

Variations in Soil Physico-Chemical Properties as Influenced by Landuse in a Toposequence

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Abstract

Soil, water and air work interchangeably for optimum growth and productivity. Soil as a resource provides crops with essential nutrients necessary for growth and human consumption. With the insurgence of high population growth leading to pressure on lands, poor land management etc., this tendency of the soil as a nutrient pool is seen to be dwindling. It is therefore prudent to investigate and understand the dynamism of soil properties to inform proper management. Understanding topography effects and assessing soil properties on different slope positions is a first-hand step in ensuring proper soil management practices. This paper considers the assessment of physico-chemical properties of soils located on different slope gradients and land use types on the Wamaso research site in Ghana made principally of cape coast granite. In all, eighteen samples were collected from identified horizons of five distinctive subsections of the slope were delineated as follows, summit (PP1), shoulder (PP2), middle (PP3), foot slope (PP4) and toe slope (PP5) respectively. Remarkable variations were observed within PP1 to PP3 and then PP5. Pearson's correlation index revealed that the associations between most of the soil physico-chemical were not consistent across the identified slope positions. The biplot of the first two principal components together is 68.3% of the total variation and might be interpreted as change in Cation exchange capacity, sodium, sand and clay. On the first axis highlights the influence of sand and clay on soil fertility, also the relationship between pH and Na. Organic carbon derived from organic matter contributes to the availability of the basic soil cations and therefore enhances ECEC of the soils and hence the relationship obtained from the biplot. In sum, this research achieved the objective which sought to substantiate indeed the impact topography has on soil physico-chemical properties thereby serving as a reference for the classification of the soils identified.

Keywords

Physicochemical, Principal Component Analysis, Soil, Toposequence, Wamaso

1. Introduction

Soil plays a critical role in attaining the objectives of sustainable development goals (SDGs 15: Life and Land) (Bonfante, Basile, & Bouma, 2020). It is estimated that approximately 50% - 70% of global soils are degraded or contaminated due to rampant anthropogenic land degradation which ultimately threatens food security (Gomiero, 2016). Also, 11% of the total global land surface in the categories of Class I-II¹ arable lands are noted to be only available which can support a growing demand of 50% agricultural produce to feed approximately 9.5 billion people by 2050 (Zilberman, Dale, Fixen, & Havlin, 2013). It is therefore essential to understand soil systems, their formation and characteristic behaviour to support landuse options that can influence their ecological health and sustainable yield (Fierer, Wood, & Bueno de Mesquita, 2021; Havlin & Heiniger, 2020).

Soil quality refers to the function of soil living ecosystems to support plants, animals and human activities including agriculture (Williams, Colombi, & Keller, 2020). Soil quality can be assessed by a set of indicators involving physical, chemical and biological soil properties. According to (Andrews, Karlen, & Cambardella, 2004), a suitable indicator should have a strong relationship to the particular soil function, replicable and inexpensive to analyze. Reliance on soil physicochemical properties to establish the soil health of particular ecosystems has been applied across several studies (Musa & Gisilanbe, 2017; Sadiq, Maniyunda, Anumah, & Adegoke, 2021; Worku & Bedadi, 2016) hence makes it a suitable indicator for this study. Recent reports have observed a decline in soil quality across the African region caused by a loss in biological activity, soil structural degradation and reduction in the availability of micro and macronutrients (Gachimbi, 2002). Other research has confirmed that a negative soil nutrient balance is prevalent across the region and includes an average of 0 - 63% soil organic carbon (SOC) as well as macronutrients (N: 22 kg·ha⁻¹), (P: 2.5 kg·ha⁻¹) and (K: 15 kg·ha⁻¹) (Vågen, Lal, & Singh, 2005). The negative soil nutrient balance infers that primary soil nutrients are being diminished potentially of which reduced landuse management practices are considered a notable cause (Sanchez, 2002). In Ghana, the situation isn't different as the extent of soil macronutrient depletion across the various agro-ecological zones continuously rises. From 1982 to 1984, the annual per hectare depletion rate of nitrogen (N), phosphorus (P) and potassium (K) were reported as (30 kg·ha⁻¹), P (3 kg·ha⁻¹) and K (17 kg·ha⁻¹)

¹Class I-soils with few limitations that restrict their use. Class II-Soils with some limitations that reduce the choice of plants or require moderate conservative practice.

(respectively) (Bationo, Fening, & Kwaw, 2018).

Natural landscapes are found to have a direct influence on soil chemical and physical properties and also affect the pattern of soil distribution even when the soils are derived from the same parent material (Lawal et al., 2014). Particularly, slope gradients can significantly change soil properties through water control movement and distribution of materials which affect the spatial distribution of soil properties (Wang, Fu, Qiu, & Chen, 2001). Musa and Gisilanbe (Musa & Gisilanbe, 2017) reported that variability in soil properties across a slope can result in detachment, transportation and accumulation of soil materials. Steeped slopes also influence the direct and indirect distribution of physicochemical properties as observed in the loss of soil organic matter and nitrogen from several higher to lower slopes (Afshar, Ayoubi, & Jalalian, 2010). Also, coarser soil particles are found to accumulate at upper slopes positions mostly while finer particles accumulate at lower slope positions. A similar trend is observed in Ghana, where generally eroded sediments contained a higher concentration of organic matter and plant nutrients in available forms than their parent soils (Quansah, Safo, Ampontuah, & Amankwah, 2000). Topography-induced microclimate differences, are also attributable causes (Esu, 2010).

Dash et al. (2019) defined a toposequence as the occurrence of soils that can be related to a defined geographical area with a regular sequence and differing soil formations due to existing topographic features (Dash et al., 2019). A narrower description is offered by Gessler et al. (1996) as a spatial object that maintains flow connectivity from the summit to its base of a sloping or inclined landform. It practically defines the process resulting in differentiation in properties i.e. (Physical, chemical, mineralogical and morphological) across soil horizons (Sağlam & Dengiz, 2015). Hence, the location of specific soil types in the toposequence can be used to differentiate soil types as they are linked to variation in geomorphic features (Conforti et al., 2020). Further, these topographic positions of soils play critical roles in establishing local soil classification guides for proper landuse management (Braithwaite, 2002). According to Dipak Sarkar and Velayutham (2001), a typical toposequence has its lower part of the slope deeper and retains the most amount of soil moisture. The toe of the slope merges with the depressions resulting in hydromorphic conditions resulting in gleying. Therefore, consideration of soil properties at the toe end for optimum and sustained utilization should be critical to assess its vitality.

