Scientific Research Publishing

Open Journal of Soil Science, 2021, 11, 448-477
https://www.scirp.org/journal/ojss
ISSN Online: 2162-5379
ISSN Print: 2162-5360

An Assessment of Soil Variability along a Toposequence in the Tropical Moist Semi-Deciduous Forest of Ghana

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How to cite this paper: Awoonor, J.K. and Dogbey, B.F. (2021) An Assessment of Soil Variability along a Toposequence in the Tropical Moist Semi-Deciduous Forest of Ghana. *Open Journal of Soil Science*, **11**, 448-477.
https://doi.org/10.4236/ojss.2021.119023

Received: August 30, 2021
Accepted: September 20, 2021
Published: September 23, 2021

Abstract

Understanding the variability of physico-chemical properties of soil along a toposequence is essential for smallholder farming communities. However, these resource constraint farmers in Ghana's Moist Semi-Deciduous Forest (MSDF) zone poorly understand how slope positions affect soil properties. Therefore, soil variability assessment along a toposequence was carried out on Bekwai-Nzima/Oda compound association. From the summit to valley bottom slope positions, soil samples were taken at two depths (0 - 20 and 20 - 50 cm). As shown by the coefficient of variation, topsoil (0 - 20 cm) had the highest variation compared to the subsoil (20 - 50 cm). The variations observed in most soil attributes (clay, silt, pH, CEC, SOC and TN) for the 0 to 20 and 20 to 50 cm depths were between eroded (summit and upper slopes) and depositional (lower slope and valley bottom) zones. The highly variable soil attributes were silt, TN, Av. P, and Av. K. However, bulk density and sand were the least variable irrespective of soil depth or toposequence. Pearson correlation analysis indicated a significant correlation ($p < 0.05$) between most soil attributes at the 0 - 20 and 20 - 50 cm depths at different slope positions. Principal component (PC) analysis indicated that the first four PCs explained more than 80% and 70% of the total variation for the 0 - 20 and 20 - 50 cm soil depths, respectively. Statistically, our results revealed a significant effect of slope position on soil properties ($p < 0.05$) and topography influenced soil characteristics and development. Soil pH, sand, silt and clay contents were less affected by slope gradient, which confirms the inherent nature of these highly weathered tropical soils. The findings of this study can serve as a reference for the formulation of soil management strategies for smallholder farm communities.

Keywords

Soil Variability, Correlation Analysis, Principal Components, Soil Physico-Chemical Properties, Toposequence, Ghana

1. Introduction

Soil, an essential natural resource, is a key component of West African agro-ecosystems [1]. Our existence is dependent on this natural capital [2]. This resource provides food, feed, fibre and timber for the local and international market [3]. The soil, as a system, functions simultaneously with other earth systems that support the delivery of ecosystem services in the tropics of sub-Saharan Africa [4]. Soil suitability for producing food, feed, and fibre depends on soil's physical, chemical, and biological properties [5] [6]. However, several research findings indicated that environmental factors significantly influence the variability of soil properties in a toposequence [7] [8] [9]. These factors include parent material, topography, climate, vegetation and anthropogenic perturbation, especially on the highlands of this agro-ecologically sensitive zone [3] [10] and these, in turn, cause the variability in soil properties [8] [11] [12]. The soil-landscape plays a significant role in determining the shape of a landscape and is directly influenced by slope position, aspect, and gradient. This has resulted in local and regional climatic systems that influence rainfall, temperature, humidity, and evapotranspiration. These significantly affect soil properties and plant growth processes related to ecosystem function [13]. As a major topographic factor, slope position, significantly affects soil physical, chemical, and biological properties [14] [15]. According to Begum *et al.* (2010) [16] and Wang *et al.* (2016) [17], this affects water and nutrient movement in the soil landscape, causing variation in soil properties [18] [19].

Furthermore, a change in slope length and the angle of inclination increase or decrease soil erosion, resulting in the transportation of fine soil particles associated with high carbon and nitrogen. For landscapes with long slopes, soil particle loss is dominant at upper slopes compared to lower slopes which serve as a sink for eroded sediments. Hook and Burke (2000) [20] confirm the assertion that slope position affects soil particle distribution, temperature, moisture contents, soil C and N nutrient cycling processes [21] [22] in land-use systems. Therefore, slope is a critical topographic factor that influences soil properties, plant species, micro-climate, ecosystem processes and functions in most terrestrial ecosystems [15]. Extensive studies on horizontal and vertical soil properties [23] [24] developed a series of statistical methods. Soil variability has been studied extensively in temperate soils compared to tropical soils [25] [26]. A study conducted by Pierson and Mulla (1990) [27] revealed that soil C and aggregate stability were higher at foot and toe slopes than upper slopes. Also, Tsui *et al.* (2004) [28] concluded in their research findings that organic carbon, total nitrogen, extractable Fe and exchangeable Na were significantly high on summits compared to pH, available P, exchangeable Ca and Mg. Rezaei *et al.* (2015) [29] observed that slope position affected soil morphological and physico-chemical properties and concluded that soil profile thickness, clay content, cation exchange capacity, soil C and N concentration differed significantly on the upper, middle, and middle-lower slopes [21] [30].

Moorman *et al.* (2004) [31] revealed that foot and toe slopes had higher soil concentrations on backslope positions. According to Moorman (1981) [32] and Okusami *et al.* (1985) [33], there is a strong correlation between topography and soils in the high rain forest zones of West Africa. In the MSDF, the topography is closely related to the underlying parent rock. This resulted in the classification of soils considering topographic positions, hence the formation of sedentary soils (formed *in-situ* at the crest and/or upper slope) and drift soils (those formed at the lower slope or valley) through transportation and deposition of sediments. This leads to the formation of soils with different taxonomic classes from the crest to lower slope positions (Ogunkunle, 1989 [34]; Olusegun, 2015 [35]).

The variability of soils differs from soil physical, chemical and biological properties. Mulla and McBratney (2002) [36] observed that a slight change in soil topography causes soil variability at the series level. This affects the transport and storage of water across and within soil profiles. From the above, research findings in the temperate and tropical world confirmed that a significant change in slope position significantly changes the concentration of soil physical, chemical and biological properties on a soil-landscape [37]. According to Adhikari *et al.* (2012), information on soil variability is essential for evaluating and initiating management decisions on landscapes as affected by the activities of smallholder farmers. Also, knowledge of soil spatial variability is important for making decisions on soil sampling designs for collecting spatially independent soil samples [38]. Therefore, soil suitability analysis for land use purposes such as fertilizer application, irrigation, etc., requires detailed soil classification knowledge. As a result, this requires understanding the point-to-point variation of selected soil properties along a toposequence. However, a generalization based on soil profile properties cannot be specific enough to predict soil conditions using taxonomic classes. For example, Costigan *et al.* (1983) [39] observed significant differences in crop yield between plots of the same soil series. The findings of this study stressed on inadequate potassium in a particular research plot. However, a soil variability assessment of the entire landscape before the cropping season would have indicated such differences.

Understanding the variability of soil is essential for location-specific management strategies. However, few research works examined the vertical variability of soils compared to horizontal soil variability [40]. Soil forming factors affect soil differently, and soil nutrient and water uptake differ in different soils and at soil depths [41]. For example, soil pH, organic matter, nitrogen, and CEC increase with increasing depth, as Ogunkunle and Ataga (1985) [42] observed. However, soil pH and porosity are the minor variables, while soil variables linked to water and/or solute transport are the most variable. Several scientific papers have concluded that most often, sand ranges from low to moderate variability, organic matter and clay range from moderate to high variability and available phosphorus and potassium were observed to be highly variable [43] [44] [45] [46]. In the MSDF zone, deforestation, unsustainable land management practices such as bush burning, and poor management of the biological component of soil have resulted in soil degradation, thereby making it sensitive to human-related activities in their quest for a livelihood [3] [47]. To restore these degraded landscapes, require an understanding of the variation in soil physico-chemical properties along a toposequence. Unfortunately, there are few studies conducted in Ghana that promote the restoration of these degraded slopes to increase crop production and minimize the effect of farming activities on soil water and nutrient movement along slope positions.

Gisilanbe *et al.* (2017) [37] observed no consistent conclusions on how soil physico-chemical properties are affected by slope positions. Lack of sufficient data makes making informed decisions on sustainable land management (SLM) practices that balance ecological, economic and social considerations affecting smallholder farming communities difficult. Also, the determination of soil variability involves a wide range of statistical techniques that uses factor rating base on soil-related constraints to crop production [25] [48] [49] [50]. However, Wilding (1985) [24] stressed that the variability of soil could be determined as the relative magnitude of variability sources on soil attributes combined with effects on the variability of some soil properties. The coefficient of variation (CV) is often used to measure soil variability [24]. Also, the use of principal component analysis (PCA) has increased due to the ability of this statistical procedure to reduce dimensions of data into components without a significant loss of information. This procedure can group soil physical and chemical properties into functional groups [51] hence making straight forward interpretation of data. From the above discussion, the mechanism that controls how different slope positions affect soil properties remains poorly understood and has not been extensively investigated in the MSDF agro-ecological zone of Ghana. The objectives of this study were to: 1) assess how soil properties are influenced by landscape attributes (soil depth and topographic positions) and their interactions on a toposequence; 2) examine the variation in soil physico-chemical properties along the toposequence, and 3) determine the relationship between soil properties at different slope positions. We hypothesize that soil physical and chemical properties change due to a change in slope positions. Lower slopes have higher nutrient input of SOC and TN contents compared to upland soils.

