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Full Length Research Paper

Soil Characterization and Variability Analysis in the Legon Hill Catena, Accra Plains, Ghana

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Properties of five soils developed on different positions of a Legon hill catena in the Accra Plains, Ghana, were studied. Nyigbenya, Toje, Adenta, Haatso and Alajo series were located on the higher upperslope, lower upperslope, middle slope, lower slope and bottom slope positions, respectively. All the soils had bulk density between 1.00 and 1.40 Mg m^{-3} and pH (KCl) > 5.1. Alajo series showed relatively higher pH (H_2O) (6.6 to 7.6), than all the other soils. Clay fraction increased from 263 g kg^{-1} at the upper to 721 g kg^{-1} at the bottom slope. All the soils except Alajo series showed very low levels of exchangeable bases and cation exchange capacity (CEC). Alajo series contained close to 10-fold levels of exchangeable bases and CEC compared to those of the other soils. Phosphorus retention was low (< 35%) in all the soils except the last horizon of Alajo series which showed a very high amount (96.2%) and had stronger correlation with clay content of the upper 30 cm of the soils. Alajo series showed the highest levels of organic C (1.8 to 9.5 g kg^{-1}). This study shows that: (1) The properties of Nyigbenya, Toje, Adenta and Haatso series suggest that they were formed from stratified parent materials; (2) The within and across pedon textural differences along the catena were caused by sedimentary differentiation, illuviation and pedogenic formation of clay in the subsoil; (3) The levels of phosphate retention, CEC and exchangeable bases in the soils could be attributed mainly to the type and amount of clay they contained. Nyigbenya and Toje series were classified as Rhodic Kandiustalf according to *Soil Taxonomy*. Adenta series was classified as Typic Kandiustalf and Haatso series as Kandic Haplustalf. Alajo series, on the other hand was classified as Typic Natraquert. According the WRB classification system, Nyigbenya and Toje series were Nitisols whereas Adenta and Haatso series were Lixisols. Alajo series was classified as Natric Vertisol.

Key words: Alfisols, catena, pedogenesis, soil taxonomy, World reference base.

INTRODUCTION

Soils on a long and sloppy landscape frequently occur in a well-defined and fairly regular sequence. This sequence of soils has been referred to as toposequence (Moorman, 1981, Okusami et al., 1985). Soils on a toposequence would form a catena if they show different drainage characteristics at different hillslope positions.

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Soils occurring on a catena vary in morphological, physical and chemical properties. Consequently, the potentials of such soils for crop production often also vary from the crest to the valley bottom. The distribution of individual soil series on a catena has a considerable influence on the land use pattern of an area and is a function of water movement pattern through the landscape (Moore et al., 1993; De Alba et al., 2004).

Characterisation of soil morphological, physical and chemical properties helps in delineation and management of soils. According to Marbut (2000), soil morphology is defined as the field observable attributes of the soil within the various soil horizons and the description of the kind and arrangement of the horizons. For classification purposes, Marbut (2000) further opined that soil morphology is more reliable for soil classification than the theories of pedogenesis because theories of pedogenesis are both ephemeral and dynamic. Soil morphology provides a long term record of hydric period and soil aeration and it is widely used to identify wetlands.

The physical and chemical properties of a soil are determined by the soil forming processes under which they form though all soils are created by the various development processes including additions, transformations, translocations and removals. Pedogenesis is the transformation of the soil parent materials and the interaction of soil forming factors over a period of time in a synergistic process that results to a soil matrix. Targulian and Krasilnikov (2007) perceived pedogenesis as integration of specific pedogenic processes each of them characterized by a definite set of solid-phrase pedogenic feature. Pedogenic studies such as this would provide information on the properties (spatial and temporal) and nature of soils of an areas and how these properties influences or are influenced by the disparities in their positions on a landscape. It will also make available information on the land resource characteristic of the area, upon which conclusions can be drawn on the most appropriate land use to ensure sustained productivity.