The complexity of the relationship between management of agricultural landscapes and soil health can be site-specific (Jimoh, Mbaya, Akande, Agaku, & Haruna, 2020; Vanacker et al., 2019). Jimoh et al. (2020) reported a significant relationship among soil moisture (SM), soil organic matter (SOM), bulk density (BD), pH, sand, silt, available phosphorus (P_{av}), exchangeable acidity (EA) and land topography. Similarly, the trend in change and variation of soil properties along various slope positions revealed that clay, bulk density, pH, soluble salt, cation exchange capacity (CEC) were more significant in lower topographic re-

gions of landscapes (Deressa, Yli-Halla, Mohamed, & Wogi, 2018). Extractible bases and micronutrients are reported as highly prominent at surface layers of the upper topographic (Nahusenya, Kibebew, Heluf, & Abayneh, 2014). The relationship between CEC, OM, and TN is higher along a slope compared to the upslope position of a hill in Nigeria (Ezeaku & Eze, 2014) and similar results have been described across slopes in the African region (Dessalegn, Beyene, Ram, Walley, & Gala, 2014). Seifu et al. (2020) showed that altitudinal gradient affected BD, total porosity (TP), whilst P_{av} of soils in watershed influenced landscape. Likewise, variation in electrical conductivity (EC), SOM, soil organic carbon (SOC), TN were associated with interaction effects of landuse types and slope gradient. Nevertheless, results contrary to these associations were recently reported by (Tamene, Adiss, & Alemu, 2020) indicating that establishing a relationship between soil properties and topography is highly dependent on regional analysis.

The land resources of the University of Cape Coast, Wamaso Research site are gradually been degraded due to severe erosion and inappropriate soil management practices. Efforts to restore any degraded portions of the land need to be undertaken prior to its intended use. As it is well established, knowledge on the variation of soil physico-chemical properties are an important determining factor of soil health to inform landuse and land management practices. To the best of our knowledge, there isn't adequate soil data characterization on the toposequence of the Wamaso site. Further, there is a knowledge gap on the effect of various slope positions impact on soil physico-chemical properties at the Wamaso site. This work generally explores the variation of soil physicochemical properties and their relationships along the slope gradient of a hilly side in Wamaso, Central Region of Ghana. The area is predominantly pristine with a few dotted agricultural activities hence we hypothesized that soil physicochemical properties will potentially change down gradient with the existing topographic formation. Specifically, we aim to investigate 1) how soil physicochemical properties change along with topography, and 2) the relationships between soil physicochemical properties at different soil profile depths along the toposequence.

2. Materials and Methods

2.1. Study Area

The study area covers an estimated land-take of 419 acres and is approx. 17 km northwest of Twifo Praso in the Twifo Heman/Lower Denkyira District, Central Region, Ghana and 1.2 km west of Wamaso (latitude: 5.708333 and longitude: -1.658333) (Figure 1). The dominant vegetations are thickets consisting of an impenetrable mass of shrubs, climbers, coppice shoots and young trees and soft-stemmed leafy herbs e.g. *Ageratum conyzoid*, *Bambusa vulgaris* that appear in abandoned farms and cultivated lands grown to cocoa, maize, plantain, cassava and rice. The topography generally shows a gentle slope that varies from 1% -

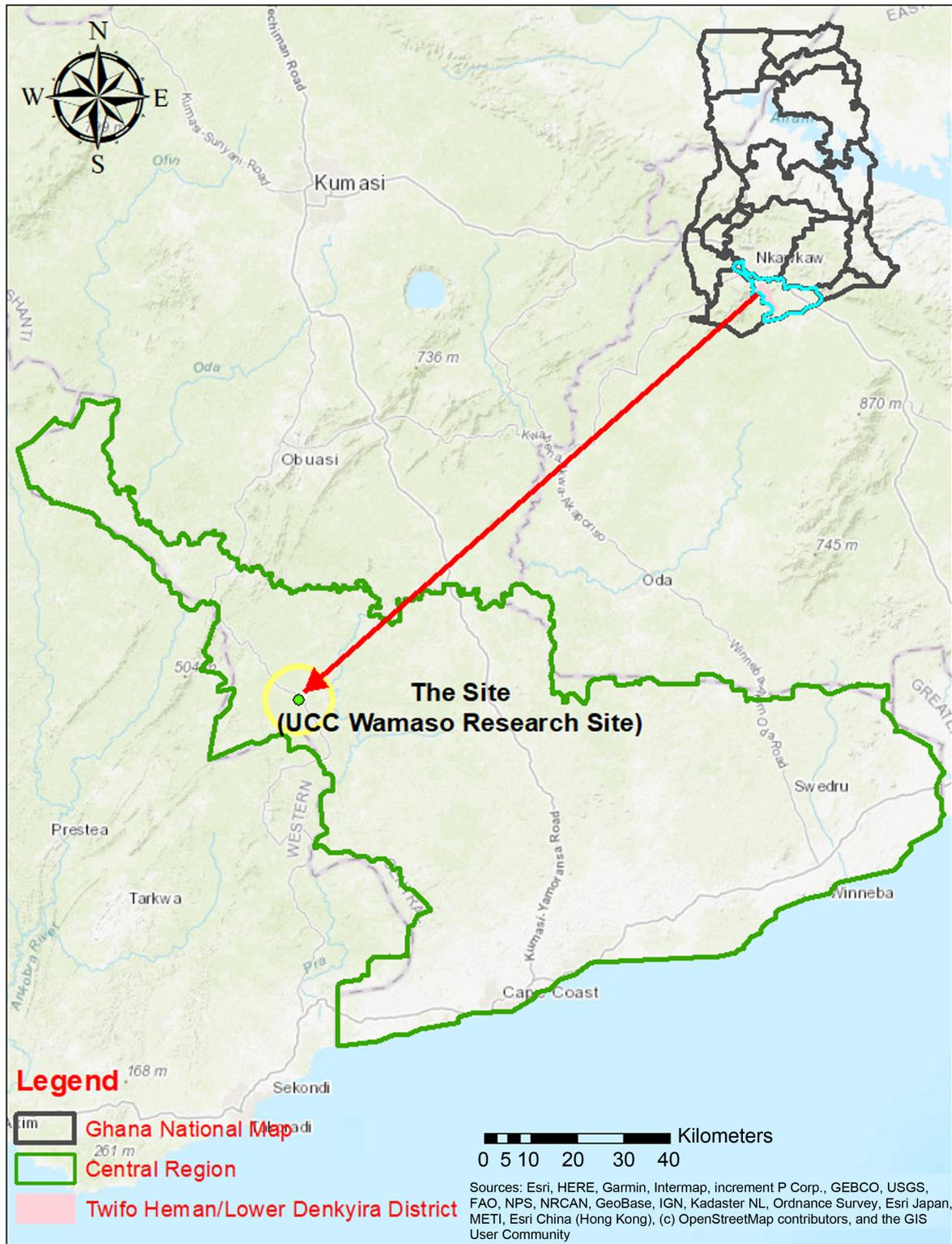


Figure 1. Map of study location.

10% whilst the elevation ranges from 40 - 70 m above sea level (asl). Minimum plateaued summits were between 87.18 - 91.77 m with the highest summits ranging from 118.40 - 123.56 m. A few seasonal streams border the study site and

tend to flood during the rainy seasons. The temperature and rainfall pattern across the study area is shown in (Figure 2). The geology of the area is generally undulating with gently rolling, steeped slope topography at few places, including a Cape Coast granite and Wamaso albitized rock type (Gyamera, 2014).