2. Materials and Methods

2.1. Study Area

The study site is located in the Adansi North District of the Ashanti region. It falls within the moist semi-deciduous forest (MSDF) zone. This zone is characterized by a humid tropical climate with an annual mean rainfall of about 1400 mm falling from March to mid-July and from September to November. The major dry period is from December to February. However, relative humidity and mean air temperatures are 70% - 80% and 23˚C - 32˚C, respectively. According to Christensen and Awadzi (2000) [52], annual evapotranspiration is about 1200 with an annual mean temperature of about 28˚C with slight variation yearly.

2.2. Geomorphology and Soils

The landscape is gently rolling, and soils on these slopes form the most common catena [53] in the tropical MSDF zone of Ghana. The catena is about 500 - 600 metres long with an average slope gradient of about 5% - 10%. On the toposequence is Bekwai/Nzima-Oda association [47] as classified according to the Ghana Interim Soil Classification System (ISCS) [54]. The catena consists of soils derived from Pre-Cambrian phyllite, dominated by low activity kaolinitic clay with sesquioxides of iron and aluminium oxides [10] [47].

These soils developed over the lower Birrimian phyllite consist of phyllite, greywackes, schists, sandstones and gneisses [10] [55]. According to Wills (1962) [56], soils on the upper slope (Bekwai and Nzima series) are red/brown to yellowish-brown, concretionary, acidic, well-drained kaolinitic clays formed from phyllite with quartz intrusions as the main constituents. The relatively low pedogenic clay mineral indicates that kaolinite is one of the end products of the weathering sequence of soils on the Bekwai/Nzima-Oda compound association. Very few rock outcrops were encountered because most of these profoundly weathered rocks were encountered at a depth of 150 to 200 cm [10] [57]. These weathered rocks impede drainage in the wet seasons forming temporary groundwater that produces gleyic features at the base of most soil profiles. Kokofu and Kakum series (**Table 1**) at the middle and lower slopes are slightly acidic to acidic yellowish-brown clay loams formed in gravel-free colluvium deposits due to soil erosion downslope [47]. The valley bottom soils (Temang and Oda series) are imperfectly drained greyish clay loam to sandy loams are usually flooded at the peak of the rainy season (**Figure 1**).

Water-holding capacity is moderate, although surface layers are subject to dry season drought. The soil moisture and/or temperature regime are udic and isohyperthermic, respectively [47] [61] [62]. The original vegetation type is the *Antiaris-Chlorophora association* (Lawson *et al*., 1970) and has been subjected to deforestation of timber resources for the local and international market. The vegetation in and around each plot was classified as indicated in **Table 2**. However, in search of arable lands by smallholders, these degraded forest lands were subsequently converted into farmlands. The land-use types identified were grouped into undisturbed (forested) and disturbed (cropped) lands. Cropping systems encountered were maize/cassava intercrop, oil palm/maize, oil palm and coconut plantations. Most of these farmlands have been cultivated for decades with little or no fertilizer use.

Table 1. Soil classification and key soil morphological features of soil series [Ghana Interim Soil Classification (Brammer, 1962 [58]), Soil taxonomy (Soil Survey Staff, 2010 [59]), and FAO/world reference base (IUSS, 2014 [60]).

Topographic unit	Summit-Upper	Middle slope	Lower slope-Valley bottom
Soil depth	>50 cm deep (moderately deep)	>50 cm deep (moderately deep	>50 cm deep (moderately deep)
Soil texture	Sandy loam	Sandy loam - Sandy clay loam	Sandy loam - Clay loam
Terrain	Slope of 4% - 10%	Slope of 1% - 4%	Slope of 0% - 1%
Drainage	Well drain	Well drain	Moderately to Imperfectly well drain
Parent material	Lower Birrimian Phyllite	Lower Birrimian Phyllite	Lower Birrimian Phyllite
Clay mineralogy	Kaolinite	Kaolinite	Kaolinite
Local Classification	Bekwai and Nzima series	Kokofu series	Temang and Oda series
FAO/WRB 2014	Ferric Acrisol (Bekwai and Nzima series)	Haplic Lixisol (Kokofu series)	Dystric Gleysol (Temang series) Eutric Gleysol (Oda series)
Soil Taxonomy 2010	Typic Paleudult (Bekwai) Kandic Paleudalf (Nzima)	Udic/Aquic Kandiudult (Kokofu series)	Aeric Endoaquent (Temang/Oda series)

Source: Owusu-Bennoah *et al.* (2000) [47] and Breuming-Madsen *et al.* (2007) [53].

Table 2. Classification of vegetation in the study area.

Vegetation type	Description
Secondary forest	A semi-continuous strand of trees with few tree crowns interlocking (canopy cover of 40%) with a ground layer dominated by grasses
Bushland	A mixture of trees and shrubs with a woody vegetation cover of 40% of the ground layer
Wooded grassland	Dominated by grasses and herbs with a woody vegetation cover of about 10% - 40% of the ground layer
Cropland	Land cultivated to annual and perennial crops
Freshwater aquatic	Consist of herbaceous freshwater swamp and aquatic vegetation

Source: NASA/USGS, (2003) [63] and Tan *et al.*, (2009) [64].

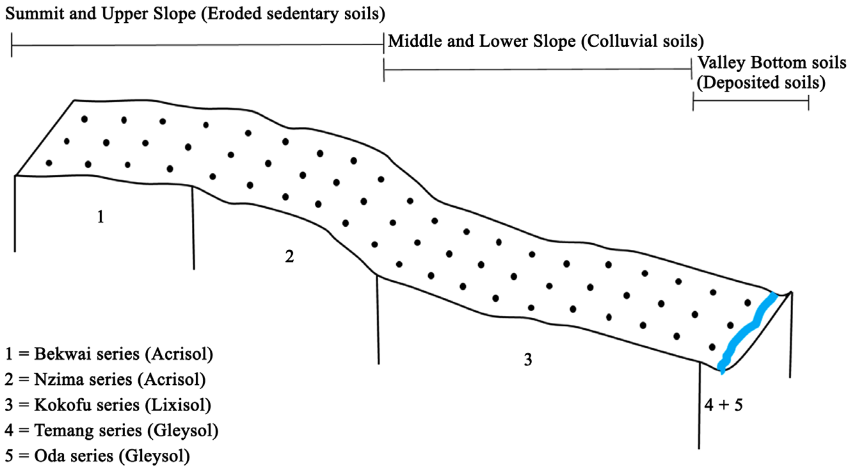

Figure 1. Illustrates topographical transects and sampling point locations for the study site (not drawn to scale). The blue line represents a stream in the valley bottom. Diagram adapted from Owusu-Bennoah *et al.* (2000) [47] and Breuning-Madsen *et al.* (2007) [53].

2.3. Soil Sampling Scheme

A total of 60 soil samples were evaluated in terms of geographic locations (longitude, latitude and elevation using GPS), land use type classes (forest, bushland, wooded grassland, cropland and freshwater aquatic) with slope gradient classes (level < 10%; sloping between 10% - 20%; and steep > 20%) and topographic position (summit, upper, middle, lower or bottomland) classes. These four landscape attributes (land use, soil depth, topographic position, and soil depth), according to Takoutsing *et al.* (2017) [65]), have a significant effect on soil properties. Therefore, soils were examined at various landscape positions (**Table 3**).

A cluster of four-point soil sampling scheme was adopted for each sampling location (**Figure 2**). Composite soil samples (500 grams) were taken at each location using an auger at regular intervals of 50 metres for the 0 - 20 and 20 - 50 cm depth for laboratory analyses. The reason for sampling at two depths is to determine the adequate rooting depth for potential food and tree crops and their occurrence on the soil landscape. Benchmark soils encountered on the field were Bekwai, Nzima, Kokofu, Temang, and Oda series [47] [67].

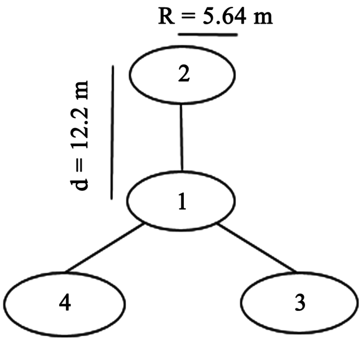

Figure 2. Illustrates soil sampling layout. **Figures 1-4** indicate sampling subplots. At a distance of 12.2 metres from the centre point (sub-plot 1) up-slope, subplot 2 was marked. Subplots 3 and 4 were offset at 120 and 240 degrees down-slope, respectively. Also, R is the subplot radius and d is the distance between sub-plots centre-points (Vagen *et al.* 2010 [66]).

Table 3. Basic information on each of the sampled sites at different slope positions.