Soil classification on the other hand is an orderly way of grouping soils based on similarity of observable and/ or measurable attributes, thereby improving systemisation of knowledge and enhancing communication. Classification opens new lines of research and allows for exchange of knowledge amongst scientists, policy makers and other stake holders. Although some countries e.g. Canada, France, South Africa and many more have developed their national soil classification systems, there are two most popular in the soil science community: World Reference Base (WRB-ISRIC-IUSS, 2006) and USDA *Soil Taxonomy* (1999).

In recent years, the prominent Legon hills have been characterized by increased human settlement including the massive expansion of the University of Ghana. Consequently, the land is being put to various uses including construction and agriculture. However, productive land use would depend on a sound knowledge of the properties of soils in the area and the prevailing environmental conditions. Fiagbedzi (1989) studied soils on a similar Legon hill catena but in the southwestern direction. The study, however, did not include all the soils on the prominent catena such as the Alajo series. Furthermore, the study did not critically examine the genesis of the soils. Thus, the objectives of this study were to examine: (1) The morphological, physical and chemical properties of all the soil series on the north-eastern catena of the Legon hill; (2) The relationship between these properties, physiographic positions and the parent materials of the soils; and (3) To classify these soils.

MATERIALS AND METHODS

Site description and soil sampling

The soils used for this study were collected from five profile pits sited along the catena that runs from the Legon hill, in the northeastern direction. The study area (Figure 1) lies approximately within latitude 05° 38' 0'' and 05° 42' 0'' N and 0° 8' 0'' and 0° 12' 0'' W. It experiences a mean annual rainfall of about 800 mm and mean annual temperature of 27°C. Generally, the study area is typical of the general ecology and geomorphology of the coastal savanna zone and the Accra Plains.

The Legon hill is an outlier of the Togo - Akwapim Range. The geology of the area as described by Junner and Bates (1945) is Togo (pre-Cambrian) quartzites with smaller amounts of phyllite, sericite, schist, sandstone and shale. On the upper slopes of the catena where Nyigbenya and Toje series are found, Togo quartzite schist is the underlying parent material. However, due to sedimentary differentiation along the catena, Adenta series is formed on colluvial deposits of Tertiary age overlying the Togo quartzite schist. Haatso series at the foot of the catena is formed on both colluvial and alluvial deposits underlain by iron-stained quartzite or sandstone at 60 to 90 cm (Brammer, 1967). Alajo series at the valley bottom of the catena is developed on Quaternary/ Recent alluvial deposits underlain by phyllite.

Soil samples were collected from the five pedons starting from the upper slope to the bottom slope positions of the catena. Nyigbenya series was located at the higher upper slope followed by Toje series at the lower upper slope. Adenta series was located at the middle slope. Haatso series and Alajo series were at the lower slope and bottom slope positions, respectively. The Legon hill experiences a mean annual rainfall of about 800 mm and mean annual temperature of 27°C. The vegetation is mainly coastal grassland and scrub. The soils had ustic moisture and isohyperthermic temperature regimes. The location, elevation, land-form, vegetation cover, and basement rocks of the pedons are shown in Table 1. Soil colour, texture (field), structure, root, and boundary characteristics were determined and described according to the Guidelines for Soil Profile Description (FAO, 2006).

Laboratory analyses

Particle size distribution was determined by the method of Bouyoucos (1962). Bulk density was determined using the core method (Blake, 1965). Undisturbed core samples were weighed, dried in an oven at 105°C for 24 h and reweighed and the bulk density determined. The pH in both H_2O and 1N potassium chloride were determined with a glass electrometer in a 1:1 (soil to solution)

