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Characterization and classification of greenbelt soils in Yambio and Nzara counties, Western Equatoria State, South Sudan

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The objectives of this study were to characterize, classify and evaluate the potential and constraints of the soils of Sakure and Nginda Payams in Nzara and Yambio counties in the Greenbelt zone of Western Equatoria State, South Sudan. Ten soil pits were dug, described and sampled based on FAO soil profile description guideline and samples were analysed using standard routine lab analyses for physical and chemical properties. Data generated were analysed statistically using the coefficient of variation (CV) and correlation. Results showed that top and subsoil were dominated by sandy clay loams. The soil reactions were strongly to slightly acidic (pH = 5.4 - 6.7). The most limiting nutrients were P and N. SOC was highest in the top soil and consistently decreased with depth, the CEC was low (4 - 14.4 Cmol kg^{-1}). The soils were classified into six major soil types: Ferralsol, retisols, acrisols, umbrisols, fluvisols, and chernozems. The soils have poor inherent soil fertility. It is recommended that further soil survey be carried out in the Greenbelt zone and to conduct more research to determine the type of soil fertility management feasible.

Key words: Acid soils, Nginda Payam, Sakure Payam, soil fertility management, shifting cultivation.

INTRODUCTION

Soil characterization provides the basic information necessary to create functional soil classification patterns and assess soil fertility to provide insight of some unique soil properties which are key to sustainable use of the soil resources (Adegbite et al., 2019; Yacob and Nigussie, 2022; Gomes et al., 2023). It provides information for understanding of the physical, chemical, and mineralogical and uses soil horizons and factors of soil formation as basis of classification on which crop/forest growth depend (Umare, 2018; Kafle, 2022). The characterization also analyses and quantifies the morphology of the surface earth in terms of landform characteristics to better understand the physical, chemical, and biological processes that take place within the landscape (Adegbite

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et al., 2019). It is also important for soil researchers to promote the importance of soil in supporting human life and wellbeing to better support environmental, agricultural and climate policies to policy makers and society/farmers (Bouman et al., 2019; Panagos et al., 2022; Gomes et al., 2023).

The soils of the Greenbelt deteriorate quickly in fertility under cultivation. Because of this, farmers tend to adopt shifting cultivation as a natural way to improve soil productivity in the absence of the use of fertilizer (ASPF, 2012). Shifting cultivation is destructive to the natural environment (Wineman et al., 2021; Kadoya et al., 2022; Gomes et al., 2023), but Nath et al. (2022) and Martin et al. (2023) urgue that there is a need for a careful diagnosis of this system and a rethink before claiming that the system is unsustainable. However, increasing agricultural production without land expansion requires increased fertilizer inputs as well as improved water management (Leitner et al., 2020). In addition, crop production through intensification, also requires efficient soil-plant-nutrient management, where the amount of mineral fertilizer to be applied depends on how much of each nutrient is already in the soil and readily available to plants (Yacob and Nigussie, 2022), Denmark has succeeded to reduce crop land areas by 6.5% in the last 30 years (Gomes et al., 2023) using fertilizer. To determine nutrient credit balance, area specific soil classification and suitability assessment for different crops is required (Lal, 2015; Gomes et al., 2023). According to Lal (2015), it is logical to find site specific farming systems to meet the site specific needs in terms of nutrient managements. Currently, South Sudan lacks or has limited data that can be used for soil fertility management (Odra, 2004; ASPF, 2012; WOSSAC, 2017). Tothil (1948) and Lebon (1956) had reported that there were no land use nor soil maps for any part of South Sudan and it has remained so to date. This type of information is required. According to Gomes et al. (2023), when the Danish government realized that the information on soil in agricultural land was insufficient for effective land use planning, they embarked on soil assessment.

Although, the Greenbelt could be the breadbasket of the whole country, yet the production per unit area is low and the farmers' practice of shifting cultivation is on the rise. This study aimed at characterizing the soils of Sakure and Nginda Payams in Nzara and Yambio counties of the Greenbelt zone to evaluate their potential and constraints for maize.

MATERIALS AND METHODS

Description of the study area

The study area of approximately 475 km^2 (47 500 ha) was delineated on-screen from topographic base map, of scale 1:500 000 produced by the Centre for Development and Environment (CDE), University of Bern (2010) using Quantum Geographical Information System (QGIS) software (Figure 1). The coordinates of the study area are: 4°20‘0“ N; 28°24‘0“ E and 4°40‘0“ N; 28° 08‘0“ E.

The study area is located in the Greenbelt zone, one of the six agro ecological zones that covers approximately 14% of the total land (648 000 km^2) of South Sudan (AfDB, 2013). The zone is characterized by tall broad leaf trees and thick forest. It runs along the boarders of South Sudan, DR Congo and Uganda. Maize can be planted and harvested twice a year and it has the greatest potential to produce a variety of annual and perennial crops (ASPF, 2012). The rainfall and temperature of the study area is presented graphically (Figure 2). The data were extracted from the University of East Anglia website in 2021 (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.04), using ArcMap version 10.5.

Study design

Stratified preliminary map units were established by unsupervised reclassification according to elevation using the 30 m (1 arc) Shuttle Radar Topography Mission (SRTM) terrain model (USGS, 2014) and conditioned Hypercube Latin Sampling (cLHS) was used in R-software environment to generate thirty points for pit/auger observations on the study area. For soil description the FAO (2006) guideline was used.

Data collection and analysis

Geographic Positioning System (GPS) was used to navigate to the identified profile sites in preliminary mapping unit (MU). Site characteristics including land use, elevation, vegetation and slope characteristics were recorded in a Soil Profile Description Form, adapted from the National Soil Services, Tanzania. Soil profiles were dug in identified representative locations (Musell Colour Charts, 2009).