Slope Positions	Geographic Position	Slope Range (%)	Number of sampled points	Soil series	Landuse
Summit	06˚18'39.80" 01˚29'59.90"	>10	12	Bekwai	Secondary Forest
Upper slope	06˚18'49.60" 01˚30'05.20"	4 - 10	18	Nzima	Secondary Forest
Middle slope	06˚18'41.50" 01˚30'07.90"	2 - 4	18	Kokofu	Oil palm/Coconut/Maize
Lower slope	06˚18'43.00" 01˚30'02.90"	1 - 2	6	Temang	Oil palm/maize
Valley Bottom	06˚18'44.40" 01˚30'00.30"	0 - 1	6	Oda	Thickets with grass patches

2.4. Soil Processing and Laboratory Analyses

Soil samples were taken to the laboratory and air-dried at 25˚C for fifteen (15) days, ground and sieved (2 mm) for laboratory analysis. After eliminating organic matter with H_2O_2 treatment and dispersion with 5 percent Na-hexametaphosphate, soil particle size analysis (sand, silt, and clay) was determined using the standard Bouyoucos hydrometer method. With a glass electrode and pH meter, soil reaction (pH) was determined in a distilled water at a soil: water ratio of 1:2.5 [68]. Total nitrogen (N) was determined by the Kjeldahl method [69], soil bulk density (BD g/cm^3) was determined using the core method [70], available phosphorus (P) was determined colorimetrically after extraction with Bray's P1 solution [71], available potassium (K) by flame photometry after extraction with Bray's P1 solution [71]. Cation exchange capacity (CEC) was determined by ion extraction with ammonium acetate solution and subsequent determination of the extracted cations [72]. Soil organic carbon (SOC) was determined with Walkley and Black's wet combustion method as described by Jackson (1973) [73].

2.5. Statistical Analysis

Descriptive statistics were computed for soil properties for the 0 - 20 and 20 - 50 cm depths. Pearson correlation and regression analysis were tabulated to identify the relationship within and among selected soil attributes. All soil variables were log-transformed and standardized to zero mean and unit variance [14]. This made it possible to compare and contrast soil indicators with different dimensions measured and presented in different units of measurement. Principal component analysis was carried out to identify Eigen factors that explain variability as observed along the toposequence. Eigenvalues, defined as the amount of variance explained by each factor were determined. However, the PCs with eigenvalues greater than one were retained. Those less than one were eliminated because these explained less of the variance of a measured attribute [49]. The retained PCs were subjected to varimax rotation to maximize the correlation between PCs. Mulla and McBratney (2002) stressed on using the discrete soil sampling method for soil variability estimation. This method involves collecting soil sampled at predetermined locations (summit, upper, middle, lower and valley bottom) and with depths (0 - 20 and 20 - 50 cm) along a toposequence. The coefficient of variation (CV) is the normalization of how a dataset is distributed around the mean. However, soil properties with a large CV value indicate a high variability compared to attributes with low CV values. Wilding (1985) [24] introduced a classification scheme base on the extent of variability for soil properties using CV values. The coefficient and standard error (SE) of skewness and kurtosis of the dataset were used to measure the symmetry of the samples [26]. Soil samples were accepted as normally distributed when skewness or kurtosis was simultaneously not significant. The minimum number of soil samples required to estimate the mean value of soil properties was computed using the equation proposed by Starr *et al.* (1992) [74].

$$N = \left(t\alpha \mathrm{CV}\varepsilon^{-1}\right)^2 \tag{1}$$

where: N is the minimum number of required samples and $t\alpha$ is the value of a normal variate at $p = 0.05$, and t is the computed t value for the desired confidence level (α) of the soil samples. The log-transformed data used in Equation (1) produced values of N. Values of N were dependent on the units of the measured data. Also, CV is the coefficient of variation (%) where soil samples were discretely considered and ε is the degree of precision pre-defined with allowable uncertainty of the exact value of the mean (10%). This means that at 95%, sampling at a chosen intensity would yield a mean value between 90% - 110% of the actual mean because arithmetic means give excellent estimates of the central tendency only for customarily distributed datasets. The normality test was calculated by log-transformation before deriving the CV. Varimax rotation, was performed on the variance-covariance matrix to quantify variability [14] [75]. All statistical procedures were performed using GenStat 12th edition and SPSS version 20.

3. Results

3.1. Descriptive Statistics of Soil Properties for the 0 - 20 and 20 - 50 cm Soil Depth

Descriptive statistics of all physical and chemical properties at the five identified slope positions for the 0 - 20 and 20 - 50 cm soil depths are summarized in **Table 4** and **Table 5**; **Figure 3** and **Figure 4**. **Figure 3** comprised of sand, silt, SOC, TN, AWC and Av. P. Whereas, **Figure 4** comprised clay, Av. K, BD, CEC and pH. Variability, as shown by coefficient of variation data at the summit, upper, middle, lower and valley bottom were 0.97% - 95.99%, 1.21% - 96.91%, 1.13% - 86.56%, 0.28% - 75.83% and 0.02% - 63%, for the 0 - 20 cm soil depth, respectively. For the 20 - 50 cm, the summit, upper, middle, lower, valley bottom were 1.61% - 111.24%, 1.05% - 282.42%, 0.05% - 74.50%, 5.08% - 120.34% and 0.41% - 41.73%, respectively. The minimum and maximum variable coefficient of soil physico-chemical properties at the five different slope position gradients were soil bulk density (CV = 1.61%, 1.66%, 1.33%, 1.05%, 0.41%) and available potassium (57.09%, 282.42%, 58.29%, 120.34%, 35.27%) for the summit, upper, middle, lower and valley bottom, respectively. For the summit slope position gradient, positive skewness ranged from 0.16 to 1.28 and 0.03 to 0.96 for the 0 - 20 and 20 - 50 cm soil depth while the negative skewness from −0.47 to −1.52 and −0.01 to −0.33 for the 0 - 20 cm and 20 - 50 cm soil depths.

For the middle slope gradient, skewness was positive (ranged from 0.05 to 1.11) and negative (range from −0.15 to −0.85) at the 0 - 20 cm soil depth. For the 20 - 50 cm soil depth (**Table 4** and **Table 5**), positive skewness ranged from 0.19 to 1.15, and negative skewness ranged from −0.22 to −0.99 for the middle slope gradient. Positive skewness ranged from 0.01 to 1.03 and 0.13 to 0.80 for

Table 4. Descriptive statistics of soil attributes along the toposequence for the 0 - 20 cm soil depth.

Soil attributes	Landform	Min	Max	Median	Mean	SD	Variance	Skewness	Kurtosis	CV (%)
Sand (%)	Summit	56.00	80.00	71.00	69.50a	10.75	86.75	−0.33	−1.71	15.47
	Upper	45.68	74.40	70.00	65.02a	13.46	135.91	−0.90	2.15	20.70
	Middle	45.68	72.00	69.00	63.92a	12.48	116.90	−0.99	2.86	19.53
	Lower	44.40	80.00	66.00	64.10a	16.81	212.03	−0.20	−3.54	26.23
	Valley	45.68	66.96	53.04	54.68a	8.91	59.50	0.60	2.03	16.29
Silt (%)	Summit	14.00	28.00	21.00	21.00a	6.22	29.00	0.00	−2.43	29.61
	Upper	12.36	37.28	18.62	21.41a	11.03	91.25	0.89	2.49	51.52
	Middle	14.00	27.28	17.00	18.82a	6.31	29.86	0.59	−0.45	33.53
	Lower	12.00	34.00	24.18	23.59b	11.21	94.30	−0.05	−5.27	47.53
	Valley	11.28	28.36	26.28	23.05a	7.95	47.40	−1.07	3.47	34.49
Clay (%)	Summit	6.00	16.00	8.00	9.50b	4.73	16.75	0.69	0.44	49.75
	Upper	10.00	17.04	13.62	13.57b	2.89	6.27	1.16	−0.06	21.31
	Middle	14.00	27.04	14.00	17.26ab	6.52	31.88	1.15	4.00	37.78
	Lower	8.00	23.24	9.00	12.31b	7.35	40.49	1.10	3.65	59.69
	Valley	19.24	27.04	21.40	22.27a	3.35	8.43	0.80	2.46	0.15
AWC (%)	Summit	0.93	2.59	1.26	1.51a	0.24	0.41	0.96	2.94	42.67
	Upper	0.93	1.63	1.14	1.21a	0.26	0.07	0.75	2.47	21.26
	Middle	0.98	1.51	1.06	1.15a	0.22	0.05	0.90	2.21	18.84
	Lower	0.81	1.58	1.17	1.18a	0.33	0.11	0.05	−4.80	27.70
	Valley	1.10	1.51	1.41	1.36a	0.15	0.02	−1.53	2.71	11.40
BD (g/cm^3)	Summit	1.44	1.46	1.45	1.45a	0.01	0.41	0.13	−4.67	0.97
	Upper	1.44	1.48	1.47	1.47a	0.02	0.00	−0.60	0.41	1.21
	Middle	1.45	6.00	1.48	1.46a	0.02	0.00	−0.95	2.52	1.13
	Lower	1.44	1.45	1.45	1.43a	0.00	0.00	−0.15	−3.83	0.28
	Valley	1.45	1.50	1.47	1.47a	0.02	0.00	0.75	2.20	0.02
pH (1:2.5)	Summit	5.10	7.32	6.32	6.27ab	0.95	0.67	−0.17	−0.54	15.09
	Upper	5.40	6.20	6.05	5.93ab	0.36	0.10	−0.98	−0.98	6.07
	Middle	4.10	6.60	4.85	5.10b	1.19	1.06	0.36	−2.14	23.26
	Lower	4.20	6.10	1.52	5.00b	0.80	0.48	0.59	1.50	16.08
	Valley	6.60	7.30	7.05	7.00a	0.29	0.07	−0.54	1.50	0.04
SOC (%)	Summit	0.62	2.15	0.94	1.16b	0.51	0.38	0.75	1.04	61.07
	Upper	1.00	1.94	1.20	1.33ab	0.42	0.13	0.91	2.56	31.49
	Middle	1.04	2.59	1.98	1.86ab	1.41	0.33	−0.22	−0.73	35.71
	Lower	1.28	2.18	1.52	1.62ab	0.39	0.12	0.79	2.02	24.28
	Valley	1.59	2.91	2.16	2.20a	0.62	0.29	0.13	−3.83	0.28
TN (%)	Summit	0.07	0.22	0.10	0.13a	0.07	0.00	0.73	0.78	54.78
	Upper	0.10	0.25	0.12	0.15a	0.07	0.00	1.10	3.72	47.47
	Middle	0.10	0.27	0.18	0.18a	0.07	0.00	0.19	1.55	38.11