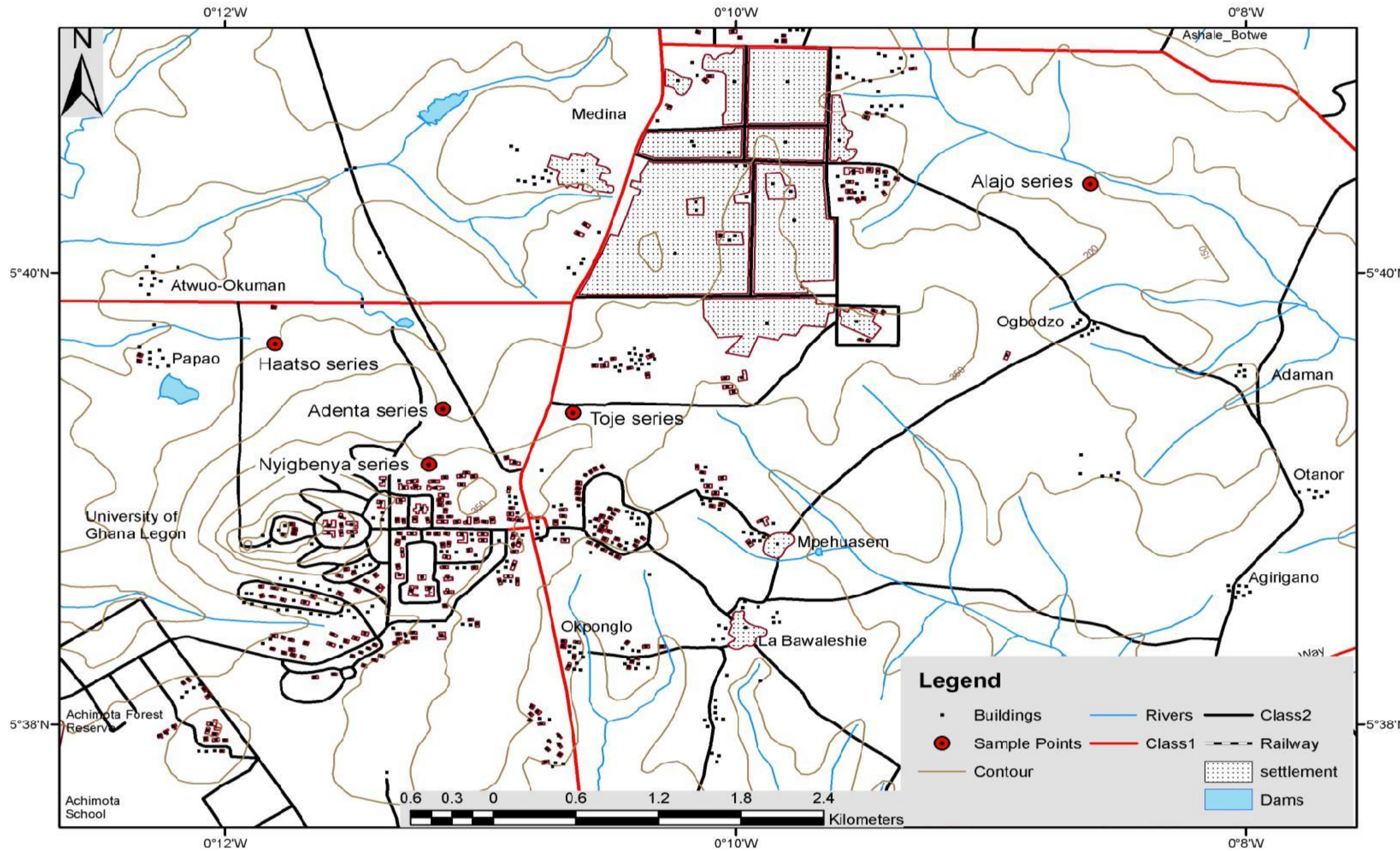

Figure 1. Map of the study area.