2.2. Soil Survey and Sampling

The free survey method of soil investigation was adopted where the use of aerial photography obtained from the drone were used to make interpretation coupled with massive field observations to aid in characterization of the toposequence (Beckett & Burrough, 1971). This method is conducive for the field setting as there were significant open spaces to allow for field walkovers and tracing of footpaths for broadened observations and judgement of the soil features. Current landuse features were assigned unique identification numbers. To further obtain a widened aerial view of the study area, an unmanned drone (DJI Phantom 3 Professional) was used to obtain photographs of the approximate landmass. The aerial photographs were processed in Pix 4D Mapper software together with Mission planning software (Map pilot) (Burnham, 2019) and topographic maps generated in ArcGIS environment (ArcGIS 10.7). The topographic maps were used to develop respective landuse maps. Overall, five (5) topographic maps based on observed land uses were developed. Soil profile pits (PP's) were established randomly in each of the identified land uses along the toposequence. Five PP's using a soil auger were sunk to obtain representative soil samples along the toposequence (Figure 3). Three discrete samples were collected vertically at varying depths across respective PP's. The PP's were then described per Soil Survey Manual (Soil Science Division Staff, 2017). The field-moist soil samples were collected in sealable plastic bags, with stones, roots, and large organic residues removed. Sample labels codes/IDs corresponded uniquely to the soil profile

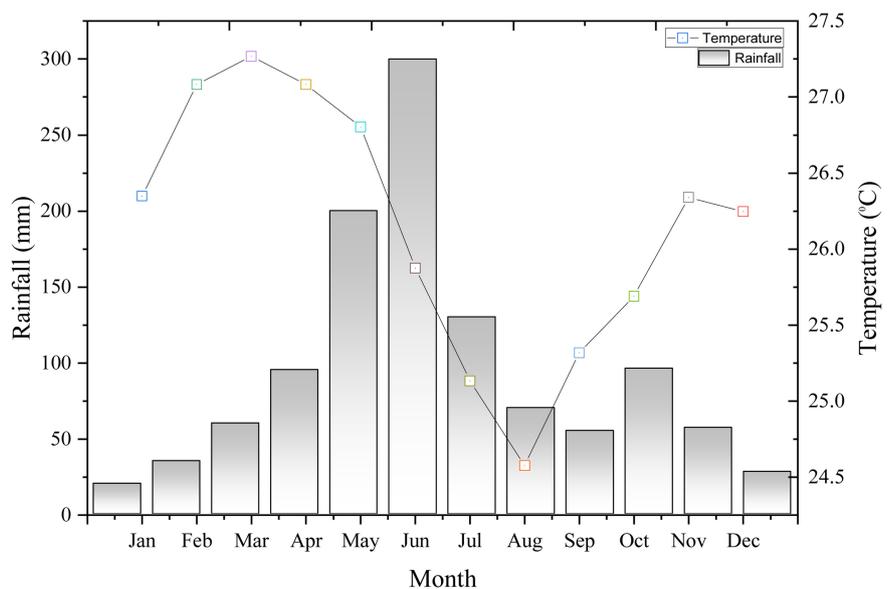


Figure 2. 2020 average rainfall and temperature pattern across the study area.

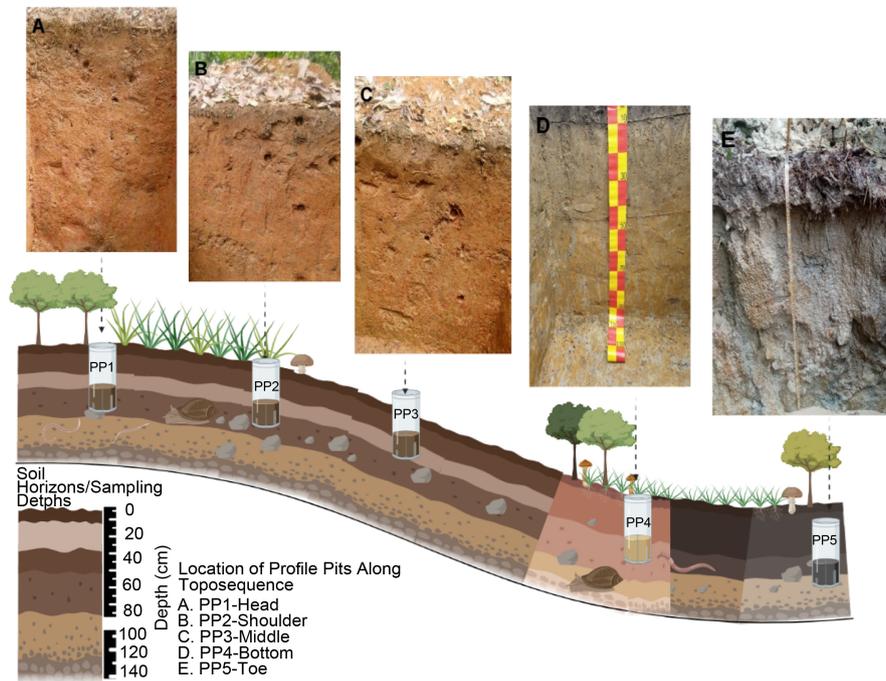


Figure 3. Cross-section of the Wamaso Toposequence.

test pits. Overall 270 samples (i.e. 18 samples obtained from 5 profile pits at 3 samples at respective depths each). They were transported to the laboratory in an ice cooler to maintain the temperature at 4°C. The remaining organic materials were removed, soil samples air-dried at room temperature for 15 days, pulverized and sieved (2 mm mesh-size) for storage.

2.3. Analytical Methods

A summary of the various laboratory analytical methods employed are shown in **Table 1**. Before any analytical analysis, all glassware was washed in distilled water and Hydrochloric acid (HCl) solution and oven-dried at 105°C. Fresh soil samples were used for each run of batch analysis to avoid cross-contamination of chemical parameters. Detailed description of analytical methods is provided as in the supplementary information.

2.4. Statistical Analysis

Ata were tested for normality of distributions and homogeneity of variances before analysis (Kolmogorov-Smirnov, $p > 0.05$). Standard skewness and kurtosis were determined to test whether the data originated from a normal distribution. Statistical values which were outside the range of -2 to $+2$ were considered as departures from normality. Differences in soil physicochemical properties across the toposequence were compared using one-way analysis of variance (one-way ANOVA) with Tukey post hoc test. Subsequently, all relationships between soil properties were evaluated using Pearson's correlation tests and correlation coefficient (R^2). Principal component analysis (PCA) was applied to examine the

Table 1. Experimental analytical methods for determining soil physicochemical properties.

ID	Parameter	Method	Reference
1	pH	1:2.5 soil/water	(Thomas, 1996)
2	Exchangeable bases	NH ₄ OAc saturation method	(Chapman, 1965)
3	Soil organic matter	Walkley-Black wet digestion	(Walkley & Black, 1934)
4	Total nitrogen	Kjeldahl analysis	(Mulvaney, 1982)
5	Available phosphorus	Olsen's method	(Trouw, 1930)
6	Particle Size	Pipette Method	(Kettler, 2001)
7	Bulk Density	Undisturbed Core Method	(Blake, 1986)
8	Cu, Zn and Fe	(DTPA) extraction method	(Udo, bia, Ogunwale, Ano, & I.E. Esu, 2009)

degree of contribution of the variables towards overall variation within the soil's physicochemical properties. All statistical significance was tested at ($p > 0.05$). The study area map was created using the ArcGIS 10.7 software (ESRI, Inc., Redlands, CA, USA software version 10.7). All statistical analysis and graphing were performed using OriginPro v2021 software (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Descriptive Statistics on Soil Properties

The descriptive statistics of soil properties across profiles pits are shown in (Table 2). Overall the data demonstrated a platykurtic distribution indicating significant variation across samples. The maximum coefficient of variations was recorded for P_{av} (1.00), Zn (0.98), EC (0.92) which could signify as major source and cause of variation in the soil datasets. The mean values of soil particle size decreased from sand (58.46) > clay (32.8) > silt (8.64) while maximum pH across the profile pits was recorded at 5.89.