Continued

	Lower	0.14	0.25	0.15	0.17a	0.05	0.00	1.13	3.88	30.23
	Valley	0.13	0.30	0.24	0.23a	0.08	0.01	−0.25	−3.43	35.96
Av. P ($mg \cdot kg^{-1}$)	Summit	0.77	13.01	7.22	7.06a	6.77	34.40	−0.01	−5.92	95.99
	Upper	2.47	10.52	4.60	5.55a	3.58	9.63	0.71	1.06	64.58
	Middle	2.47	7.04	3.75	4.25a	2.08	3.25	0.57	−0.40	48.98
	Lower	1.93	5.33	2.95	3.29a	1.51	1.72	0.59	1.50	16.08
	Valley	0.24	1.67	1.32	1.14a	0.62	0.29	−0.89	2.85	54.64
K ($mg \cdot kg^{-1}$)	Summit	0.06	0.33	0.18	0.19ab	0.06	0.01	0.03	−5.59	74.03
	Upper	0.05	0.17	0.12	0.14b	0.03	0.00	−0.06	−0.47	96.91
	Middle	0.04	0.32	0.11	0.15ab	0.04	0.01	0.62	0.04	86.56
	Lower	0.05	0.23	0.15	0.11b	0.03	0.01	0.96	2.68	75.83
	Valley	0.16	0.66	0.29	0.35a	0.09	0.04	0.72	1.09	63.72
CEC ($cmol_{(+)} \cdot kg^{-1}$)	Summit	6.64	9.24	7.42	7.68b	1.10	0.91	0.74	2.32	14.38
	Upper	5.10	15.05	9.59	9.83b	3.62	15.98	0.10	−3.59	46.95
	Middle	4.54	15.18	5.92	7.89b	1.99	18.71	0.98	2.82	63.29
	Lower	4.11	11.03	6.62	7.09b	0.88	6.22	0.55	2.01	40.61
	Valley	16.28	19.19	18.81	18.27a	1.35	1.37	−1.05	3.33	7.39

Abbreviation: BD: Bulk density, AWC: Available water content pH: Soil pH, SOC: Soil organic carbon, TN: Total nitrogen, Av. P: Available phosphorus, Av. K: Available potassium, CEC: Cation exchange capacity. Means for each variable followed by the same letter are not significantly different by LSD test at $P < 0.05$.

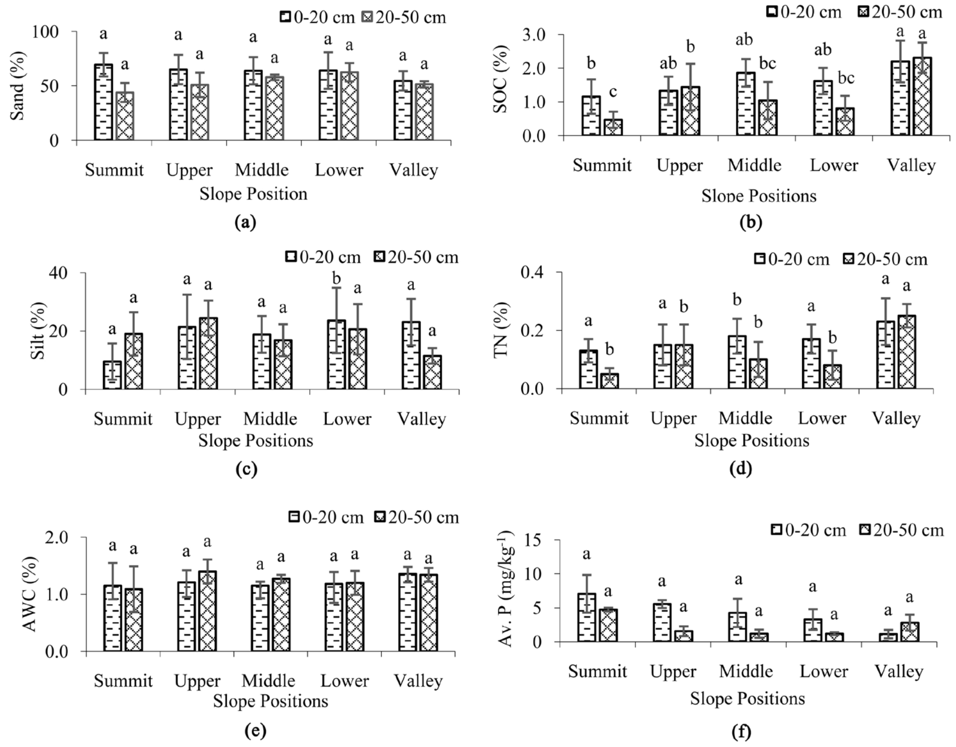

Figure 3. Illustrates changes in selected soil properties ((a) to (f)) at different slope positions for the 0 - 20 and 20 - 50 cm depth for the summit, upper, middle, lower and valley bottom. On each error bar, letters represent significant difference at $p < 0.05$.

Table 5. Descriptive statistics of soil attributes along the toposequence for the 20 - 50 cm soil depth.

Soil Attributes	Landform	Min	Max	Median	Mean	SD	Variance	Skewness	Kurtosis	CV (%)
Sand (%)	Summit	66.50	94.00	64.00	66.50a	8.73	350.75	0.55	−0.68	28.16
	Upper	40.44	68.00	47.70	50.95a	11.21	125.63	0.52	−0.99	27.74
	Middle	53.68	60.00	59.00	57.92a	2.58	6.66	−0.85	1.75	4.46
	Lower	54.00	72.00	62.20	62.60a	8.43	71.08	0.03	−5.78	13.47
	Valley	47.68	54.40	51.96	51.50a	2.91	6.36	−0.44	−0.12	5.65
Silt (%)	Summit	2.00	30.00	22.00	19.00a	7.44	109.00	−1.32	2.09	54.95
	Upper	18.00	33.36	23.18	24.42a	6.01	36.11	0.42	−1.32	33.38
	Middle	10.00	25.28	16.00	16.82a	5.46	29.86	0.44	1.83	32.49
	Lower	12.00	30.00	20.18	20.59a	8.61	74.12	0.02	−5.86	41.81
	Valley	−0.84	2.19	23.82	11.47a	2.64	5.24	−0.84	2.19	11.47
Clay (%)	Summit	4.00	26.00	14.00	14.50b	7.87	78.75	0.16	−3.72	61.20
	Upper	14.00	33.24	25.62	24.62a	4.88	47.34	−0.43	1.76	49.15
	Middle	21.04	30.00	25.00	25.26a	3.26	10.60	0.22	0.26	12.89
	Lower	16.00	18.00	16.62	16.81ab	0.85	0.73	0.49	−3.25	5.08
	Valley	21.24	29.76	25.40	25.45a	4.58	15.70	0.01	−5.81	17.98
BD (g/cm^3)	Summit	1.47	1.17	1.45	1.44b	0.46	2.12	−0.63	1.58	1.61
	Upper	1.43	1.48	1.46	1.47b	0.48	2.20	−0.02	−5.79	1.66
	Middle	1.46	1.51	1.48	1.48a	0.19	0.00	0.07	−3.86	1.33
	Lower	1.46	1.50	1.49	1.45a	0.13	0.00	−1.06	0.38	1.05
	Valley	1.46	1.47	1.47	1.48ab	0.37	0.10	−0.68	1.15	0.41
AWC (%)	Summit	0.49	1.54	1.17	1.09a	0.40	0.16	−0.47	−0.12	36.22
	Upper	1.08	1.62	1.44	1.40a	0.21	0.04	−0.47	−0.74	14.95
	Middle	1.21	1.39	1.24	1.27a	0.07	0.01	1.02	3.11	5.70
	Lower	0.97	1.41	1.21	1.20a	0.21	0.04	−0.01	−5.85	17.37
	Valley	1.14	5.10	1.39	1.34a	0.12	0.01	−0.95	2.98	8.88
pH (1:2.5)	Summit	4.00	6.31	6.10	5.63a	0.94	0.89	−1.95	3.85	16.77
	Upper	6.30	7.00	6.55	6.60a	0.25	0.07	0.54	1.50	1.05
	Middle	4.00	7.00	5.25	5.38a	1.39	1.92	0.05	−5.52	0.05
	Lower	4.20	5.90	5.30	5.18a	0.71	0.50	−0.43	−3.43	13.69
	Valley	5.10	6.40	6.25	6.00a	0.61	0.28	−1.09	3.64	10.09
SOC (%)	Summit	0.07	0.72	0.55	0.50c	0.24	0.06	−1.52	2.85	51.41
	Upper	0.40	2.29	1.53	1.44b	0.69	0.47	−0.37	0.87	171.85
	Middle	0.24	1.78	1.08	1.04bc	0.55	0.30	−0.18	1.48	52.37
	Lower	0.40	0.14	0.72	0.81bc	0.37	0.14	1.14	1.68	45.70
	Valley	1.81	2.90	2.26	2.31a	0.45	0.15	0.38	1.68	19.49
TN (%)	Summit	0.05	0.07	0.06	0.05b	0.02	51.83	−1.50	2.42	51.83
	Upper	0.15	0.25	0.15	0.15b	0.07	0.01	−0.18	0.64	264.05
	Middle	0.02	0.19	0.10	0.10b	0.06	0.00	0.12	1.12	59.09