The soil samples obtained from the ten profiles were prepared and analysed for physical and chemical soil properties according to the descriptions in Okalebo et al. (2002). Particle size distribution was determined by Bouyoucos hydrometer method after dispersing soil with calgon. The pH was measured in water at the ratio of 1:2.5 soil-water. Organic carbon was determined by the Walkley and Black method. Total Nitrogen by Kjeldahl method and available phosphorus was extracted by Bray I method. The Cation Exchange Capacity (CEC) and exchangeable bases were extracted by saturating soils with neutral 1 M NH_4OAc and the absorbed NH_4^+ displaced by K^+ using 1 M KCl and then determined by Kjeldahl distillation method for the estimation of CEC of the soil (Summer and Miller, 1996). The bases Ca^{2+}, Mg^{2+}, K^+, Na^+ displaced by ammonium were measured by atomic absorption spectrophotometer (Ca^{2+} and Mg^{2+}) and flame photometry (K^+ and Na^+) (Reeuwijk, 2002). One percent EDTA was used to extract micronutrients (Cu, Mn, Zn and Fe). Booker Tropical Manual (Landon, 1991) was used for soil results interpretations unless specified. Statistical analysis was done using MS Excel version 2013 to calculate descriptive statistic and minitab for pearson corelation of all the selected physical and chemical soil properties in eight pedons excluding two pedons, 5 and 8 where only top soil horizon in each was taken.

RESULTS AND DISCUSSION

Soil morphology

The morphological and topographical properties of the

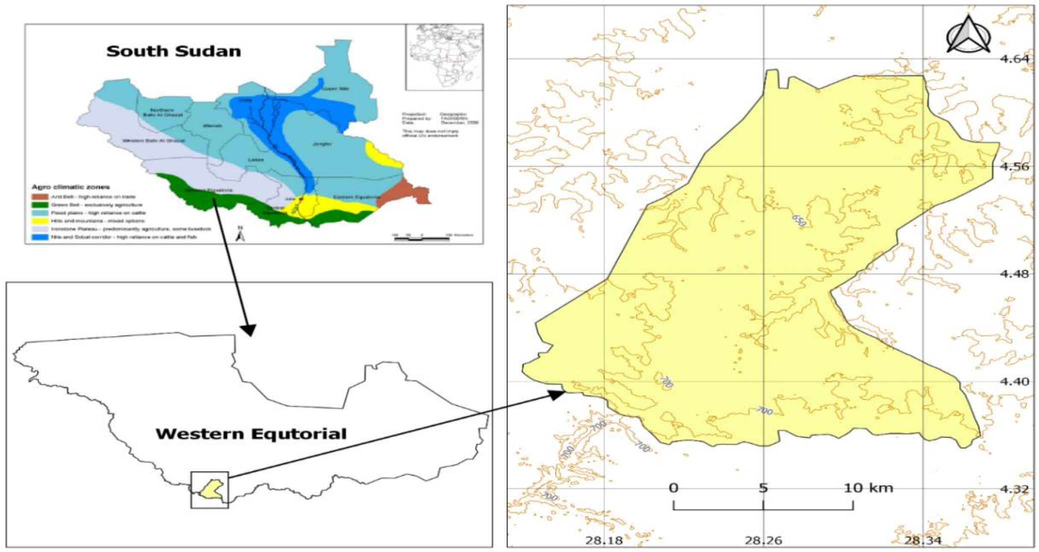

Figure 1. Location of Sakure and Nginda Payams in Western Equatoria.
Source: CDE, University of Bern (2010).

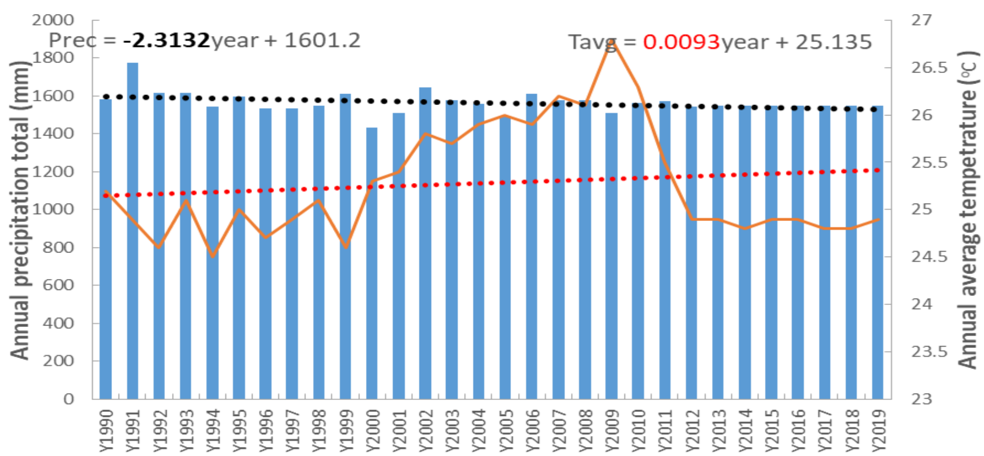

Figure 2. Total annual precipitation and temperature from 1990 - 2019.
Source: University of East Anglia (2021).

soils are shown in Table 1 and Figure 3, respectively. All colours reported were measured under moist condition. Pedon 1 ranges from 10 YR3/1 (dusky red) to 10YR 5/6 (red), pedon 2, 7.5 YR2.5/1 (Reddish black) to 7.5 YR 4/6 (Red), pedon 3, 7.5YR 3/1 (Dark redish gray) to 7.5YR4/6 (Red), pedon 4, 5YR3/2 (dusky red) to 2.5 YR 3/6 (Dark red clay), pedon 5, 2.5 YR3/2 (Dusky red) only one horizon, pedon 6, 5YR4/2 (Weak red) to 5YR 4/6 (Red), pedon 7, 5 YR4/3 (Weak red) to 5YR3/2 (Dusky red), pedon 8, 7.5YR 4/1 (Dark reddish gray) to 7.5 YR 7/3 (Pale red), pedon 9, 10YR 2.5/1 (Dusky red) to 5YR 4/4 (Weak red) and pedon 10, 10 YR4/2, weak red only one horizon. The structure is dominated by sub-angular blocky and angular sub-angular blocky (pedon 1, 8, 10, and 3, 6, 9, respectively), pedon 2 is massive, pedon 4 is angular sub angular, pedon 5 is platty and pedon 7 is granular. The soil consistency under moist condition is predominantly friable. However, seven out of ten pedons top and subsoils consistency were slightly sticky to sticky when wet; but pedon 7 was weak and none sticky. All the pedons are well drained. About 60% have clear and weavy boundaries of the horrizons, while the others include clear smooth, gradual and irregular, gradual smooth, gradual weavy, and abrupt weavy. The pedons are very deep > 120 cm except for pedon 7 < 100 but pedons 5 and 10 < 20 cm. Few/Very few fine roots have been observed at greater depth above 120 cm. Topographic maps: Elevation, slope aspect, slope and

Table 1. Soil morphological and physical properties of the studied sites in Sakure and Nginda Payams.