3.2. Morphological Characteristics of the Toposequence

All the pedons had moderately deep profiles (≈ 120 cm). PP1 and PP2 contained four generic soil horizons, PP3 was made up of three, PP4 had four whereas PP5 had three generic horizons. The pedons of PP1, PP2, and PP3 representing the summit, shoulder and mid slopes respectively were well-drained whilst the lower (PP4) and valley bottom slopes (PP5) were poorly drained. This was observed by small water pools possibly caused by intermittent heavy rains. The pedons of PP1 comprised secondary forest with thicket vegetation lying on a soil potentially

Table 2. Descriptive statistics on soil properties.

	Mean	SD	SE	Skewness	Kurtosis	CV	Min	Median	Max
pH	5.06306	0.31824	0.07501	2.02382	3.80118	0.06286	4.75	4.99	5.89
Ca	1.50944	0.62934	0.14834	1.13826	0.3324	0.41693	0.78	1.265	2.99
Mg	0.66333	0.45531	0.10732	1.61899	2.59083	0.68639	0.23	0.515	1.95
Na	0.06389	0.0233	0.00549	2.04226	6.63986	0.36467	0.03	0.06	0.14
K	0.11056	0.06655	0.01569	0.42466	-1.09146	0.60197	0.02	0.095	0.23
Fe	13.36556	6.81287	1.60581	0.78962	1.04325	0.50973	3.88	14.22	30.64
Cu	0.74056	0.50376	0.11874	0.09452	-1.75627	0.68024	0.1	0.77	1.54
Zn	0.47056	0.46145	0.10876	2.11211	4.4224	0.98065	0.1	0.3	1.88
P _{av}	0.32389	0.32673	0.07701	0.88599	-0.84662	1.00878	0.03	0.1	0.98
OC	0.70667	0.53074	0.1251	1.06551	0.06585	0.75104	0.07	0.54	1.83
TN	0.07667	0.04615	0.01088	0.95138	0.23225	0.6019	0.02	0.065	0.18
Sand	58.46167	16.23512	3.82665	-0.52872	-0.95541	0.27771	28.61	60.29	79.29
Silt	8.64889	3.13457	0.73882	2.08036	3.92958	0.36242	5.51	7.795	17.12
Clay	32.89056	14.49551	3.41663	0.428	-1.03987	0.44072	12.86	31.82	56.84
EA	0.00539	0.00336	7.93E-04	0.40295	-0.19484	0.62408	0.001	0.0055	0.013
CEC	2.35333	0.93504	0.22039	0.86552	-0.85481	0.39732	1.3	1.84	4.11
EC	35.77778	32.96845	7.77074	0.83681	-0.33466	0.92148	0.16	31.3575	105.1
BD	1.34243	0.23592	0.05561	0.38695	-0.92787	0.17574	1.01178	1.2774	1.82106

*Available Phosphorus (P_{av}), Cation Exchange Capacity (CEC), Electrical Conductivity (EC); Total Nitrogen (TN), Organic Carbon (OC), Exchangeable Acidity (EA), Bulk Density (BD), Coefficient of Variation (CV), Standard Deviation (SD), Standard Error of Mean (SE).

evolved from the current geologic formation. Pedons PP2, PP3, PP4 and PP5 were established in an abandoned cocoa plantation surrounded by a secondary forest with thicket vegetation while pedons.

The topsoils for all five pits had weak fine to moderate granular structures whereas the subsurface soils had moderate and strong, medium and coarse, angular and subangular blocky structures. Non-sticky and slightly sticky (wet) soil consistencies were obtained in the surface soils while sticky (wet) as well as firm (moist) consistencies were mainly obtained in the subsurface soils.

Layer boundaries were distinctively visible from the topsoil through to the last horizon of each of the pits. Burrows of ants and worm casts were also detected within the pits which is an indication of faunal pedoturbation. Lateral roots, tip roots and root hairs were present in the soil column, predominantly within the first three identified layers of the various profile pits. The soils exhibited variable colouration, both in surface and subsurface soils (**Figure 4**). The first layer in all the profile pits revealed significant distinction in soil colour. The colouration

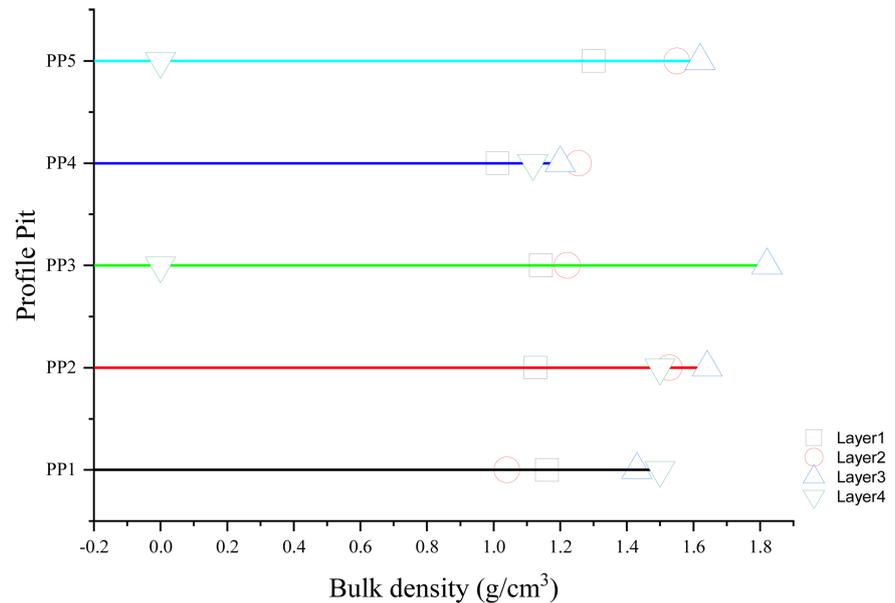


Figure 4. Bulk densities across soil profile pits.

varied from very dark greyish brown 10Yr 3/2 for PP5, 10Yr 3/3 dark brown for PP4, reddish-brown 5Yr 3/4 for PP3, reddish-brown 5Yr 3/2 for PP2, and 5GY 2.5/1PP greenish-black surface soils for PP1. The pedons were in constant exposure to erosion. The uplands and mid soils revealed light-coloured soils caused by erosion strips. The greatest erodibility was observed from the upper slope which exhibited coarse texture and very low SOM whereas the lower and valley bottom slopes experienced minimal erosion with mostly deep, organic-rich leached soils

The soil texture varied from sandy loam to sandy clay loam in the surface horizon for all five profiles (Table 3). The bulk densities increased proportionally to the respective profile pit depths (Figure 5).