Continued

	Lower	0.03	0.16	0.06	0.08b	0.05	0.00	1.53	2.49	64.11
	Valley	0.21	0.31	0.24	0.25a	0.04	0.00	0.69	1.50	17.28
Av. P ($mg \cdot kg^{-1}$)	Summit	0.31	13.21	2.72	4.74a	0.27	0.78	1.28	0.87	111.24
	Upper	0.85	2.71	1.33	1.56a	0.71	0.50	0.77	1.61	83.56
	Middle	0.31	2.01	1.22	1.19a	0.60	0.36	−0.15	1.39	50.73
	Lower	0.85	1.39	1.27	1.20a	0.22	0.05	−1.04	−0.36	18.61
	Valley	1.20	3.83	3.11	2.81a	1.17	1.03	−0.67	0.68	41.73
K ($mg \cdot kg^{-1}$)	Summit	0.04	0.23	0.11	0.12ab	0.07	0.00	0.82	0.76	57.09
	Upper	0.03	0.26	0.12	0.14ab	0.09	0.01	0.21	−2.77	282.42
	Middle	0.05	1.94	0.06	0.08b	0.05	0.00	1.11	3.71	58.29
	Lower	0.03	0.38	0.04	0.12ab	0.03	0.02	2.00	3.99	120.34
	Valley	0.21	0.41	0.23	0.27a	0.10	0.01	1.03	3.13	35.27
CEC ($cmol_{(+)} \cdot kg^{-1}$)	Summit	5.26	7.42	6.21	6.27bc	0.77	0.59	0.44	1.34	12.28
	Upper	5.91	17.31	12.76	12.18ab	4.08	16.69	−0.41	1.59	69.12
	Middle	2.20	16.28	5.76	7.50abc	2.59	31.23	0.64	0.13	74.50
	Lower	3.64	7.54	4.94	5.26c	1.68	2.82	0.39	−3.79	31.90
	Valley	9.50	17.29	12.80	13.10a	3.22	7.76	0.31	1.36	24.56

Abbreviation: BD: Bulk density, AWV: Available water content pH: Soil pH, SOC: Soil organic carbon, TN: Total nitrogen, Av. P: Available phosphorus, Av. K: Available potassium, CEC: Cation exchange capacity. Means for each variable followed by the same letter are not significantly different by LSD test at $P < 0.05$.

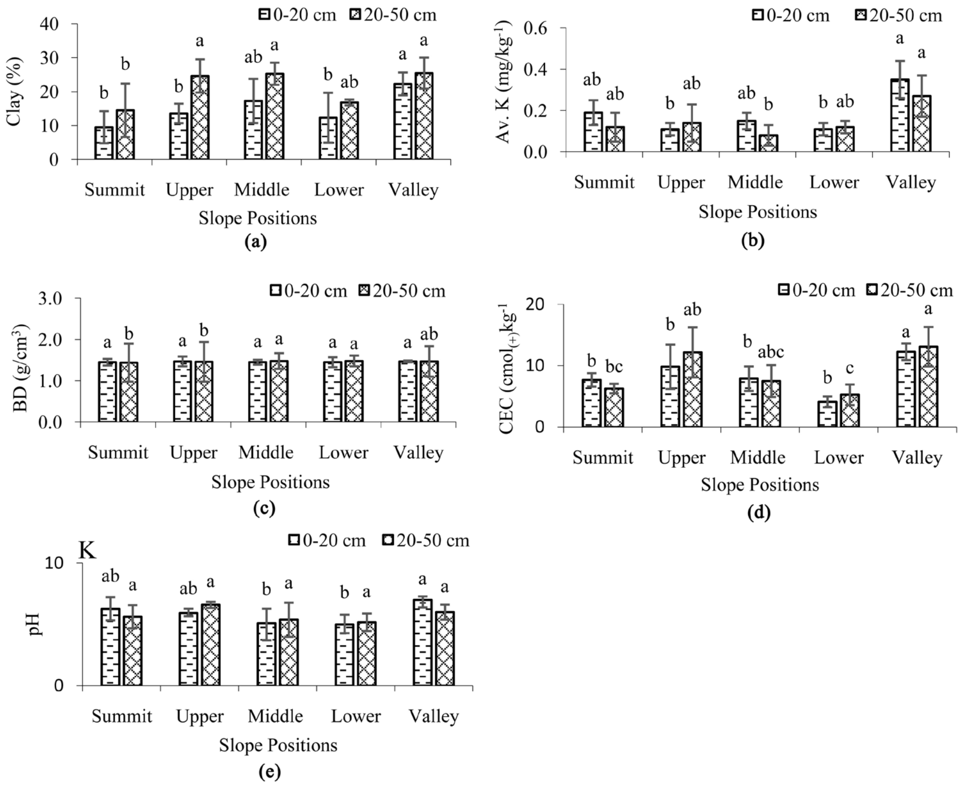

Figure 4. Illustrates changes in selected soil properties ((a) to (e)) at different slope positions for the 0 - 20 and 20 - 50 cm depth for the summit, upper, middle, lower and valley bottom. On each error bar, letters represent significant difference at $p < 0.05$.

the 0 - 20 and 20 - 50 cm soil depths for valley bottom soils. Negatively, skewness ranged from −0.44 to −1.09 and −0.25 to −1.53 for soil depths of 0 - 20 and 20 - 50 cm. Some soil physical and chemical properties recorded positive and negative kurtosis at both soil depths. For the 0 - 20 cm soil depth, positive kurtosis ranged from 0.44 to 2.94, 0.04 to 4.00 and 1.50 to 3.47. It negatively ranged from −0.12 to −3.72, −3.86 to −5.52, and −0.12 to −5.81 for the summit, middle and valley bottom, respectively. Positive kurtosis ranged from 0.76 to 3.85, 0.13 to 3.71, and 0.68 to 3.64, and negative kurtosis ranged from −0.12 to −3.72, −3.86 to −5.52, and −0.12 to −5.81 for the summit, middle and valley bottom slope gradients of the 20 - 50 cm soil depth, respectively (Table 4 and Table 5). Using a CV as a criterion for expressing variability, Clay, AWC, SOC, TN, Av. P, and Av. K was the most variable for the 0 - 20 cm whilst Silt, Silt, Clay, AWC, SOC, TN, Av. P and Av. K for the 20 - 50 cm with a CV greater than 35%; Sand, silt and pH for the 0 - 20 cm, whilst sand and pH were moderately variable with CV between 15% and 35%.

BD and CEC were the least variables with less than 15% CV (Table 6) for the summit slope gradient. For the middle slope gradient, SOC, TN, Av. P, Av. K,

Table 6. Variability grouping of soil properties along the toposequence for the 0 - 20 cm.