Horizon	Depth (cm)	Clay	Silt	Sand	TC	SCR	Colour (moist)	Structure[1]	Consistency[2] (moist)	Root[3]	Drainage[4]	Horizon boundary[5]
Pedon 1 - NDUKU/2 – Sakure, Elevation: 662 asl, N 04.38778; E 28.21173												
A1	0 - 30	28.84	4.56	66.6	SCL	0.16	10YR3/1, Dusky red	SBK	fr, ss	Co123	wd	cw
A2	30 - 56	33.84	9.56	56.6	SCL	0.28	10YR3/6, Dark red	SBK	fr, s	Co123	wd	cw
B1	56 - 78	52.84	2.56	44.6	C	0.05	10YR4/6, red	SBK	fr, vs	F 1 2	wd	gi
B2	78 - 160	53.84	2.56	43.6	C	0.05	10YR 5/6, red	AB	fr,s	V 1 2	wd	-
Pedon 2, T- 12 – Sakure - Elevation: 717 asl, N 04.543974; E 28.19393												
O	0 - 10	16.84	6.56	76.6	SL	0.39	7.5 YR2.5/1, Reddish black	MA	fr, ns	M	wd	cw
A1	10 - 24	20.84	6.56	72.6	SCL	0.31	7.5YR3/3, Dusky red	MA	fr, ss	Co 1 2 3	wd	gs
A2	24 - 65	30.84	4.56	64.6	SCL	0.15	7.5YR4/3, Weak red	MA	fr, s	Co 1 3	wd	gs
B1	65 - 100	44.84	4.56	50.6	SC	0.10	7.5 YR 4/6, Red	MA	fr, s	F 1 3	wd	cs
B2	100 - 149	48.84	6.56	44.6	C	0.13	7.5 YR 4/6, Red	MA	fr, s	VF1	wd	cs
B3	149 - 200	44.84	10.56	44.6	C	0.24	7.5 YR 4/6, Red	GR+SA	fr, s	VF 1	wd	-
Pedon 3, T-13 - Sakure - Elevation: 656 asl, N 0447175; E 28.24896												
A1	0 - 31	20.84	4.56	74.6	SCL	0.22	7.5YR 3/1, Dark redish gray	ASBK	fr, s	Co1 2 3	wd	cw
A2	31 - 56	32.84	2.56	64.6	SCL	0.08	7.5 YR 3/4, Dusky red	ASBK	fr, s	F 1 2	wd	cw
B1	56 - 100	35.84	4.56	59.6	SC	0.13	7.5YR4/6, Red	ASBK	fr, s	F 1 2	wd	cw
B2	100 - 145	42.84	6.56	50.6	SC	0.15	7.5YR4/6, Red	ASBK	weak, s	VF 1 2	wd	-
Pedon 4, T14 - Sakure - Elevation: 699 asl, N 04.43442; E 28.18229												
A1	0 - 21.	28.84	6.56	64.6	SCL	0.23	5YR3/2, dusky red	ASA	fr, ss	M 1 2 3	wd	cw
A2	21 - 40	33.84	7.56	58.6	SCL	0.22	5YR3/3, dusky red	MA	fr, s	F 2 3	wd	cw
A/E	40 - 96	46.84	8.56	44.6	C	0.18	2.5YR3/6, dark red	MA	fr, ss	F 2 3	wd	cw
Es	96 - 184	57.84	5.56	36.6	C	0.10	2.5YR3/4, Dark reddish brown	SA	vfr, ns	VF 1 2	wd	Cw
Bts	184 - 210	53.84	9.56	36.6	C	0.18	2.5 YR 3/6, Dark red clay	MA	loose, ss	VF 1 2	wd	-
Pedon 5, T 22 - Sakure - Elevation: 647 asl, N 04.53000; E 28.24700												
A p	0 - 12	28.84	8.56	62.6	SCL	0.3	2.5 YR3/2, Dusky red	Platy	fr, s	Co 1 2	wd	Cw
Pedon 6,T - 25 - Sakure - Elevation: 643 asl, N 04.33877; E 28.14816												
A1	0 - 11	20.84	8.56	70.6	SCL	0.41	5YR4/2, Weak red	ASBK	fr, s	Co 1 2	wd	Cw
A2	11 - 23	29.84	5.56	64.6	SCL	0.19	5YR3/3, Dusky red	ASBK	fr, s	Co 1 2	wd	Cw
Bt1	23 - 50	44.84	6.56	48.6	SC	0.15	5YR5/8, Red	ASBK	fr, s	F 2 3	wd	Cw
B/C	50 - 140	50.84	4.56	44.6	C	0.09	5YR 4/6, Red	SBK	fr, ss	F 1 2	wd	-

Table 1. Contd.