3.3. Comparison of Physicochemical Properties across Profile Pits

Physicochemical properties across the various soil profile pits significant across the profile pits as determined by the corresponding slope gradients of the topo-sequence. pH across the PP's were strongly acidic and ranged from 4.48 in PP1 to 5.89 in PP5 although there were no significant differences ($p > 0.05$) in the pH (Figure 6(A)). The SOC was unevenly distributed across the PP's and decreased from the summit profile pits (PP1) to the valley bottom profile pit (PP5) (Figure 6(B)). In the summit pedon's SOC ranged from 1.14% - 0.34%, 1.05% - 0.28% within the shoulder, 1.59% - 0.47% in the middle slope, 1.67% - 0.29% in the base slope and finally 1.83% - 0.07% at the toe slope. There was a significant difference ($p < 0.05$) in SOC concentration from PP1 to PP2 whilst no statistical significance was detected from PP3 to PP5 (>0.05). Soil available phosphorus (P_{av}) was averagely low from across layers of PP1 to PP4, with PP5 recording the highest value (Figure 6(C)). From the layers of PP1 to PP4, total nitrogen (TN)

Table 3. Soil fractions and textural class across profile pits.

Profile Pit (PP)	Soil Layer	Depth (cm)	Bulk Density	Soil Fraction (%)			Textural Class
				Sand	Silt	Clay	
PP1	1	0 - 10	1.16	73.71	6.8	19.5	Sandy loam
	2	10 - 40	1.04	57.99	6.12	35.89	Sandy loam
	3	40 - 60	1.43	34.27	8.89	56.84	Clay
	4	60 - 135	1.5	28.61	16.25	55.14	Clay
PP2	1	0 - 18	1.13	74.5	6.51	18.99	Sandy loam
	2	18 - 25	1.52	58.35	7.79	33.86	Sandy clay loam
	3	52 - 75	1.64	41.8	6.88	51.32	Clay
	4	75 - 137	1.5	35.15	9.48	55.37	Clay
PP3	1	0 - 17	1.14	62.23	8.98	28.79	Sandy clay loam
	2	17 - 52	1.22	56.17	8.37	35.46	Sandy clay
	3	52 - 125	1.82	39.28	17.12	43.6	Clay
PP4	1	0 - 23	1.01	70.27	7.8	21.93	Sandy clay loam
	2	23 - 44	1.25	67.4	7.77	24.83	Sandy clay loam
	3	44 - 66	1.2	63.2	7.03	29.78	Sandy clay loam
	4	66+	1.12	58.22	6.96	34.82	Sandy clay loam
PP5	1	0 - 19	1.3	79.08	5.51	15.41	Sandy loam
	2	19 - 78	1.55	79.29	7.85	12.86	Sandy loam
	3	78 - 96	1.62	72.79	9.57	17.64	Sandy loam

was averagely high in PP1 and PP2 as concentration decreased from PP3 to PP4 (**Figure 6(D)**). There were significant differences in TN concentrations from PP1, PP2 and PP4 ($p < 0.05$) but no significant difference was observed in PP3 and PP5 ($p > 0.05$).

The exchangeable bases recorded in the study were plotted to obtain a piper plot in (**Figure 7**). It is observed the samples are classified into three types, representing the Mg-Ca-K (plane 1), Fe-Zn-Cu (plane 2) and Fe+Cu-Ca+Mg (plane 3).

A comparison of the exchangeable acidity (EA) and cation-ion exchange capacities (CEC) across the various soil PP's is shown in (**Figure 8**). From PP1 EA and CEC were evenly distributed across the layers, with Layer 1 and Layer 3 recording the highest values. A similar trend was observed across PP2; however, the EA values were very low in Layer 1 but evenly distributed from Layer 2 and 3 with CEC values in Layer 1. The CEC values from layer 2 to Layer 4 were equally distributed. A similar trend of the distribution in PP2 was observed in PP3 and PP4. Meanwhile, in PP5, Layer 2 recorded values were almost half that of Layer 1 whilst in Layer 3, CEC was higher than EA values.

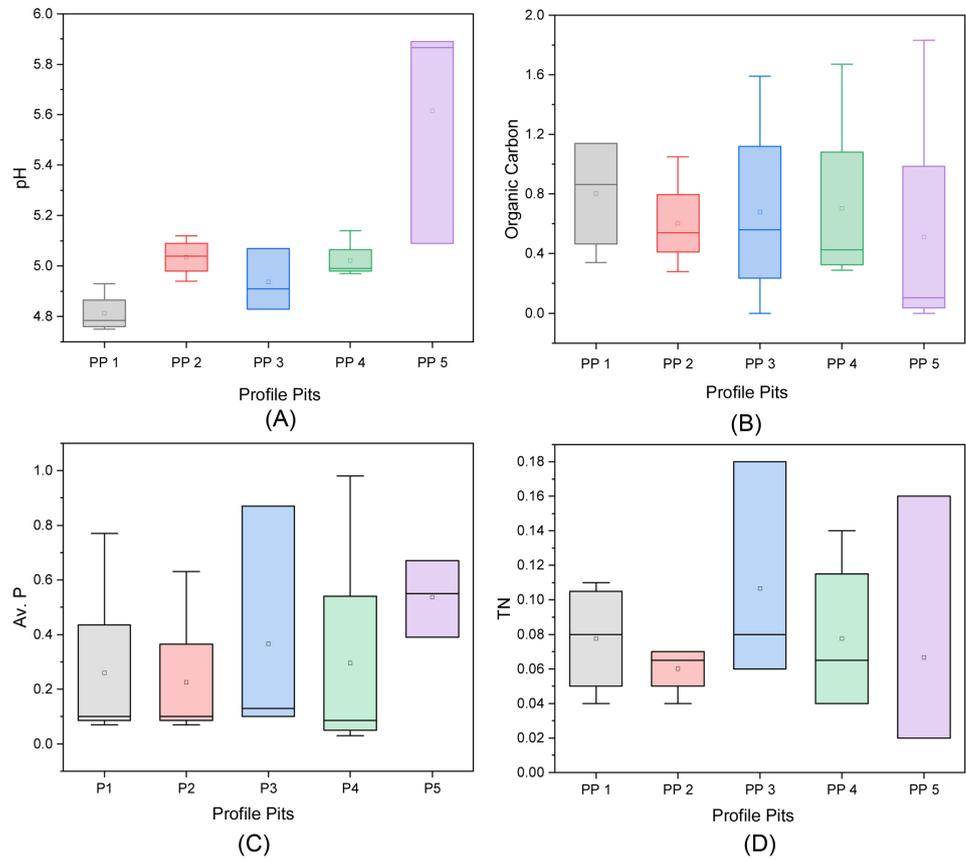


Figure 5. Changes of soil physico-chemical properties across soil profiles.