Group	CV (%)	Soil physical properties	
		0 - 20 cm	20 - 50 cm
		Summit	
Least variable	<15	BD, CEC	BD, CEC
Moderately variable	15 - 35	Sand, silt, pH	Sand, pH
Highly variable	>35	Clay, AWC, SOC, TN, Av. P, K	Silt, Clay, AWC, SOC, TN, Av. P, K
		Upper slope	
Least variable	<15	BD, pH	BD, AWC
Moderately variable	15 - 35	Sand, Clay, AWC, SOC	Sand, Silt, pH
Highly variable	>35	Silt, TN, Av. P, K, CEC	Clay, SOC, TN, Av. P, K, CEC
		Middle slope	
Least variable	<15	BD	Sand, Clay, BD, AWC
Moderately variable	15 - 35	Sand, Silt, AWC, pH,	Silt
Highly variable	>35	SOC, TN, Av. P, K, CEC	SOC, TN, Av. P, K, CEC
		Lower slope	
Least variable	<15	BD	Sand, Clay, BD, pH, AWC, pH
Moderately variable	15 - 35	Sand, AWC, pH, SOC, Av. P	AWC, Av. P, CEC, SOC, TN
Highly variable	>35	Silt, Clay, TN, K, CEC	Silt, SOC, TN, K
		Valley bottom	
Least variable	<15	AWC, BD, pH, CEC	Sand, Silt, BD,
Moderately variable	15 - 35	Sand, Clay, SOC	Clay, CEC
Highly variable	>35	Silt, TN, Av. P, K	Av. P, K

Source: Coefficient of variation (CV) rating, Wilding (1985) [24].

and CEC for the 0 - 20 and 20 - 50 cm were greater than 35%; Sand, Silt, AWC and pH for the 0 - 20 cm and only silt for the 20 - 50 cm were moderately variable with CV between 15% and 35%; and only BD for the 0 - 20 cm and Sand, Clay, BD and AWC were the least variable. Finally, AWC, BD, pH and CEC for the 0 - 20 cm and Sand, Silt, and BD for the 20 - 50 cm soil depth were the least variable with CV less than 0.15 (Table 6).

3.2. Relationship between Soil Attributes for the 0 - 20 and 20 - 50 cm Soil Depth

A significant correlation ($p < 0.05$) was observed among eight soil attribute pairs for the 0 - 20 cm soil depth. The Pearson correlation coefficient of soil attributes for the top and subsoils are presented in Table 7 and Table 8. A significant correlation ($p < 0.05$) was observed among 26 of the 56 soil property pairs at the 0 - 20 cm soil depth. There were significant positive correlations for SOC with Clay, TN; BD, Av. K and TEB; Clay with TN, Sand, Silt, Av. K, pH and TEB; N with Av. K, and TEB; K with pH and TEB; and pH with TEB. Also, significant negative correlations for SOC with P, Clay with sand, and Av. P, N with P; Sand with Silt and TEB; Silt with BD; AWC with BD; BD with P; and P with TEB for the 0 - 20 cm soil depth. For the 20 - 50 cm soil depth, there were 27 significant positive correlations with 27 among 56 soil attribute pairs. Significant positive correlations were recorded for SOC with Clay, TN, Silt, Av. K, and TEB; Clay with TN, AWC, and TEB; TN with Silt AWC, Av. K and TEB; Sand with Av. P; Silt with AWC and TEB; Av. K with TEB and pH with TEB for the 20 - 50 cm soil depth.

There was a significant negative correlation among SOC with Sand; Clay with Sand and Av. P; TN with Sand; Sand with Silt, AWC with TEB; and BD with pH. There was a significant positive correlation between soil physical and chemical properties at the different slope positions.

Table 7. Correlation coefficient for the 0 - 20 and 20 - 50 cm (above and below diagonal, respectively).

Attributes	SOC	CLAY	TN	SAND	SILT	AWC	BD	Av. K	Av. P	pH	CEC
SOC (%)	-	0.60	0.95	−0.33	0.02	−0.20	0.46	0.46	−0.73	0.05	0.55
CLAY (%)	0.57	-	0.56	−0.81	0.44	0.17	0.18	0.41	−0.49	0.45	0.73
TN (%)	0.99	0.54	-	−0.35	0.09	−0.13	0.37	0.49	−0.64	0.11	0.55
SAND (%)	−0.63	−0.81	−0.61	-	−0.88	−0.34	0.23	−0.15	0.31	−0.33	−0.47
SILT (%)	0.46	0.34	0.46	−0.83	-	0.39	−0.50	−0.11	−0.08	0.14	0.14
AWC (%)	0.57	0.74	0.54	−0.97	0.85	-	−0.49	0.22	0.34	0.37	0.10
BD (g/cm^3)	−0.03	0.16	−0.07	0.04	−0.21	0.00	-	0.15	−0.47	−0.15	0.23
Av. K ($mg \cdot kg^{-1}$)	0.63	0.16	0.67	−0.32	0.36	0.31	−0.27	-	0.02	0.65	0.60
Av. P ($mg \cdot kg^{-1}$)	−0.05	−0.49	−0.01	0.40	−0.17	−0.39	−0.29	0.33	-	0.14	−0.41
pH (1:2.5)	0.24	0.00	0.28	−0.08	0.12	0.02	−0.40	0.38	0.17	-	0.73
CEC ($cmol_{(+)} \cdot kg^{-1}$)	0.77	0.41	0.78	−0.49	0.40	0.46	−0.35	0.47	0.00	0.65	-

Correlation is significant at $P \le 0.05$.

Table 8. Rotated principal component and contribution of each physical and chemical properties to soil variation at the 0 - 20 cm depth.

Soil attributes	PC1	PC2	PC3	PC4	Communalities
Eigen values	4.49	2.81	1.76	0.71	
Variance (%)	40.84	25.53	16.02	6.46	
CV (%)	40.84	66.37	82.39	88.85	
Factor loadings (Rotated component matrix)					
Sand (%)	−0.11	**−0.56**	−0.09	−0.01	0.34
Silt (%)	−0.13	**0.63**	−0.06	0.00	0.41
Clay (%)	0.37	0.30	0.25	0.01	0.31
AWC (%)	0.01	0.07	−0.09	−0.02	0.90
BD (g/cm^3)	**0.71**	−0.33	0.04	−0.08	0.64
SOC (%)	0.11	0.02	−0.05	**0.59**	0.36
TN (%)	−0.03	0.03	−0.04	**0.66**	0.44
Av. K (mg·kg^{-1})	−0.24	−0.24	0.39	0.40	0.46
Av. P (mg·kg^{-1})	−0.45	−0.17	0.09	−0.18	0.31
pH (1:2.5)	−0.14	0.01	**0.68**	−0.14	0.50
CEC (cmol$_{(+)}$·kg^{-1})	0.18	0.07	**0.54**	0.02	0.33

3.3. Principal Component Analysis

According to their respective eigenvalues, physical and chemical properties of the 0 - 20 and 20 - 50 cm depth were assigned to principal components. At the 0 - 20 cm depth, the first PC explained 40.84% of the variance with positive loadings on clay (0.37), BD (0.71) and negative loadings for Av. P (−0.45). The selected variables are essential components of soil structure, a positive loading on BD and AWC, and a negative loading on Av. P were observed for PC1. An increase in BD and AWC can affect soil structural properties. Correlation analysis showed a significant negative correlation (−0.47) between BD and Av. P and a weak positive correlation (0.34) between AWC and Av. P (Table 7). Also, the second PC explained 25.53% of the variance with a negative loading on sand (−0.56) and a positive loading on silt (0.63) and clay (0.30). Again, BD partly belongs to PC2 with a negative loading of −0.33 (Table 8). The selected variables for PC2 (Sand, Silt, Clay and BD) influence water movement in the soil along the catena and could be termed the soil texture factor. Also, sand, silt and clay play a significant role in influencing soil physical properties such as texture, bulk density, available water content, and possess the capacity to store and release nutrients to plants. The negative loading for sand implies that soils with high sand content generally have a low SOM and CEC.

Correlation analysis showed that sand was negatively correlated with silt (−0.88) and clay (−0.81). This PC best explains the relationship between soil physical properties with SOC. The third PC (PC3) explained 16.02% of the variance with a positive loading on Av. K (0.39), pH (0.68) and CEC (0.54). These variables explain the fertility management component of the soil and could be referred to as the SOC factor. The loadings of soil pH, CEC and Av. K on this PC indicate the influence of soil acidity on Av. K availability. These soil attributes relate to the soil medium's organic matter component and explain the fertility level of the soil. Correlation analysis indicated that SOC and clay (0.60), TN (0.95), BD (0.46), and Av. K (0.46) were positively correlated while SOC and Av. P (−0.73) were negatively correlated for the 0 - 20 cm soil depth. This implies that a change in SOC will affect TN and Av. K in the soil. The communality estimates indicated that this PC explained 90% of the variability in AWC, more than 60% in BD, and more than 50% in pH, more than 40% in silt, TN, and Av. K at the 0 - 20 cm soil depth (Table 8). For the 20 - 50 cm depth, PC1 explained 46.14% of the variance with a negative loading on sand (−47) and a favourable loading on silt (0.60) and AWC (0.51) (Table 9). Therefore, PC1 could be termed the soil texture factor, and soils with low clay content tend to have low SOM. The second PC explained 19.67% of the variance with positive loadings on SOC (0.55), TN (0.54), Av. K (0.35) and CEC (0.30) and could be referred to as the fertility factor. For PC3, BD (0.46) had a favourable loading as compared to pH (−0.64) and CEC (−0.44) with negative loadings for the 20 - 50 cm soil depth. The 20 - 50 cm depth recorded low communality values with Av. P explaining 50% of the variability, more than 40% in Silt, BD, and pH.