ratio following the standard laboratory methodology of USDA (2004). The Walkley and Black (1934) method as modified by Allison (1965) was used to determine organic carbon content of the soils. In determining KCl-extractable Al, 25 ml of 1 mol L^{-1} KCl was added to 10 g of soil samples and the mixture was shaken for 30 min. The supernatant was collected and the precipitate subjected to the extraction process three more times. The amount of Al extracted was then determined by potentiometric titration with 0.05 ml^{-1} NaOH. Ammonium acetate (1 mol L^{-1}, pH 7.0) was used as the extractant and the concentration of the exchangeable bases were determined using atomic absorption spectrometer (AAS 3 CALZEISS JENA). The cation exchange capacity was determined by the ammonium saturation method at pH 7.0 (Soil Survey Staff,

Table 1. Macromorphological properties of soils on a Legon hill catena.

Horizon	Depth (cm)	Colour (moist)	Structure*	Texture#	Consistency (moist)	Roots&	Boundary^
Nyigbenya series							
Ap	0-10	7.5YR 2/3	2gr	Gr. SCL	Loose	a	cs
A2	10-50	7.5R 3/4	2sbk	Gr. SC	Firm	c	gs
Bt	50-77	10R 3/4	3sbk	Gr. C	Firm	f	gs
BC	77-150	10R 3/6	2sbk	Gr. SC	Firm	n	-
2Cr	150^+	Partially decomposed quartzite schist					
Toje series							
Ap	0-10	2.5YR 2/3	2mgr	SCL	Friable	a	as
A11	10-24	2.5YR 3/3	2msbk	SCL	Firm	a	as
A12	24-45	10R 3/6	2msbk	SC	Firm	c	gs
Bt1	45-90	10R 3/6	2msbk	C	Firm	f	gs
Bt2	90-115	10R 3/6	2msbk	C	Firm	f	gs
BC	$115\text{-}150^+$	10R 3/6	1msbk	Gr. SC	Firm	n	-
Adenta series							
Ap	0-8	5YR 2/4	1mgr	SCL	Friable	a	cs
A11	8-20	5YR 2/4	2mgr	SCL	Friable	a	cs
A12	20-35	5YR 3/6	2mgr	SC	Friable	c	gs
Bt1	35-56	2.5YR 3/4	2msbk	C	Firm	c	gs
Bt2	56-90	2.5YR 4/6	1msbk	SC	Firm	f	as
BC	$90\text{-}150^+$	2.5YR 3/4	2msbk	SC	Firm	n	-
Haatso series							
Ap	0-5	10YR 4/4	1mgr	SL	Friable	a	cs
A11	5-28	5YR 5/6	1mgr	SCL	Friable	a	cs
A12	28-58	7.5YR 5/6	2mgr	SCL	Friable	c	gs
Bt1	58-90	7.5YR 5/6	1msbk	SCL	Firm	c	gs
Bt2	90-140	10YR 6/6	1msbk	SL	Firm	f	gs
BC	$140\text{-}200^+$	10YR 6/6	1msbk	SCL	Firm	n	-
Alajo series							
Ap	0-8	10YR 2/1	2mgr	C	Firm	a	cs
A11	8-26	10YR 2/1	2msbk	C	Firm	a	gs
A12	26-46	10YR 3/1	3msbk	C	Very firm	c	gs
Bt1	46-81	10YR 3/1	3mabk	C	Very firm	f	gs
Bt2	81-120	2.5Y 5/3	3mabk	C	Very firm	f	gs
BC	120-200	2.5Y 5/3	massive	C	Very firm	n	-

*1-weak, 2-moderate, g-granular, gr-gravelly, sbk-subangular blocky, m-massive; #Gr.-gravelly, SCL-sandy clay loam, SC-sandy clay, C-clay; &a-abundant, c-common, f-few, n-none; ^a-abrupt, c-clear, g-gradual, s-smooth.

1984). Phosphate retention of the soils was determined by the method of Blakemore et al. (1987). The electrical conductivity of the soil samples was determined with a glass electrode in a 1:1 (soil: water) ratio using an electrical conductivity meter.