Pedon 7, MKT – Sakure - Elevation:712 asl, N 04.39729; E 28.21531												
A p	0 - 25	10.84	4.56	84.6	LS	0.42	5 YR4/3, Weak red	GR	weak, ns	Co 1 2	wd	gw
A1	25 - 46	8.84	4.56	86.6	LS	0.52	5YR3/3, Dusky red	GR	weak, ns	Co 1 2	wd	gw
A2	46 - 80	6.84	4.56	88.6	S	0.67	5YR3/2, Dusky red	GR	weak, ns	F 1 2	wd	aw
Pedon 8, JA–Nginda - Elevation:651 asl, N 04.59430; E 28.34834												
A 1p	0 - 17	27.84	7.56	64.6	SCL	0.27	7.5YR 4/1, Dark reddish gray	SBK	fr,s	Co 1 2	wd	cw
A2	17 - 28	28.84	8.56	62.6	SCL	0.30	7.5YR 2.5/1, Reddish black	SBK	fr, s	F 1 2	wd	cw
AC	28 - 60	39.84	5.56	54.6	SC	0.14	7.5 YR 3/1, Very dark gray	SBK	fr, ss	VF 1	wd	cw
C	60 - 170	44.84	6.56	48.6	SC	0.15	7.5 YR 7/3, Pale red	SBK	fr, ss	VF1	wd	-
Pedon 9, T 19 – Nginda - Elevation: 674 asl, N 04.60100; E 28.33900												
Ap1	0 - 13	32.84	7.56	56.6	SCL	0.23	10YR 2.5/1, Dusky red	ASBK	fr, ns	Co1 2 3	wd	cw
Ap2	13 - 25	33.84	6.56	59.6	SCL	0.19	7.5YR 3/2, Dusky red	ASBK	fr, ns	F 1 2	wd	cw
B1	25 - 50	41.84	5.56	52.6	SC	0.13	5 YR 3/3, Dusky red	SBK	fr, ss	VF 1 2	wd	cw
B2	50 - 90	49.84	9.56	40.6	C	0.19	5 YR 4/6, Red	SBK	fr, ss	F 1 2	wd	cw
B3	90 - 170	54.84	4.56	40.6	C	0.08	5YR 4/4, Weak red	SBK	fr, s	F 1 2	wd	-
Pedon 10,T18-Nginda Payam-Elevation:657 asl, N 04.61000; E 28.31200												
A p	0 - 12	26.84	12.56	60.6	SCL	0.45	10 YR4/2, weak red	SBK	fr, ss	VF1	wd	aw

SBK= Sub-angular blocky, AB=angular blocky, GR= granular, SA=sub-angular, MA=massive, 2) FR= friable, SS= slightly sticky, S=sticky, NS= non-sticky, VS= very sticky 3) M=many, Co=common, F=few VF=very few, 1=fine, 2=medium, 3=coarse, 4) wd=well drained, 5) cw=clear & weavy, gi=gradual & irregular, gs=gradually smooth, cs=clear smooth, gw=graudally weavy aw=abrupt weavy.
Source: Author.

streams are shown in Figure 3.

Soil physical properties

Soil texture and silt/clay ratio

Thirty seven genetic horizons were observed and sampled, and the results are indicated in Table 1. Figure 3B shows the trend of the clay, silt and sand fractions. Sixteen horizons were sandy clay loam, 10 clay, 7 sandy clay, 2 loam sand, and sand and sandy loam one each. The top soil and subsoil up to about 40 cm down the profile had more sand in most of the profiles ranging from 50 to 85% sand in all profiles. The dominant texture of sandy clay loam is consistent with the report of Ombina (2008) in Nzara County. The soils being well drained imply that the topsoils and subsoil have high proportions of sand and silt to clay; therefore, rainwater infiltration rate into the soil is fast and it carries with it the nutrients. In all profiles the clay contents consistently increased with depth, suggesting illuviation and formation of argillic horizon while the sand fraction decreased except for pedon 7 where clay content decreased downward while the sand fraction increased. Pedon 7 was obstracted by hard rock at 80 cm deep and it was classified as fluvisol. Probably, the parent material here conforms to the description of Morison et al. (1948), 'the geology of the Nile Congo divide are all composed of Basement Complex of Schists and Gneissess with intrusions; except it is overlaid by ironstone or more recent deposits.'' The silt content did not have any particular trend throughout the ten profiles.

The silt-clay ratio is recorded in Table 1. The values ranging between 0.05 and 0.67 in pedon

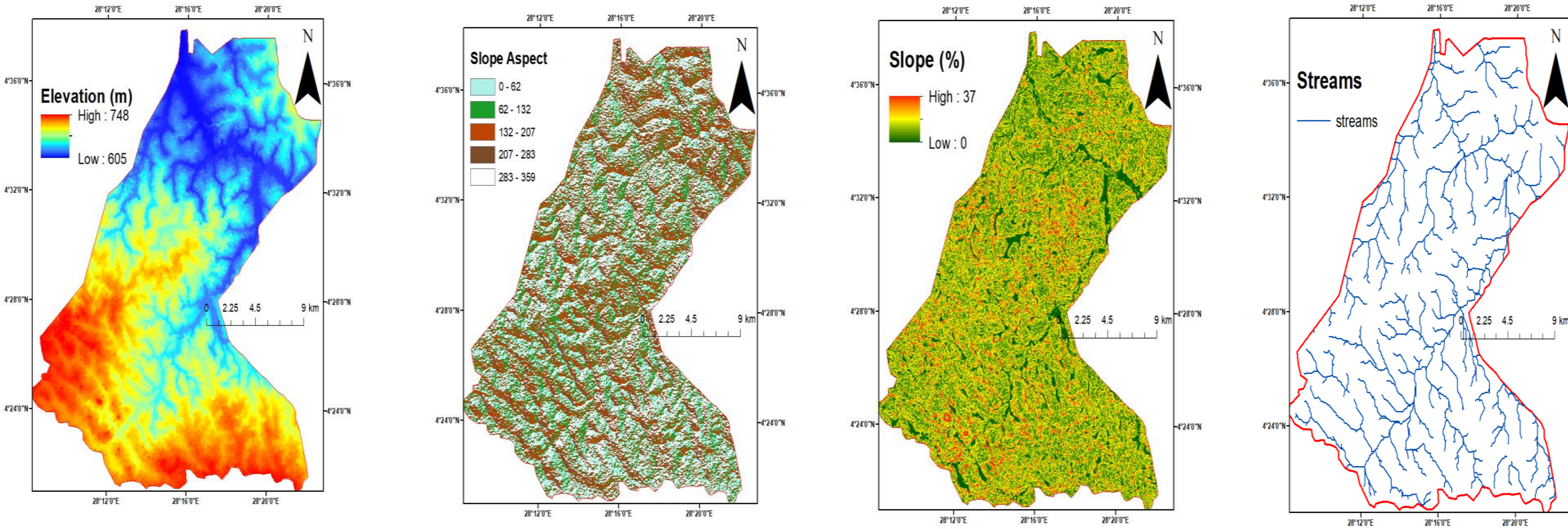

Figure 3. Topographic map of elevation, slope aspect, slope and streams.
Source: Author.