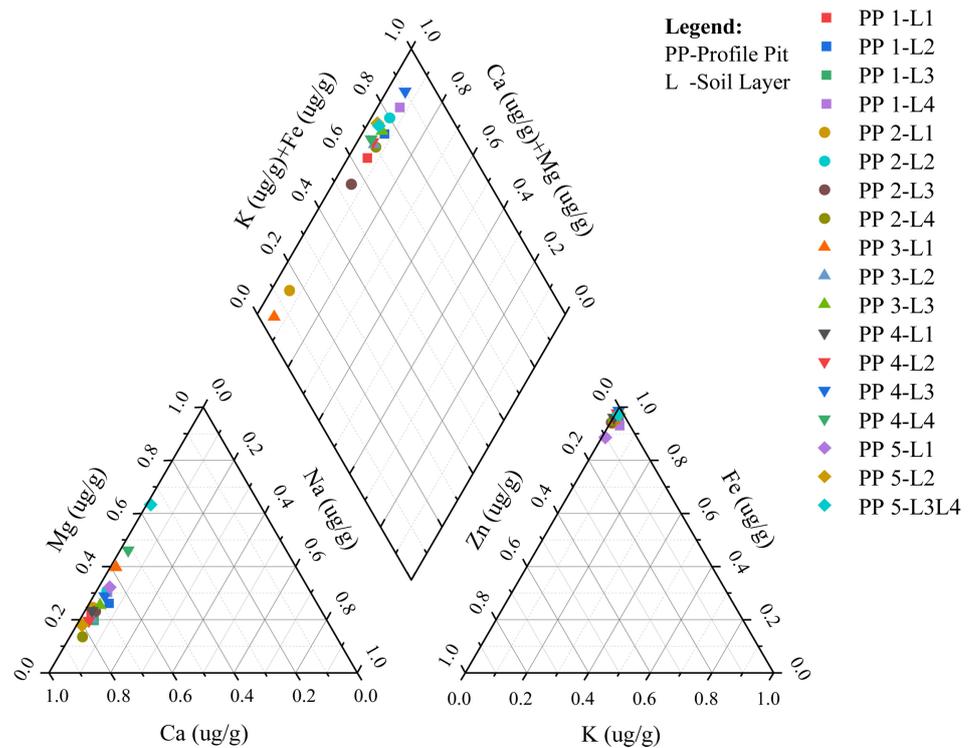


Figure 6. Trilinear plot of major cations across profile pits.

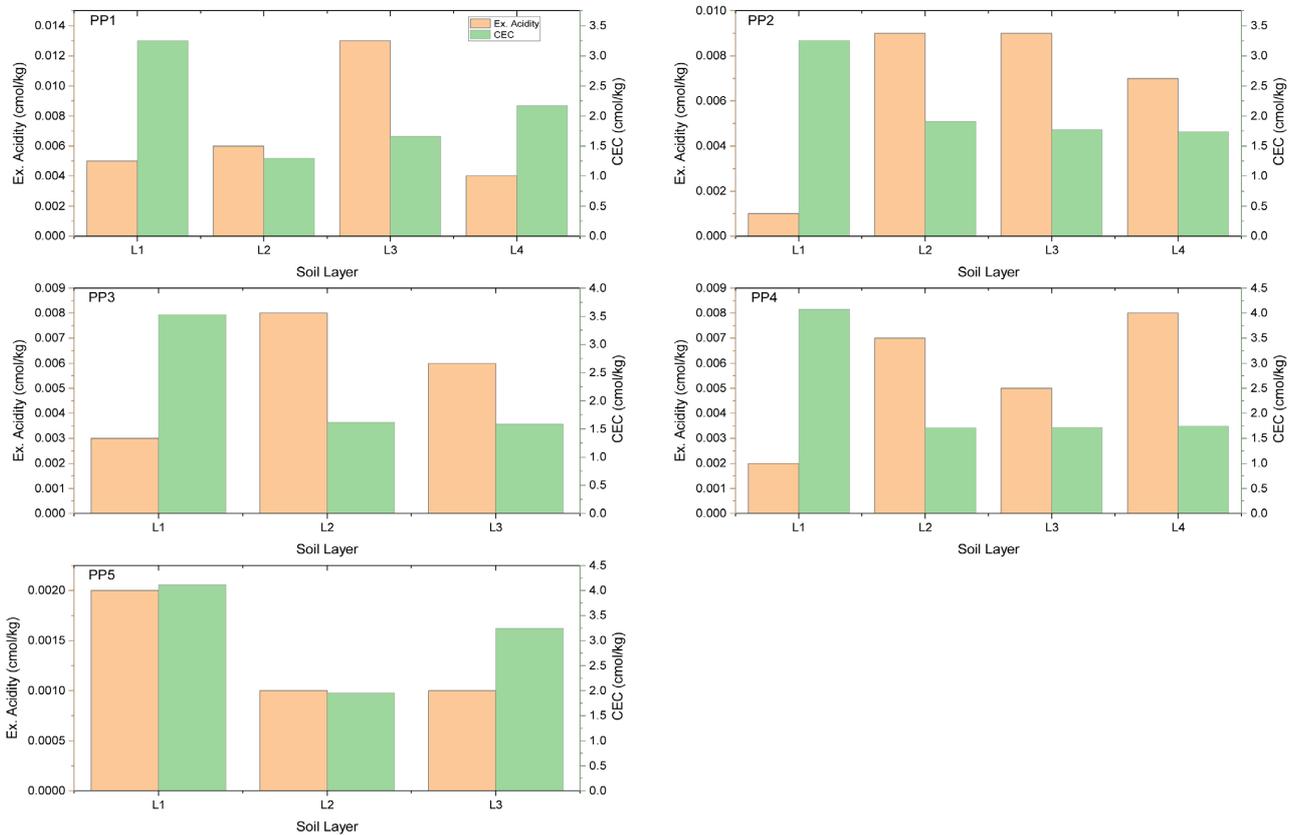


Figure 7. Comparison of EA and CEC.

3.4. Relationship between Soil Physico-Chemical Properties across Profile Pits

Pearson's correlation analysis revealed significant correlations between most of the soil physicochemical properties, and that the correlation between soil Physico-chemical properties was consistent across the profile pits (Figure 8). The analysis showed more positive correlations amongst chemical parameters such as between Cu, Zn, Ca, Mg, Na, and similar positive correlations observed between available phosphorus, Cu, Na, and Fe. However, there was a negative correlation between TN and pH while TN showed a positive correlation with Ca, Na, Zn and OC. pH also negatively correlated with OC, EA, Ca and Na. Also, EA exhibited a negative correlation across all cations in the soil profiles. CEC on the other hand yield a positive correlation with cations in general and showed a negative correlation association with EA. There was however a difference in the correlation of soil textural properties with the exchangeable bases. Sand exhibited a positive correlation with the major ions while the opposite was observed with silt and clay soils. Similarly, bulk densities across the profile pits correlated negatively with exchangeable bases.