RESULTS

Morphological properties

The morphological properties of the soils are shown in Table 1. Nyigbenya series, higher upper slope position, was at 107 m a.s.l. while Alajo series at the foot slope was at 46 m a.s.l. The soils showed deteriorating drainage characteristics from the upper slope to bottom slope. Two kinds of vegetation were observed on the catena. There were mainly grasses at the upper slope position whereas trees with grass undergrowth were observed at the middle slope, lower slope and bottom slope positions. The vegetation also got thicker as one moved down the catena.

Horizonation of the profiles were fairly the same. They all had A, B, and C horizons with varying degrees of accumulation of mobile soil constituents. Alajo series was characterized by the presence of cracks varying in width from 1 to 12 cm, generally extending to depths more than 30 cm. It also showed slickensides at 120 to 200 cm depth. The soils tended to be deeper from the upper slope to the bottom slope of the catena (Table 1).

The colours of the soils ranged from red to black (Table 1). The red soils had a hue of 10 R to 2.5 YR. The colour graded to redder hues with depth. The colour values ranged from 2 to 6 and chromas from 3 to 6 for the red soils. Nyigbenya and Toje series showed redder colour than Adenta and Haatso. Alajo series, on the other hand, had very dark colour. Its hue ranged from 10YR to 2.5 Y; value from 2 to 5 while chroma was uniformly 1 throughout the profile with the exception of the last horizon which had a chroma of 3.

Nyigbenya, Toje, Adenta and Haatso soil series had granular structure in the surface horizons and which graded to subangular blocky with depth. Alajo series showed medium to strong subangular blocky to angular blocky structure in the surface horizon. The subsoil horizons had strong, very coarse angular blocky structure and extremely hard (dry) and extremely firm (moist) consistence. Alajo series thus showed characteristic features of soils with smectite as a dominant mineral (Coulombe et al., 1996). There were abundant roots in the surface horizons of all the soils which decreased with depth. The bottom horizons had no roots at all.

Nyigbenya, Adenta, Haatso and Alajo series showed clear smooth boundaries in the surface horizons and gradual smooth boundaries in the lower horizons. Toje series, on the other hand, showed abrupt smooth boundaries between Ap and A and between A and Bt1 horizons. The lower horizons of Toje series, however, had gradual smooth boundaries.

Nyigbenya, Toje and Adenta series were located on gentle slopes (2 - 6%) while Haatso and Alajo series were located on flat or almost flat terrains (0 - 2%). The topography of the area surrounding Nyigbenya series was rolling (8 - 16%) while that of Toje and Adenta series was undulating (2 - 8%). Haatso and Alajo series were surrounded by a flat topography. The basement rock of Nyigbenya, Toje, Adenta and Haatso was Tertiary Togo quartzite schist. Alajo series, at the bottom slope, was probably be underlain by phyllites which abound in the area.

Physical properties

Physical properties of the soils are shown in Table 2. The sand content of the soils varied from 25 to 79%, and tended to decrease with depth. The silt content of the soils ranged from 10 - 30%. Alajo series showed the highest amounts of silt and clay compared to the other soils. The bulk densities of the soils ranged from 1.03 to 1.36 Mg m^{-3}. Bulk density values generally increased with depth in all the pedons. Nyigbenya, Toje and Adenta series had sandy clay loam texture in the surface horizons and sandy clay texture in the lower horizons. Alajo series at the bottom slope of the catena had clay texture throughout the profile.