1 and 7, respectively. The low silt-clay ratio suggests that the soils of the study area are highly weathered and leached (Adegbite et al., 2019; Yacob and Nigussie, 2022). The low silt-clay ratio also suggests that the soils have moderate resistance to erosion. According to Adegbite et al. (2019), soils with a threshold of less than 1 SCR are susceptibe to erosion.

The results of correlations have been run for 8 pedons excluding the pedon 5 and 10 that had only one horizon sampled. The results showed that SCR was positively and strongly correlated to sand ($r = 0.758$, $p < 0.000$), and weakly correlated to silt ($r = 0.333$, $p < 0.05$) but negatively and strongly correlated to clay ($r = - 0.825$, $p < 0.000$). In the analysis of individual pedons, SCR was strongly and negatively correlated to silt ($r = - 0.979$, $p < 0.05$) in pedon 1, and clay ($r = - 0.811$, $p < 0.05$) in pedon 2, to clay ($r = - 0.886$, $p < 0.05$) in pedon 4 but in pedon 8 SCR was strongly and positively correlated to silt ($r = 0.946$, $p < 0.05$).

Soil chemical properties

The selected soil chemical properties of the investigated pedons have been presented in Figure 4 and the means and the coefficient of variations of the individual pedons are discussed but no table is provided because the tables are too long. In the statistical analysis, pedon 5 and 10 have been excluded because in both only one horizon each was sampled, however, the results are captured in the graphs (Figure 4). Throughout the discussions, positive correlation coefficient (r) value indicates both soil parameters (x) and (y) show positive relationship and negative R-values indicate that one parameter increases and the other decreases and vice versa. Only significant values have been recorded.

Soil pH

The observed pH in the studied soils is strongly to slightly acidic (5.4 - 6.7) in all profiles (Figure 4A) that is good for nutrient uptake by most crops (Landon, 1991; Adegbite et al., 2019). This range

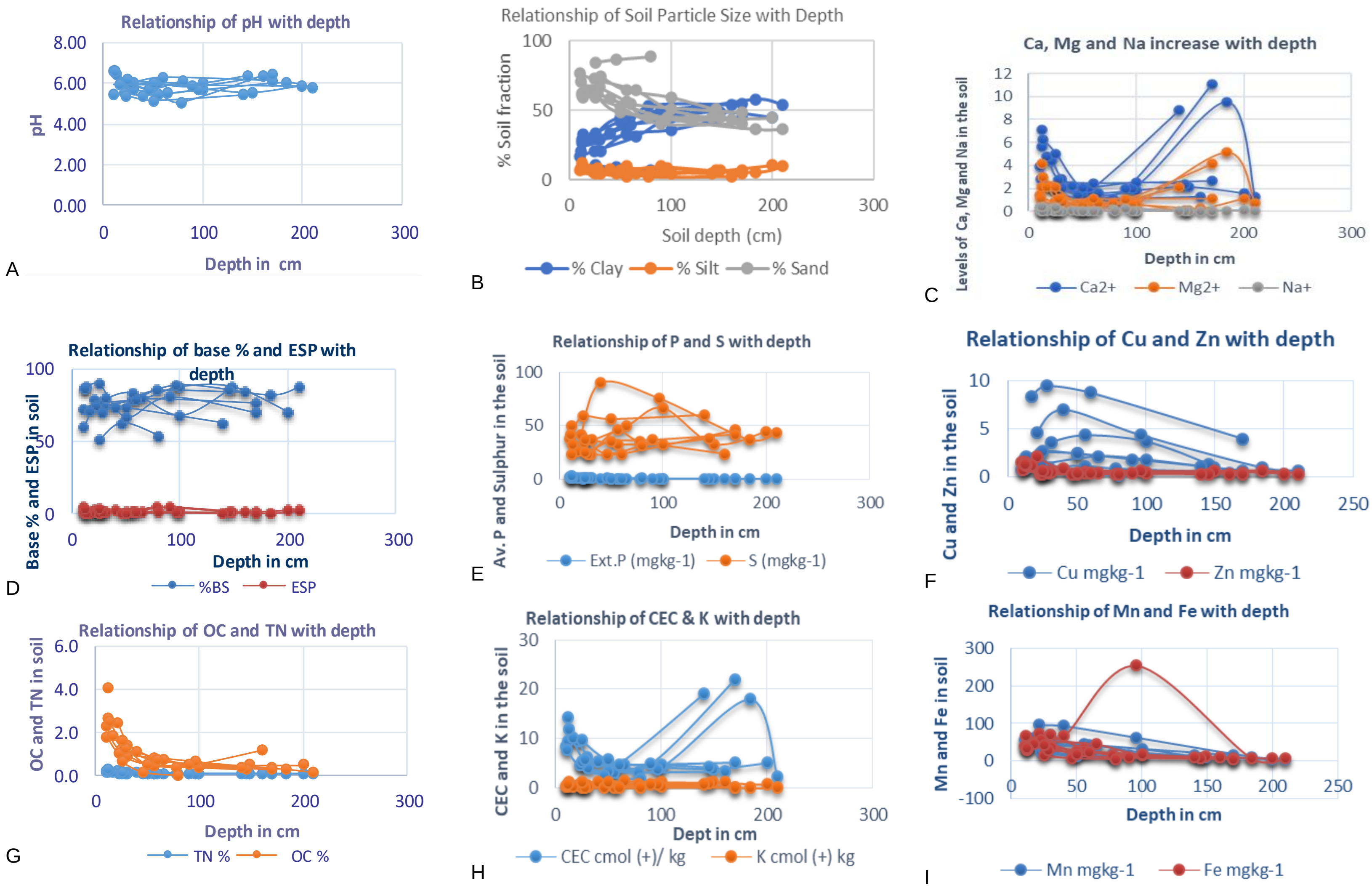

Figure 4. Relationship of selected soil physical and chemical properties with with depth.
Source: Author.

is suitable for micro and macro nutrients and particularly the application of phosphorus where phosphate ions will readily be available to plants. This study is consistent with the report of Deng and Marchelo-d Ragga (2020), in a study conducted in the Hills and Mountains

Table 2. Coefficient of variation ranked to Wilding (1985).