3.5. Principal Component Analysis of Soil Physico-Chemical Properties

The weights for the variables are along the principal components are shown in

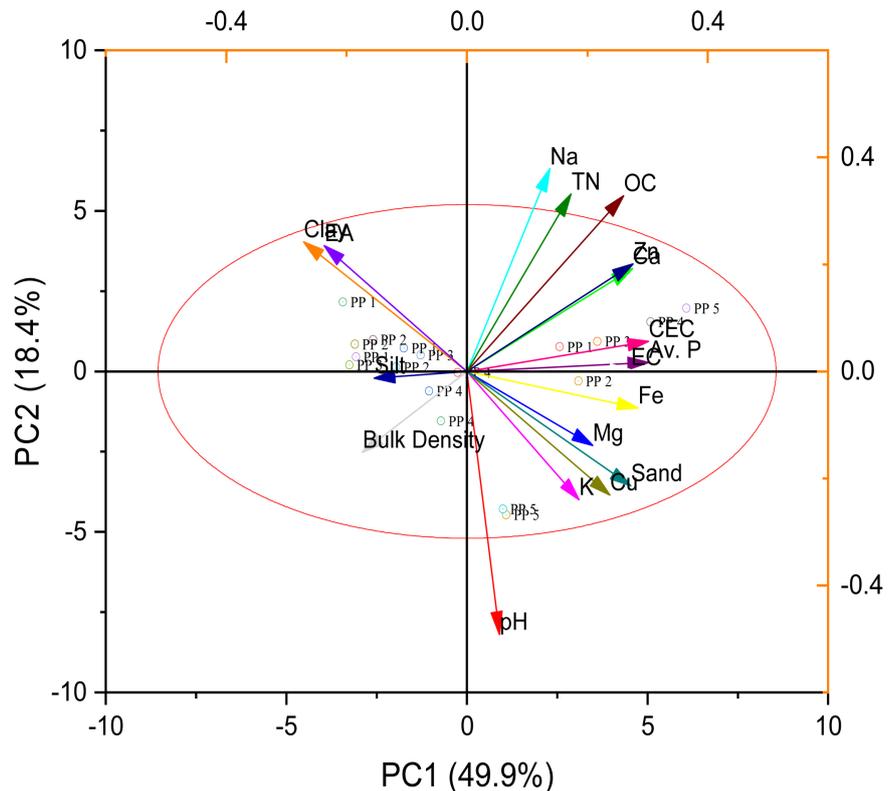


Figure 9. PCA biplot of soil physicochemical properties.

4. Discussion

4.1. Characteristics of Soil Physico-Chemical Properties at Different Profile Pits

The key determinants in soil characteristics are mainly the soils parent material and the degree slope. Soil properties such as particle size and pore space distribution, hydraulic conductivity among others are all inherent properties derived from the parent materials. Overall, the pedons exhibited differences in slope, water percolation and degree of water erosion. Hydrological information of the study area was previously reported by (Gyamera, 2014).

Physicochemical properties of soils across the various ecological zones in Ghana have been documented (Bationo et al., 2018). Our study area represented a typical semi-deciduous forest agro-ecological zone (Issaka, Buri, Tobita, Nakamura, & Adjei, 2012) which is characterized by moderately acidic soils to low Nitrogen and Phosphorus levels (Table 4) and results obtained were consistent with reports by Bationo (Bationo et al., 2018). The descriptive statistics revealed that most of the variation occurred at the upper and base slopes of the toposequence with relatively little change occurring in the middle-shoulder portions. Across all layers of the PPs, clay percentages increased from surface soils down the subsurface soils revealing typical pedogenic eluviation-illuviation processes particularly within the upper to middle slope profiles while the opposite was observed for soil and silt compositions (Mulugeta & Sheleme, 2010). Increasing

Table 4. Comparison of current soil properties to referenced semi-deciduous forest soil properties in Ghana.

Soil properties	This Study			Reference (Bationo, Fening, & Kwaw, 2018)	Description
	Mean	Minimum	Maximum		
Soil pH	5.06306	4.75	5.89	5.5 - 6.2	Moderately acid to slightly acid
Organic C	0.70667	0.07	1.83	1.59 - 4.80	Medium to high
Total N	0.07667	0.02	0.18	0.15 - 0.42	Low to medium
Available P	0.32389	0.03	0.98	0.36 - 5.22	Low
Available K	0.11056	0.02	0.23	62.01 - 84.82	

clay amount with depth could have also resulted in the moderate and strong, coarse, subangular and angular blocky structures as well as the firmness that increased with soil depth.

Generally, soil pH in the surface and subsurface layers of the pedons were rated as medium to low per rating scores by Landon (2014). Soil acidity assumed a descend across the pedons with corresponding depths. This could be related to the relatively higher content of basic cations observed at the subsurface layers. The highest pH, which was observed in PP5, could be due to the high solubility of ions e.g. Na^{2+} Ca^{2+} and Mg^{2+} . The results are consistent with observations by (Ogbodo, 2011) that basic cations are capable of naturally displacing H^+ from exchangeable complexes into soil solution where they are leached. The leaching process and accumulation of ions at particular soil pedons trigger changes in pH. Strongly acidic soils are likely to contain a significant amount of exchangeable Al^{3+} and H^+ which affect plant growth (Schoeneberger, Wysocki, & Benham, 2012) while they become deficient in some bases such as Ca and Mg (MM & Ahmad, 2020). Such soil conditions can induce phosphate fixation and reduce the ability of micro-organisms to fix atmospheric nitrogen. There was no significant difference in pH across the pedons which could further be attributed to soils buffering and self-regulating abilities which can balance the changes of the external acid and alkali environment to some extent.

The significant colour variations across could be attributed to the impact of topography and patterns coupled with the influence of water infiltration rates, surface runoffs, erosion and also deposition of the eroded soils. The dark, brown and dark yellowish-brown surface soil colouration indicates either uniformity in SOM distribution or mineralization occurred at the same rate while dominant reddish and yellowish subsurface colours indicate the presence of hematite and goethite as forms of Fe oxides, defining ferrugination. Similar results were reported by (Townsend, Vitousek, & Trumbore, 1995). The reddish and brownish colouration indicated that soils on slopes become well-drained with adequate aeration and less saturated even under frequent rainfall. Foth (1990) attributed this phenomenon of soils to the availability of metal compounds in oxidized states (e.g. CO^{2+} , Fe^{3+}). The varied colours associated with the horizons in the

pedons within the region of depression can also be attributed to the reduction reaction caused by water saturation, such pedons mostly are located in poorly drained and waterlogged regions where soils are water-saturated most of the time and thus tend to have the greyish colour (Foth, 1990). This scenario was observed down the profile of the fifth profile pit with surface soil colour N5/5 grey.

SOC decreased with increasing depth across all five (5) pedons with the highest values recorded in the surface soils of each. The observation was consistent with reports by (Gaudinski et al., 2000) who indicated that such properties are typical of SOC content in moist soils. Previous environmental conditions, in the study area, could also influence SOC content due to “soil’s memory” (Janzen, 2005). Overall, the soils were classified as medium in SOC as values obtained were below 2.0% (Enwezor et al., 1988). They were rated as low in accordance per (Landon, 2014) which indicates that the soils are vulnerable to water erosion. The influence of climatic variables according to (Hobley et al., 2015) is eminent mostly in surface soils and diminishes moving down a pedon making site and landuse factors more important in soil organic carbon storage down a pedon. Earlier reports have indicated that SOC less than 1.16% for tropical soils is an indication of soil degradation involving a highly raised risk of soil erosion (Barrow, 1991). This effect could be attributed to loss of TN across the pedons as explained by (Sheleme & Singh, 2011) concerning the transport of organic matter and variation in clay content of soils. Further, (Bürkle, 1989; Jobbágy & Jackson, 2000) linked site factors such as soil type, texture and soil mineralogy as key determinants in the distribution of soil organic matter along pedon. Organic matter correlated positively with clay content and negatively with sand. This is consistent with the findings of this research where soil organic carbon decreased down the profiles and this could be attributed to climate, landuse, soil type and mineralogical properties of the parent material.

The bulk density increased down gradient the pedons possibly attributed to high SOC in the surface layers. This effect reported by (Worku & Bedadi, 2016) where SOC is found lighter than mineral matter tend to improve soil porosity but reduces soil bulk density.