Chemical properties

Chemical properties of the soils are shown in Table 2. The pH (H_2O) of the soils ranged from 5.0 to 7.6 (moderately acidic to slightly alkaline) and tended to decrease with depth in Nyigbenya, Toje, Adenta and Haatso series. Alajo series had relatively higher pH (H_2O) values (6.6 - 7.6). The change in pH values (ΔpH = pH KCl – pH H_2O) were negative in all the soils. All the soils except the C horizon of Alajo series showed very small amounts of P- retention. The P-retention values correlated positively with clay content in all the soils except Alajo series which showed a negative correlation. All the soils contained the largest amounts of organic carbon in their surface horizons. The amounts of organic carbon decreased with depth. However, the average organic carbon content in the A horizons of the pedons decreased along the catena in this order: Nyigbenya (4.6 g kg^{-1}) > Toje (4.5 g kg^{-1}) > Adenta (4.0 g kg^{-1}) > Haatso (2.8 g kg^{-1}). Alajo series, however, had the highest amount of organic carbon (1.8 to 9.5 g kg^{-1}). The soils generally had low KCl extractable Al. The values ranged from 0.04 to 0.36 $cmol_c$ kg^{-1}. Nyigbenya, Toje, Haatso and Alajo series showed erratic levels of KCl extractable Al in their profiles. On the contrary, the KCl-extractable Al values for Alajo series decreased uniformly with depth.

The electrical conductivity values of the soils ranged from 0.05 to 0.48 dS m^{-1} indicating that the soils were nonsaline. While the EC values were very low in Nyigbenya, Toje, Adenta and Haatso series, they were relatively higher in Alajo series and also tended to increase with depth. Cation exchange capacity (CEC) was low in Nyigbenya, Toje, Adenta and Haatso series, but was about 10-fold higher in Alajo series. Nyigbenya series at the upper slope tended to show slightly higher levels of CEC (3.01 - 4.12 $cmol_c$ kg^{-1}) than Toje, Adenta and Haatso series which showed similar levels of CEC. Due to the low organic carbon contents of these soils, their CEC might be controlled mainly by the type and amounts of clay they contained. Apart from Haatso series which contained the highest amount of sand, the level of CEC of the soils tended to correlate positively with the amount of clay. Alajo series at the bottom slope of the catena which had higher levels of CEC ($\geq$ 30 $cmol_c$ kg^{-1}) also tended to contain relatively higher levels of clay which was probably smetitic. All the soils except Alajo series contained small amounts Ca^{2+} and Mg^{2+} and very small amounts Na^+ and K^+ probably due to leaching. This order of abundance of the bases is in agreement with the view of Jenny (1941) that leaching caused preferential

Table 2. Physico-chemical properties of soils on a Legon hill catena.