Level (%)	Ranking
CV < 15	Little variation
CV > 15 = 35	Moderate variation
CV > 35	High variation

Source: Wilding (1985).

Agroecological Zone in Eastern Equatoria State, South Sudan. Another study by Ombina (2008) in Nzara where he considered soils around and inside the existing teak plantations revealed that the soils were acidic. However, below < pH 5.5 aluminium toxicity may exist (Neenu and Karthika, 2019).

Pearson correlation coefficienct for 8 profiles revealed that pH was positively but weakly correlated to OC ($r = 0.376$, $p < 0.05$), available P ($r = 0.330$, $p < 0.05$) and Ca ($r = 0.345$, $p < 0.05$). However, for the individual pedons pH was positively and strongly correlated to percentage base saturation ($r = 0.962$, $p < 0.05$) in pedon 8, Na ($r = 0.978$, $p < 0.05$) in pedon 4, and in pedon 2, pH was positively correlated to OC ($r = 0.914$, $p < 0.05$), available P ($r = 0.928$, $p < 0.05$), Mg ($r = 0.909$, $p < 0.05$), CEC ($r = 0.847$, $p < 0.05$) and ESP ($r = 0.922$, $p < 0.05$). Positive correlation means that for every increase in pH the other soil properties will also increase and vice versa. Strong correlation means pH controls the base saturation of the soil, CEC and other plant nutrients such as P and Mg and also vice versa.

Soil organic carbon (SOC)

Soil organic carbon in the investigated pedons is presented in Figure 4G. In the topsoil, OC in nine out of ten pedons ranges from 0.6 to 2.7% and pedon 10 is 4.1%; these results indicate very low to high and very high OC content in the topsoil and the results conform to the description of Kimaro et al. (2001). According to Lal (2015), the concentration of SOC in the root zone must be maintained above the critical threshold level of 1.5% to enable farming systems to thrive. SOC performs a crucial role in ecosystem functioning and the global C cycle, and its decline can affect important soil processes, such as regulating water dynamics, stabilizing the soil structure, and releasing and holding nutrients for plants (Gomes et al., 2023). Based on Lal's critical level, the current study indicates that only P2, P5, P9 and P10 have good quantity of SOC in the topsoil, the other six pedons are marginally susceptible to SOC depletion. According to Prout et al. (2021), SOC is depleted under arable land use compared to natural system. Cultivation has caused losses of SOC in many parts of the world (Prout et al., 2022). The implication is that the probability of losing SOC is very high in the study area unless proper SOC management practice is undertaken. All pedons exhibited a consistent decrease of OC with depth (Figure 4G) except for pedon 1 at B2 about 100 cm deep, where there was more OC compared to the horizon above it. The high content of SOC on the surface than the subsurface layers can be attributed to the presence of plant materials as well as root and biological activity (Adegbite et al., 2019; Yacob and Nugissie, 2022). Zhong et al. (2018) reported similar results, OC decreases with depth and the report further added that clay content may also lead to more organic carbon molecules being adsorbed by clay surfaces and the presence of polyvalent cations forming organo mineral complex to control the protection of SOC from microbial and enzymatic decay, in turn increasing SOC storage. Several studies have confirmed the results that total amount of SOC increase with silt and clay sized fraction (Matus, 2021); and in addition to clay, precipitation increases the accumulation of SOC while it is decreased by high temperature (Prout et al., 2021). The means of individual pedons range from 0.3 to 1.1% with CV varying from 48.7 to 119%. The CV indicated moderate to high variations of OC within the pedons (Table 2). However, 90% of the soils indicated that the organic carbon content was in the low level category (Landon, 1991).

The ratio of carbon to nitrogen was lower than the critical level 24:1 (Schultheis et al., 2020); this means there is high level of carbon mineralization by the microbes and rapid release of nitrogen into the soil for immediate crop use. According to Schultheis et al. (2020), soils with a carbon-to-nitrogen (C:N) ratio of 24:1 have the optimum ratio for soil microbes to stimulate release of nutrients like N, P and Zn to crops. Statistically, SOC is strongly correlated to clay, sand, SCR and pH ($r = -0.873$; $r = 0.847$; $r = 0.867$; $r = 0.914$; $p < 0.05$). The negative correlation means as SOC increases the clay content will decrease.

Total nitrogen (TN)

Total nitrogen in the topsoil of the investigated pedons varied from 0.1 to 0.3% and decreased with depth in all pedons and follows a similar trend as exhibited by SOC (Figure 4G). According to Kimaro et al. (2001), TN is very low to medium. About 90% of the soil samples analyzed showed low levels of total nitrogen and only 10% showed medium levels (Landon, 1991). The CV ranged from 28.3 to 83%, this indicates moderate to high variability among the pedons. However, correlation analysis showed that TN was strongly correlated to SOC ($r = 995$; $p < 0.000$); this implies that SOC was the primary source of TN. This is consistent with other studies (Yacob and Nugissie, 2022). This means maintain organic matter on the soil will control sheet erosion, supply SOC and some of the essential plant nutrients such as N, P, S, etc., that in turn contribute to good crop performance.

Pearson correlation for the eight pedons showed TN was only correlated to silt and Silt-Clay Ratio (SCR), ($r = 0.478$; $r = 0.324$; $p < 0.05$); meanwhile in the individual pedons TN was strongly and positively correlated to CEC in pedon 1 ($r = 960$, $p < 0.05$), clay and CEC ($r = -0.824$; $r = 0.909$, $p < 0.05$) in pedon 2, phosphorus ($r = 0.978$, $p < 0.05$) in pedon 3, clay, sand and Mg ($r = -0975$; $r = 0.984$; $r = 0.886$, $p < 0.05$) in pedon 4, SCR ($r = 0.989$, $p < 0.05$) in pedon 6, Ca, Mg, K, and CEC ($r = 994$; $r = 998$; $r = 0.981$; $r = 989$; $p < 0.05$) but Na ($r = 999$; $p < .001$) in pedon 8, in pedon 9, TN was correlated to clay and SOC ($r = -0.872$, $p < 0.05$; $r = 995$; $p < 0.000$).