Available phosphorus (P_{av}) was observed to decrease down the profiles pits due to increases (P_{av}) in clay contents down the profiles (Brady & Weil, 2008). The relatively higher in surface horizons, as compared to sub-surface horizons could also be attributed to the difference in organic matter contents. Available P experienced some inconsistencies with depth but generally decreased with increasing depth. This trend however was vice-versa along with the various landscape positions. The correlation between organic carbon and phosphorus was positive indicating proportionality between SOC and (P_{av}). Also, the high occurrence of mineralization could have facilitated the liberation of phosphate ions outside the soil matrix and available to crops. These phosphorus releases also react with Al^{3+} and Fe^{2+} in acid soils to form aluminium phosphate ($AlPO_4^{-2}$)

which are not readily available for plants uptake.

A trilinear plot is an important tool to visualize the interaction of major ions across the layers of the soil profiles pits as shown in (Figure 8). Much of the ions were clustered along the $\text{Fe}^{2+}+\text{Cu}^{2+}$, Mg^{2+} and Cu^{2+} axes of the planes. This may infer that the exchangeable bases across the study area were borne from a Fe^{2+} , Cu^{2+} , and Mg^{2+} laden rock weathering process. Generally, the exchangeable bases were of lower values and fall within the threshold for critical limits for deficiency and hence the likelihood for fertilization as proposed by (Musinguzi et al., 2015). Sodium (Na^{2+}) in many circumstances is utilized by plants as a partial substitute for potassium. It is not an essential nutrient. Its absence or presence in very limited quantities is therefore not usually detrimental to plant nutrition. However, Na^{2+} in large quantities particularly in proportion to other cations present can affect crops and the physical conditions of the soil. The CEC of the soils was reasonably high as per (Landon, 2014) and the exchange complex of the soils was dominated by Ca followed by Mg^{2+} , K^{2+} and Na^{2+} . The content of exchangeable cations however experienced fluctuations with high and low values with increasing soil depth, which could be attributed to their leaching from the surface horizon down to the sub-surface according to (Gebrekidan & Negassa, 2006). The $\text{Ca}^{2+}:\text{Mg}^{2+}$ ratio of the soils was in the range of 3.2 - 2.13 from the surface soil down to the subsurface soils in the summit soil, 2.99 - 6.09 in the upper slope, 1.94 - 2.78 in the middle slope, 3.18 - 1.11 in the lower slope and then 1.20 - 0.56 in the toe slope. The exchangeable K^{2+} , Ca^{2+} and Mg^{2+} of the soils had some being above the critical values and some also below the critical values (Landon, 2014). K^{2+} and Na^{2+} values both across and along the various landscape positions fell below 0.6 and 1.0 respectively and therefore according to (Landon, 2014) are low.

4.2. Relationship between Soil Physicochemical Properties

Determining soil health by assessing disparities in soil physicochemical properties is important as it reveals necessary interactions, associations and behaviour amongst the various properties (Havlin & Heiniger, 2020). Our results reflected these features as there were significant associations by correlation effect amongst most of the soil properties. The results have shown that there are positive and negative associations amongst soil physicochemical properties in the semi-deciduous forest. pH for instance is negatively correlated to Ca^{2+} , Na^{2+} , EA and TN while it is positively correlated to other ions such as Mg^{2+} , Fe^{2+} , Cu^{2+} , K^{2+} ($p < 0.05$). The impact of pH is critical. Excessive pH tends to hinder soil microbial and enzyme processes hence suitable pH ranges are beneficial to support the entire pedon. Generally, pH showed positive correlations with soil textures (sand and silt) but a negative association with clay. This could be due to high mineralization (ions) which exist in clay samples, causing an imbalance across the pedons (Yu et al., 2017). A similar negative correlation was observed between pH and EA, TN and Cu^{2+} . Similar observations were made by (Ulakpa, Ulakpa, & Eyank-

ware, 2021).

The overall association between SOC and soil mineralization is described by (Six, 2002). Near the surface, SOC content is highest and so fine minerals are most likely to be saturated with SOC, limiting their retention capacity. Below the surface SOC content generally decreases, so that saturation of fine minerals is less likely to be an issue and mineralogy becomes more relevant to SOC storage (Grimm, Behrens, Märker, & Elsenbeer, 2008). The association between phosphorus, SOC and other mineral ions were positively correlated but not significant ($p > 0.05$). This could be related to low P_{av} which was more significant in profile pits at the toe of the slope. At the toe and below the pedons, P_{av} is easily released from the SOC matrix undergoing mineralization and accumulation. The high P_{av} can also be determined by high percentage of clay fractions as the pedons descend and high leaching effects due to pH variations which causes low binding of minerals. Similarly, P_{av} correlated positively to TN and K^{2+} and the results conform to other reports by (Jiang et al., 2021).

The results of the study further revealed that the TN, SOC and P_{av} exhibited positive correlation, while the association between TN and SOC were not significantly related ($p > 0.05$) unlike TN and P_{av} ($p < 0.05$). A similar association is described in (Agboola & Corey, 1973). The association can be explained by the fact that SOC as part of soil organic matter (SOM) in the study area influences a series of soil properties and nutrient cycling, while soil enzymes are mainly adsorbed on the soil organic matter particles or combined with humus (Liu et al., 2020). High SOC is also reported to cause an increase in TN and K^{2+} levels (Wang & Huang, 2001) as observed from the results of this study.

4.3. Relationship between Different Samples and Soil Physico-Chemical Properties

In this study, we showed that there are significant variations with soil physico-chemical parameters, contributed by variations in profile pits across the toposequence. The eigenvalues from the PCA of pH, Ca^{2+} and Mg^{2+} which were greater than 1 could have together contributed the total variance of 49.9%. The position of the variables in the multivariate space further confirms the results of Pearson correlation analysis and association significant positive correlation amongst soil exchangeable ions in the study area. The second principal component explained 18.4% of the total variation with a positive correlation to EA and clay contents while exhibiting a negative correlation with BD. The findings are consistent with reported studies in (Sadiq et al., 2021).

5. Conclusion

In summary, our study vividly reveals that slope position showed a significant effect on soil physicochemical properties with the majority of these significant variations occurred between the summit to middle soils and then the toe slope soils. These findings suggest that soil physico-chemical properties should be explicitly considered in the implementation of land management techniques, pro-

vision of mention note for crop species selection and land use. Undoubtedly, findings in this nature will specifically inform stakeholders on the choice of reasonable crop species or trees to introduce on the land, their population densities, their spatial allocation and many more. The incidence of habitat characteristics informs growth adaptability, in light of this future studies geared towards soil physico-chemical properties within the various slope positions and microbial growth could be a breakthrough for the introduction of appropriate crops or vegetables suitable for the land. Also, the soil physico-chemical and biological properties could be used to develop soil quality indicators to assist in the restoration of degraded lands. This data obtained and results of the study establish a suitable baseline to implement landuse and soil management practices at the site before any crop or vegetation planting program.

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Author Contributions

Conceptualization (Angela Arthur); Field sampling and laboratory analysis (Angela Arthur), writing, data curation and analysis (Angela Arthur); supervision and review, (Daniel Okae-Anti).

Consent to Participate

All authors consented to be involved in this study.

Consent for Publication

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest to declare that is relevant to the content of this article.

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