Horizon	Depth	Sand	Silt	Clay	TC	Colour	BD	H_2O	KCl	Org. C	Ca	Mg	Na	K	TEB	CEC	Al (KCl-ext)	ECEC	BS	PR
	cm		%			(moist)	(Mg m^{-3})	pH		(g kg^{-1})				(cmol$_c$ kg^{-1})						%
Nyigbenya series																				
Ap	0-10	69.1	4.6	26.3	SCL	7.5YR 2/3	1.03	5.6	5.2	4.8	2.08	1.20	0.07	0.16	3.15	3.80	0.24	3.99	92.37	22.4
A2	10-50	49.6	5.2	45.2	SCr	7.5R 3/4	1.03	5.3	5.1	4.4	2.24	0.96	0.11	0.13	3.44	3.82	0.13	3.76	90.05	26.6
Bt	50-77	40.3	3.4	56.3	C	10R 3/4	1.09	5.4	5.1	3.8	2.48	0.80	0.10	0.09	3.47	4.12	0.16	3.73	84.22	32.2
BC	77-150	52.4	5.1	42.5	SC	10R 3/6	N.D	5.0	5.3	3.8	1.36	0.80	0.09	0.09	2.34	3.01	0.12	2.96	77.74	27.5
2Cr	150+								Partially decomposed quartzite schist											
Toje series																				
Ap	0-10	71.5	3.3	25.2	SCL	2.5YR 2/3	1.18	6.1	5.3	4.7	1.36	0.64	0.06	0.15	2.21	2.80	0.16	2.51	78.93	22.2
A11	10-24	68.1	3.7	28.2	SCL	2.5YR 3/3	1.25	5.9	5.2	4.2	1.28	0.80	0.07	0.10	2.25	2.83	0.16	2.45	79.51	23.0
A12	24-45	49.2	3.3	47.5	SC	10R 3/6	1.31	5.8	5.2	1.3	1.28	0.40	0.11	0.09	1.88	2.40	0.17	2.62	78.33	25.8
Bt1	45-90	34.6	3.3	62.1	C	10R 3/6	1.31	5.8	5.3	1.3	1.76	1.20	0.13	0.03	3.12	3.55	0.15	3.32	87.87	27.2
Bt2	90-115	34.6	3.3	62.1	C	10R 3/6	1.36	5.6	5.2	0.9	1.84	0.64	0.11	0.02	2.61	3.20	0.04	2.87	81.56	27.5
BC	115-150+	58.2	5.5	36.3	SC	10R 3/6	N.D	5.6	5.1	1.0	1.60	0.48	0.09	0.02	2.19	3.20	0.14	2.58	68.44	29.1
Adenta series																				
Ap	0-8	66.2	3.4	30.4	SCL	5YR 2/4	1.08	6.5	5.4	4.5	1.44	1.04	0.03	0.09	2.60	2.98	0.04	2.89	87.25	23.7
A11	8-20	61.4	8.3	30.3	SCL	5YR 2/4	1.23	5.9	5.2	3.5	1.28	0.96	0.03	0.09	2.36	2.98	0.36	2.83	79.19	20.6
A12	20-35	50.1	3.4	46.5	SC	5YR 3/6	1.26	5.9	5.2	1.8	1.28	0.90	0.06	0.05	2.29	3.21	0.18	2.53	71.34	26.1
Bt1	35-56	42.6	5.2	52.2	C	2.5YR 3/4	1.32	6.0	5.1	1.8	1.76	1.20	0.05	0.03	3.04	3.87	0.18	3.44	78.55	28.6
Bt2	56-90	50.2	5.1	44.7	SC	2.5YR 4/6	1.28	5.9	5.3	1.8	1.68	0.66	0.13	0.02	2.49	3.98	0.08	2.59	62.56	30.1
BC	90-150+	56.5	8.4	35.1	SC	2.5YR 3/4	N.D	5.8	5.1	1.2	1.60	0.58	0.13	0.03	2.34	2.98	0.16	2.62	78.52	31.5
Alajo series																				
Ap	0-5	79.1	8.4	12.5	SL	10YR 4/4	1.18	6.1	5.4	2.9	2.32	0.80	0.05	0.16	3.33	3.82	0.18	3.57	87.17	22.6
A11	5-28	71.8	5.2	23.0	SCL	5YR 5/6	1.18	6.1	5.4	2.4	1.28	0.24	0.03	0.09	1.64	2.30	0.24	2.05	71.30	22.7
A12	28-58	67.1	5.2	22.7	SCL	7.5YR 5/6	1.24	5.9	5.2	0.9	1.28	0.16	0.06	0.08	1.58	2.32	0.36	2.01	68.10	24.5
Bt1	58-90	59.0	8.8	32.2	SCL	7.5YR 5/6	1.24	5.9	5.2	0.9	0.96	0.24	0.08	0.08	1.36	2.24	0.36	1.91	60.71	24.5
Bt2	90-140	59.0	5.5	35.3	SL	10YR 6/6	1.24	5.8	5.1	1.2	1.20	0.24	0.07	0.06	1.57	2.24	0.36	2.12	70.09	28.8
BC	140-200+	61.2	5.2	33.6	SCL	10YR 6/6	N.D	5.7	5.1	0.6	1.20	0.65	0.09	0.10	2.04	2.88	0.30	2.58	70.83	28.8
Haatso series																				
Ap	0-8	39.5	10.0	50.5	C	10 YR 2/1	1.26	6.6	5.6	9.5	10.16	6.40	0.39	1.94	18.89	32.45	0.21	29.34	89.28	25.9
A1	8-26	37.0	10.3	52.7	C	10 YR 2/1	1.28	7.1	5.7	4.7	9.68	5.20	1.96	2.28	19.12	35.10	0.20	32.59	91.79	26.2
Bwss1	26-46	23.6	8.2	68.2	C	10 YR 3/1	1.28	7.1	5.7	3.9	11.20	5.44	4.17	1.28	22.09	38.29	0.16	33.54	86.89	26.9