Available phosphorus (P)

The results of the P in the topsoils of the investigated pedons ranged from 1.2 to 2.7 mg/kg and all pedons exhibited a consistent decrease of P with depth (Figure 4E). In this study, P has measured very low in all the soil samples, far below the low level < 7 mg/kg by Bray-Kurtz 1 method (Kimaro et al., 2001). In another study in Torit county, Eastern Equatoria State by Deng and Marchelo-d Ragga (2020) also found all sixteen top soil samples taken randomly from farmers fields exhibited low phosphorus. In Nzara County, Ombina (2008) found that phosphorus was very low in absolute terms.

This study indicates that P is negatively correlated to clay and positively and strongly correlated to SOC; this implies that as the clay increases with depth, available P decreases and vice versa for the SOC. The decrease of P in the lower layers within the profile could be attributed to P-fixation. This is consitent with the study of Yacob and Nigussie (2022).

The general correlation of soil properties in 8 pedons indicated relationship of phosphorus with clay ($r = -532$), SCR ($r = 0.401$), pH ($r = 0.330$), SOC ($r = 0.477$) at $p < 0.05$ and sand ($r = 0.510$; $p < 0.001$). Correlation run for individual pedons revealed there was significant correlation between phosphorus and sand, Ca and Mg in pedon 1 ($r = 0.978$; $r = 0.991$; $p < 0.05$ and $r = 0.999$; $p < 0.001$), in pedon 2, correlation exist among P and SCR, pH, Mg, ESP and SOC ($r = 0.815$; $r = 0.928$; $r = 0.909$, $r = 0.992$; $p < 0.05$; $r = 0.977$, $p < 0.001$). Pedon 3 SOC ($r = 0.959$; $p < 0.05$), pedon 4, Mg and SOC ($r = 0.967$; $r = 0.973$; $p < 0.05$), pedon 6, clay, SCR and SOC ($r = -950$; $r = 0.986$; $r= 0.998$, $p < 0.05$); pedon 7, SOC and CEC ($r = 0.999$; $r = 0.999$, $p < 0.05$) and pedon 9, clay and SOC ($r = -0.933$; 0.922, $p < 0.05$).

Base saturation percentage (BS %)

In the topsoil BS% ranged from 51 to 88% and all pedons did not exhibit any trend (Figure 4D). The means of individual pedons ranged from 55.6 to 82.0% and the CV ranged from 5.8 to 13.3, this result means low variability (Table 3). Generally, base saturation ranges are low < 20; medium 20 - 60; high > 60 (Landon, 1991). The studied soils base saturation ranges are within medium to high base saturation percentage in acid soils. According to Landon (1991), some soils are base saturated at pH 5 and this explains why acid-sensitive crops can be grown in the tropics and liming does not increase their yield.

According to Kimaro et al. (2001), since the studied soils are dominated by kaolinitic and sandy soils the Ca (2.1 - 7.1) cmol (+) kg^{-1} (Figure 4C) is moderate to very high, Mg (0.51- 4.2 cmol (+) kg^{-1}) (Figure 4C) is moderate to very high, K (0.1 - 1.25 cmol (+) kg^{-1}) (Figure 4H) is low, 9 out of ten pedons exhibit very low and Na (0.2 - 0.43 cmol (+) kg^{-1}) (Figure 4C) is very low too. This implies that Ca and Mg are optimum, but potassium is in short supply.

Base saturation percentage in 8 pedons correlated to clay, sand and SCR ($r = 0.514$, $p < 0.001$; $r = -0.559$, $p < 0.000$; $r = -0.434$, $p < 0.05$) in individual pedons; Pedon 2: clay, SOC, CEC and sand, ($r = 0.951$; $r = -0.853$; $r = -0.828$, $p < 0.05$; $r = -0978$, $p < 0.001$) ;and Pedon 8: silt, SCR and pH ($r = -0.974$; $r = -969$; $r = 962$; $p < 0.05$).

Cation exchange capacity (CEC)

All ten topsoils of the investigated soils exhibited CEC range between 4 and 14.4 cmol (+) kg^{-1} and the means ranged from 3.3 to 10.9 cmol (+) kg^{-1} and coefficience of variation varied from 14.7 to 81.8%. In general, CEC decreased with depth in each pedon but it was not consistent (Figure 4H). According to Kimaro et al. (2001), CEC is very low to medium levels, seven pedons are in the low level, this implies that the soils easily lose their fertility and have low water holding capacity as well (Brown and Lemon, 2021). Brown and Lemon (2021) remarked that CEC is the inherent soil characteristic and is difficult to alter significantly, however, the addition of organic matter will increase the CEC of a soil but requires many years to take effect.

Correlation for eight pedons showed CEC relationship with Ca ($r = 0.950$), Mg ($r = 0.687$) all at ($p < 0.000$). The correlations for individual pedons showed CEC correlated to TN ($r = 0.960$, $p < 0.05$) in pedon 1; pedon 2 (clay, $r = -0.927$; sand, $r = 0.881$; SCR, $r = 0.923$; pH, $r = 0.847$; SOC, $r = 0.866$; TN, $r = 0.909$; all at $p < 0.05$); pedon 3, OC ($r = 0.954$, $p < 0.05$); pedon 4, Ca ($r = 0.981$, $p < 0.05$), pedon 6, Ca ($r = 0.995$), Mg ($r = 0.973$), pedon 7, SOC ($r = 1.000$), P ($r = 0.999$), pedon 8, TN ($r = 0.989$), Ca ($r = 0.998$), Mg ($r = 0.983$), Na ($r = 0.986$), pedon 9, Ca ($r = 0.986$), Mg ($r = 0.949$); $p < 0.05$.

Exchange sodium percentage (ESP)

In the top-soil, ESP ranged from 0.5 to 3% and there was a general decrease in all pedons downward but with no

Table 3. The results of soil classifications.