Table 9. Rotated principal component and contribution of each physical and chemical properties to soil variation at the 20 - 50 cm depth.

Soil attributes	PC1	PC2	PC3	PC4	Communalities
Eigen values	5.54	2.36	1.17	0.97	
Variance (%)	46.17	19.67	9.79	8.11	
CV (%)	46.17	65.84	75.63	83.74	
Factor loadings (Rotated component matrix)					
Sand (%)	−0.47	−0.09	0.00	−0.12	0.24
Silt (%)	**0.61**	−0.10	0.00	−0.20	0.43
Clay (%)	0.15	0.25	0.00	0.40	0.24
AWC (%)	**0.51**	0.05	0.03	0.09	0.27
BD (g/cm^3)	−0.19	0.28	0.46	0.38	0.47
OC (%)	0.02	**0.55**	0.00	0.01	0.30
TN (%)	0.02	**0.54**	−0.03	−0.02	0.30
Av. K (cmol$_{(+)}$/kg)	0.10	0.35	−0.03	−0.39	0.29
Av. P (cmol$_{(+)}$/kg)	−0.07	0.15	0.16	**−0.67**	0.50
pH (1:2.5)	−0.20	0.04	**−0.64**	−0.02	0.45
CEC (cmol$_{(+)}$/kg)	−0.06	0.30	−0.44	0.05	0.29

4. Discussion

4.1. Characteristics of Soil Properties at Different Slope Positions

Figure 2 shows the toposequence investigated on the Bekwai/Nzima-Oda association. Soil properties (**Table 4** and **Table 5**) were influenced by landscape variables such as topographic position, slope gradient, soil depth and prevailing land use type (Takoutsing *et al.*, 2017) [66]. However, these landuse variables influence soil erosion processes, and these geomorphic processes affected the redistribution of soil sediments [76]. According to Wang *et al.* (2016) [17] variations in hydrological processes linked to current weather conditions affect plant litter formation and breakdown. Landscape and land-use variables affect soil organic fractions and their distribution at the summit, upper, middle, lower, and valley bottom topographic positions [15]. According to Doetterl *et al.* (2012 and 2015) [21] [22], soil erosion and sedimentation influence the physico-chemical composition of soil attributes on geomorphic gradients and may have resulted in the reactivity of organic materials. This increases carbon storage in the lower and valley bottom soils. However, the middle and lower slopes (depositional positions) are characterized by a thick layer of colluvium and were classified as Luvisol according to the World Reference Base (WRB) for Soil Resources classification (IUSS, 2014 [60]; **Table 1**). The soil pH of the study site was slightly acidic in the summit, moderately acidic in the middle slope to neutral in valley bottom for the 0 - 20 cm depth and moderately acidic in the summit, middle and valley bottom soils for the 20 - 50 cm depth, respectively. The general acidity of the soil was mainly due to the chemical composition of the parent materials. Also, SOM and TN were moderate, while available phosphorus, potassium, and CEC were low for the summit, middle and lower slopes.

Descriptive statistics (**Table 4** and **Table 5**) indicated that the variable range of soil properties was high as compared to the relatively high variation observed at the upper slope. Due to prevailing environmental conditions strong winds and high evapotranspiration rates are associated with shallow soil depths due to erosion. For example, soils from eroding slope positions are usually SOC depleted than lower and valley bottom soils which can store more SOC due to burial of the topsoil with sediments eroded through geomorphic processes [22] along geomorphic gradients (toposequence). Bulk density and pH had the lowest variable coefficient for the upper, middle and valley bottom soils for the 0 - 20 and 20 - 50 cm soil depths. These results were consistent with Khan *et al.* (2013) [5], and Liu *et al.* (2020) [13]. These authors found no significant difference in soil pH at the upper, middle and lower slopes. This implies that soil is a buffer with a regulating ability [13] that regulates acid and alkali environments. Total nitrogen, available phosphorus and potassium were highly variable for the summit, middle and valley bottom soils of 0 - 20 and 20 - 50 cm soil depths. These findings explain the differences in above-ground vegetation composition, which influences physiological and ecological processes [77]. According to a review of several scientific papers, sand has low to moderate variability, organic matter and clay have moderate to high variability, and available phosphorus and potassium have high variability [43] [44] [45] [46], which is consistent with the findings of this study.

4.2. Effect of Geomorphic Gradient on Soil Properties

Generally, slope position is an important abiotic factor that influences spatial heterogeneity [13] while soil physico-chemical properties control pedogenic processes [20]. Slope positions on a toposequence in the humid tropics influence light, heat, water, air, and soil properties. Soils from the summit were shallow and characterized by low available water for moisture retention (**Table 4** and **Table 5**). Also, the underground water level was deep as compared to the lower slope and valley bottom soils. The surfaces of these landscapes were exposed to high solar radiation to increase evapotranspiration rates, resulting in the overheating of the soil surfaces and their exposure to drought conditions [78]. In a similar research Zhang *et al.* (2015) [77], Daws *et al.* (2002) [79] and Zhu *et al.* (2014) [80] observed that lower slope and valley bottom positions along the catena were cooler and exhibited more humid conditions that facilitate vigorous crop growth. These lower slope positions were associated with low solar radiation and evapotranspiration rates with very deep soils. These deep soils can accumulate more surface runoff water. The valley bottom soils are not exposed to drought conditions compared to the summit and upper slope positions.

Statistically, AWC at the lower slope and valley bottom was higher than the summit and upper slope positions. This is attributed to low altitudes at the lower slope and valley bottom. These lower positions receive low solar radiation. Also, summit and upper slopes are associated with high evaporation rates due to high solar radiation. In contrast, the lower slope and valley bottoms receive surface runoff water from the upper slopes. Also, these results may be due to the presence of grasses at the lower and valley bottomlands, which reduces water loss through evapotranspiration [81]. The results of the upper, middle and lower slopes varied significantly. This may be due to the sandy nature (kaolinitic fractions) and evapotranspiration of water loss associated with smallholder farmers' activities. This results in the breakdown of soil texture and structure which affects soil water holding capacity as observed in the study site. The middle slope soils (Kokofu series) developed from gravel-free sandy soils were formed from colluvial deposits of upland soils (Bekwai/Nzima series).

According to Breuning - Madsen *et al.* (2007) [53], these middle and lower slope soils may have derived their high nutrient (SOC, TN, Av. P, and Av. K) contents from the termite-formed top layer (mostly about 10 cm thick) of the Nzima and Bekwai soil series. These sediments were subsequently deposited via sheet erosion down the slope. However, at the bottom of the middle slope are Temang and Oda series with few quartz gravels [53]. The middle and lower slopes had high soil nutrients compared to the summit and upper slope soils. This is due to the middle and lower slopes receiving soil deposits hence increasing soil nutrient content due to the relatively flat slope position of the middle and lower slope positions. Also, the high annual rainfall favoured vertical and lateral transport processes of ion and dissolved substances. This has resulted in the formation of deep, acid, well-structured soils with a well-developed argillic horizon at the summit, upper and middle slopes with evidence of increasing wetness down the catena (slope). There were signs of redox processes in the lower slope (Temang series) and valley bottom (Oda series) soils due to increasing wetness, and the soils encountered were classified as gleysol [59].

From **Table 4** and **Table 5**, soil properties due to slope were observed in the 0 - 20 and 20 - 50 cm soil depths. An increase in clay, silt, Av. P and K occurred at depositional zones (lower slope and valley bottom). These findings were as a result of selective transportation of fine soil particles associated with available soil nutrients via erosion processes downslope as observed by Owusu-Bennoah *et al.* (2000) [47] in the MSDF zone in Ghana and by Haregeweyn *et al.* (2008) [82], Girmay *et al.* (2009) [83] and Ebabu *et al.* (2020) [84] in Ethiopia and by Takoutsing *et al.* (2017) [65], in Cameroon. These variations were possible due to selective removal of clay particles through surface runoff of available nutrients (Av. P and Av. K) and its deposition downhill. This could be due to P—rich parent rock weathering, which releases phosphorus in the lower slope positions (**Table 4** and **Table 5**). Also, the increase in depth of Av. P may be attributed to leaching due to rainfall intensity at the study site [85]. Also, low pH at foot slopes resulted in high P-fixation. The P sorption capacity in solution is high in these tropical acid soils [47]. This poses a major constraint to increasing food-crop production due to these tropical soils' inherently low fertility status. Our results were consistent with the findings of Pimentel *et al.* (1995) [86] and Ebabu *et al.* (2020) [84]. These authors observed that soil removal by erosion contains about three times more soil nutrients than the amount left uphill and is 1.5 to 5 times rich in SOM. A decreasing trend along the slope was observed (**Table 4**) at our study site. The lateral transport as observed illustrates soil-forming processes that formed a well-developed catena (Bekwai-Nzema-Oda Association) with distinct variation in lower slope and valley bottom soils. Also, Khan *et al.* (2004) [87], Webb and Dowing (1990) [88] found that an increase in soil pH with depth in this study could be attributed to the downward movement of Ca and its accumulation in the 20 - 50 cm soil depth.

