this delicate landscape. Erosion was particularly severe in soils at the toe-slope positions used for yam, cassava, plantain, and oil palm cultivation. Chemical degradation, such as low pH, decreased soil exchangeable bases, nitrogen, phosphorus, and organic matter, was also observed. Implementing site-specific conservation practices can help identify fertility deficiencies and effectively manage soil erosion at the toe-slope positions along the toposequence. To ensure sustainable soil use, precise irrigation, fertilization, and liming practices are necessary to maintain productivity while minimizing negative environmental impacts.

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Authors Contributions

FCO conducted the experiment and wrote the article.

Ethical Statement

Not applicable.

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