Pedon #	Profile Ref. #	Coordinate	Altitude (m)	Soil classify as
1	*NDUKU/2*	N 04.38778; E 028.21173	662	Ferralic Acrisols (cleyic, humic)
2	POT/12	N 04.543974; E028.19393	717	Albic Sideralic Retisols (Clayic, differentic, profondic)
3	POT/13	N 04.47175; E028.24896	656	Chromic Albic Lamellic Acricsols (Andic, clayic, profondic)
4	POT/14	N 04.43442; E028.18229	699	Albic Sideralic Retisols (clayic, ochric, profondic)
5	POT/22	N 04.53000; E028.24700	647	Skeletic Folic Pretic Leptic Umbrisols (Anthric, mineral)
6	POT/25	N 04.33877; E028.14816	643	Haplic Geric Ferralsols (Humic, loamic)
7	Mkt	N 04.39729; E028.21531	712	Leptic Anofluvic Fluvisol (Albichydromorphic, lithic, loamic)
8	PO/JA	N 04.59430; E028.34834	651	Geric Pretic Ferralsols (Albic, humic)
9	POT/19	N 04.60100; E028.33900	674	Geric Pretic Ferralsols (Albic, humic, loamic)
10	POT/18	N 04.6100; E028.31200	657	Skeletic Leptic Chernozems (Hyperhumic, tonguic)

Source: Author.

trend (Figure 4D). The means of individual pedons ranged from 0.5 to 2.0% and the CV ranged from 18.5 to 114.2. This means the variability is moderate to high. The ESP value in the studied soils is well below the critical level of 15, that is used as the criterion for distinguishing sodic from non-sodic soils (Landon, 1991). This means the soils are non sodic which is good for the plants.

Pearson correlation for eight pedons did not show any significance at 5%. However, in the individual pedons ESP exhibited strong correlation with silt (r = 0.960), SCR (r = 0.970); $p < 0.05$ in pedon 1; pH (r = 0.922, $p < 0.05$), OC (r = 0.949, $p < 0.05$), P (r = 0.992, $p < 0.000$), Ca (r = 0.987, $p<0.000$), Mg (r = 0.997, $p <0.000$); BS% (r = -0.950, $p < 0.05$) in pedon 3; CEC (r = -0.960, $p < 0.05$) in pedon 6; Ca (r = -1.0, $p < 0.05$); P9 Na (r = 0.974, $p < 0.05$) in pedon 7.

Sakure and Nginda sulphur and selected micronutrient (trace elements)

Sulphur (S)

In the studied soils of Sakure and Nginda payams S in the topsoils ranges from 23.7 to 49.7 mg kg^{-1}. The means of individual pedons ranged from 29.9 to 57.6 mg kg^{-1} and CV ranged from 7.6 to 41.1, this means sulphur is moderately variable in the soils, with no existing particular trend in the profiles (Figure 4E). According to Landon (1991), extractable S ranges from 6 to 12 mg kg^{-1}, but in other research stations, it has been found to be just < 200 mg kg^{-1} (Landon, 1991). This implies the richness of S in the studied soils associated with the SOC (Schultheis et al., 2020).

Micronutrients (Cu, Zn, Fe and Mn)

In the topsoil Cu ranged from 0.85 to 8.36 mg kg^{-1}, Zn ranged from 0.32 to 2.13 mg kg^{-1}, Fe ranged from 14.9 to 73.7 mg kg^{-1} and Mn ranged from 25.7 to 96.47 mg kg^{-1} (Figure 4F and I). According to Umare (2018) criteria, the optimum range of the micronutrients are Cu (0.2 - > 0.4 mg kg^{-1}), Zn (3.5 - > 7 mg kg^{-1}), Mn (4.5 - > 9 mg kg^{-1}) and Fe (0.6 - > 1.2 mg kg^{-1}). Based on these soil fertility rating, Mn and Fe have high content in the soil pedons and also decreases with depth meaning the two elements are more associated with sandy soil. Zinc is very low in all the pedons and also decreased with depth. Copper had no particular trend in the profile but was abundant in all the pedons. The results implied that Cu, Mn and Fe are abundant in this soils but Zn was slightly in short supply. However, if the farming systems continue as shifting and fallow cultivation, there will be no issue with the micronutrients.

Soil classification results

According to IUSS World Reference Base (2015), six major soil types were identified and classified to level three and they are: Acrisols, Fluvisols, Umbrisols, Retisols, Ferralsols, and Chernozems (Table 3).

Factors affecting soil formation

The average temperature in the study area is about 25°C, varies with altitude and rainfall. Temperatures are constant for about eight months in a year but temperature differences during cold nights will result in disintegration of parent material (physical weathering) and the heavy down pour over 1500 mm in the area initiate chemical weathering (hydrolysis, hydration, oxidation and reduction), leach nutrients from the root zone; dislodge and move materials downhill since the soils have attained advance stage in weathering SCR of <1 as mentioned under earlier. Contributing factors that accentuate the process are shifting cultivation and grass fires made annually by natives for hunting and collection of honey. Tothil (1948) had observed soil had disappeared by sheet erosion, since the topography is gently undulating but gully erosions are uncommon. Soil formation has been *in situ* impacted by physical and chemical weathering, modified by climate and other soil forming agents. Six soil categories have been classified in the study area.

Conclusion

The investigated soils are acidic, highly weathered sandy clay loam with low organic carbon, phosphorus and nitrogen being the most limiting nutrients. Bases, sulphur and trace elements are in good supply, except for K and Zn are low, the nutrient retention capacity is very low, and the implication of these is poor inherent soil fertility. Poor inherent soil fertility translates into poor crop performance, low yield and consequently food insecurity which is policy concerns to the government and practical problem for the local community.

Further soil survey is recommended in the Greenbelt zone and to conduct more research into the type of soil fertility management feasible in the Greenbelt zone. The analysis was limited by the quantity of data obtained. About 60% of planned soil observation points were not reached and observed because local people and security personel were skeptical of what we were doing and tools used such as GPS due to lack of awareness. The study area was still in low level of security. Further research may thus improve the level of details.

Despite the limitations, this study contributes to academic knowledge and will make reference for future researches in the Greenbelt zone, where very little has been done in soil research due to prolonged social and political unrest in the area.

CONFLICTS OF INTERESTS

The authors have not declared any conflicts of interests.

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