4.3. Relationship between Soil Properties

Soil pH affects plant growth and development as well as soil microbial activities. Most plants thrive very well where pH is neutral. However, the soils as observed had a pH range of moderately acidic to neutral. However, excessive pH levels inhibit plant root growth and development. Soil organic carbon, a vital soil nutrient that controls the availability of other soil nutrients, influences the soil-plant nutrient cycling process. SOC/TN, TN/Av. K, Av. K/pH and pH/CEC were positively correlated for the 0 - 20 and 20 - 50 cm soil depths. A strong positive correlation was observed between SOC and TN (0.95 and 0.99) for the 0 - 20 and 20 - 50 cm soil depth. These high correlation values for SOC and TN were expected because they are related to the organic matter content of the soil. These findings are consistent with Takoutsing *et al.* (2017), who stressed that a decrease in SOC and TN concentration were due to erosion, leaching and crop harvesting. According to Zhang *et al.* (2020) [89], the dynamics of TN are closely related to SOC, and a change in one may result in a change in the other. The positive relationship observed between clay and TN at both soil depths means TN is protected in "soil aggregates rich in clay," which may have contributed to the high concentration of TN on clay particles. This finding is consistent with that of Waswa *et al.* (2013) [90]. Also, TN and Av. K is associated with the decomposition and mineralization of SOM. An increase in SOM facilitates plant and animal residue decomposition, resulting in soil TN, Av. P, and Av. K in the soil medium. The decomposition of SOM by microbial organisms may have affected the release of soil phosphorus. Also, this may have influenced soil pH at the lower slope and valley bottom soils significantly (SOC: 0.55; K: 0.60). Available phosphorus (Av. P: −0.41) had a negative correlation with CEC and a positive relationship with clay (0.73) at the 0 - 20 cm in the lower and valley bottom positions since clay has a positive effect on SOC, making it easy to accumulate and store soil nutrients [77] [91]. Also, TN, Av. K and P showed a significant positive relationship with summit and valley bottom positions for the 0 - 20 and 20 - 50 cm soil depths. The wide range observed for most soil properties may be associated with land-use history and varying management practices. Smallholders use various methods to improve soil productivity, which may have influenced soil nutrients concentration.

4.4. Principal Component Analysis of Soil Properties

The PC analysis grouped the eleven soil parameters into three at the 0 - 20 to 20 - 50 cm soil depths. All three factors contributed to one or more soil functions. Therefore, they can be termed indicators of soil variability assessment in the MSDF zone. These three selected soil parameters represented changes caused by or associated with a change in slope and land use, and/or prevailing cropping systems. The PCA explains the relationship between soil properties at the summit, middle and lower slopes for the 0 - 20 and 20 - 50 cm soil depths. Soil pH, SOC, TN, Av. P, Av. K and CEC had the highest soil nutrient concentration at both soil depths. Several studies conducted on agricultural fields [49] [92] [93] proved that PCA is an effective statistical tool to assess the variability of soil properties and from which soil quality indicators [94] are selected to represent the changes caused by topography. In a study conducted by Bredja *et al.* (2000) [92], the twenty soil properties selected for PC analysis were reduced to only five dimensions, namely: soil texture, SOM, soil acidity, soil colour and soil Mehlich factor. Similarly, Shukla *et al.* (2004) [93], observed that after subjecting 20 soil properties to PC analysis, BD, H_2O infiltration, aggregate size, and N factors were selected for monitoring a reclaimed mined site. Also, soil properties were grouped into four components: soil organic carbon, total nitrogen, and soil textural factors [51]. However, this study identified BD, sand, silt, pH, CEC, SOC and TN as well as Silt, AWC, SOC, TN, pH, and Av. P were factors retained for the 0 - 20 and 20 - 50 cm soil depths, respectively.

Statistically, there was a significant relationship between SOC and CEC for the summit and valley bottoms. However, there was no significant relationship between soil pH, TN and Av. P for the summit and lower slopes. Soil organic carbon, total nitrogen, Av. P and Av. K and cation exchange capacity had the highest values in terms of soil nutrients due to the downward surface runoff of soil water through erosion and its deposition at the lower slope. The PC and ANOVA analysis results were similar and reflect the relationship and interrelationship between soil physical and chemical properties concerning slope positions. However, the downward transport of gravel-free materials (Bekwai and Nzima series) downhill, the continuous removal of these materials through erosion, leaching, lateral (surface and subsurface) transport processes, weathering of the soft bedrock (metamorphic) present at shallow depths, its deposition at middle and lower slopes results in the formation of greyic layers in valley bottom soils (Temang and Oda series).

4.5. General Observation

Descriptive statistics, principal components and correlation analysis proved very useful for soil variability assessment along the toposequence. The factors obtained by PC analysis suggested diverse measured soil variables for the 0 - 20 cm soil depth. For PC1, soil variables with high factor loadings for clay, BD and Av. P represents the soil structural factor, and for PC2, the measured soil attributes with high loadings were sand, silt clay and BD. These represent the soil textural factor. For PC3, Av. K, pH and CEC selected attributes with high factor loadings, represent the soil fertility factor. For PC4, SOC, TN and Av. K were attributed with high factor loadings referred to as the SOC factor. The 20 - 50 cm soil depth followed a similar trend for PC1, PC2 and PC3. In terms of textural class, the soils are sandy loam (0 - 20 cm) to sandy clay loam (20 - 50 cm). Most soils are coarse to medium textured, deep and non-gravelly, well and moderately (Nzima, Bekwai and Kokofu) to imperfectly (Oda and Temang series) drained. Nzima and Bekwai series occur on gently undulating topography (3% - 6% slopes) are relatively susceptible to slight to moderate erosion.

On these summit and upper slopes, traces of pisolites mixed with gravelly rock fragments, mostly quartz, were encountered on summits and upper slope soils in Ghana's moist semi-deciduous forest zone [10] [47] [53]. The very deep non-gravelly soils (Kokofu series) occur on gentle to lower slopes (2% - 4%). Water holding capacity is moderate because the soils encountered were prone to drought in the dry season. In terms of soil fertility, soils were low in nutrients for food crop production. Soil organic matter and/or organic carbon status, nitrogen, potassium, phosphorus and cation exchange capacity levels were low. About 70% of the sampled sites had deficient phosphorus levels (<10 ppm), and phosphorus levels decline with depth (**Table 4** and **Table 5**). Exchangeable potassium

Table 10. Fertility ratings for 0 - 20 cm.

Soil attributes	Range	Mean	Rating
pH (1:2.5)	4.10 - 7.32	5.86	Good
Soil organic carbon (%)	0.62 - 2.91	1.64	Medium
Total nitrogen (%)	0.07 - 0.30	0.17	Medium
Phosphorus ($mg \cdot kg^{-1}$)	0.24 - 13.21	4.26	Low
Potassium ($cmol_{(+)}/kg$)	0.04 - 0.66	0.18	Low
CEC ($cmol_{(+)}/kg$)	4.11 - 19.19	10.15	Medium

levels were low (0.18 $cmol_{(+)}/kg$). However, a desirable level for optimum performance is 0.20 to 0.30 $cmol_{(+)}/kg$. Nutrient availability or uptake by plants depends on soil CEC, and a CEC value above 10.00 $cmol_{(+)}/kg$ soil is suitable for plant growth. However, the study site recorded 10.15 $cmol_{(+)}/kg$ which is within the optimum amount needed for optimum growth and development for most arable crops (**Table 10**). Base saturation is the proportion of cation exchange that is saturated with basic cations. However, most of the sampled sites were highly saturated despite the low values of exchangeable potassium. This is because the CEC of the soils for most sampled sites was very low, which makes the soil saturate quickly with basic cations in the soil solution. Application of organic manure, compost, and soil conservation practices can improve fertility for sustainable crop production by smallholder farmers.

5. Conclusion

Generally, the soils were functioning at a moderate capacity for crop production. Soil texture is sandy loam to sandy clay loam for the 0 to 20 and 20 to 50 cm, respectively. Sand was higher at the lower and valley bottom. Less than 80% of the site have clay content greater than 10%, and the soils of the upper and middle slopes are highly susceptible to erosion. This study indicated that landscape position, soil depth and drainage significantly influenced soil variability and this variation relates to inherent factors of soil genesis, prevailing vegetation, and land-use systems. Also, a high variability (CV) was observed between the top and subsoil and this may be due to prevailing land management practices and inherent soil characteristics. Soil acidity and low organic carbon content were observed across the study area. The vertical and lateral flow of soil water resulted in the variation of most soil chemical properties. Also, from the above discussion, leaching of cations may be the essential process causing systematic variation in the upper, middle, to lower slopes. The PCA findings highlight the importance of a comprehensive soil fertility management. This technique can ensure soil nutrient availability while increasing nutrient reserves (stocks) via soil organic matter. The findings of this study suggest that soil management interventions should be location-specific. This could facilitate appropriate soil resource management and its rehabilitation on heterogeneous landscapes of Ghana’s moist semi-deciduous forest zone.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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