Table 2. (Contd).

Bwss2	46-81	26.3	8.1	66.6	C	10 YR 3/1	1.28	7.3	5.7	2.8	12.80	6.80	8.35	1.28	29.23	42.37	0.12	36.55	85.63	26.7
Bwss3	81-120	24.8	3.1	72.1	C	2.5 Y 4/1	1.32	7.5	5.6	2.5	13.92	6.96	11.74	1.18	33.80	46.13	0.12	39.61	85.63	24.5
BC	120-200+	37.1	4.6	58.3	C	2.5Y 5/3		1.32	7.6	5.8	1.8	11.38	6.40	8.74	1.18	27.70	41.04	0.12	39.87	96.76

TC, Textural class; BD, bulk density; TEB, total exchangeable bases; $cation exchange capacity; ECEC, effective cation exchange capacity; BS, base saturation; PR, phosphate retention.

losses of Na+ and K^+. Alajo series, on the other hand, contained very high amounts of the bases indicating a lower level of weathering and leaching from the soil. Summary of the regression analysis among selected properties are shown in Table 3.

Soil classification

The soil orders of the USDA Soil Taxonomy (Soil Survey Staff, 2006), key out as Gellisols, Histosols, Spodosols, Andisols, Oxisols, Vertisols, Aridosols, Ultisols, Mollisols, Alfisols, Inceptisols and Entisols. Nyigbenya series, gravelly, shallow and red in colour, located at the upper slope of the catena was classified as an Alfisol due to the presence of an argillic horizon. The five suborders established for Alfisols are Aqualfs, Cryalfs, Ustalfs, Xeralfs, and Udalfs. Aqualfs are saturated with water and show saturated and reducing conditions unless artificially drained. Cryalfs have cryic or isofrigid soil temperature regime. Ustalfs have ustic moisture regime, Xeralfs have a xeric moisture regime, while other Alfisols that do not meet any of these requirements are classified as Udalfs. Nyigbenya series qualified as an Ustalf at suborder level because it had an ustic moisture regime (Essibu, 2003).

Ustalfs has eight great groups namely, Durustalfs, Plinthustalfs, Natustalfs, Kandiustalfs, Kanhaplustalfs, Paleustalfs, Rhodustalfs and Haplustalfs. Since there was no duripan, plinthite or natric horizon in Nyigbenya series, it could not be classified as a Durustalf, a Plinthustalf or Natustalf. It was a Kandiustalf at the great group level because it had kandic horizon within 100 cm of the horizon which had a texture finer than loamy sand and had an apparent CEC of less than 16 $cmol_c$ (+) per kg clay (by 1N NH_4OAc pH 7.0). At the subgroup level, Nyigbenya series keyed out as a Rhodic Kandiustalf because it had hues redder than 2.5 YR and values (moist) of 3 or less and dry values not more than 1 unit. At the family level, the particle size class was gravelly sandy clay loam. It predominantly contained 1:1 as inferred from its low CEC data (Table 2) clay minerals and an isohyperthermic soil temperature (that is, a mean annual soil temperature of 22°C and the difference between the mean summer and the mean winter temperature differ by less than 6°C at 50 cm depth). Nyigbenya series was therefore classified up to the family level as a loamy-skeletal kaolinitic isohyperthermic Rhodic Kandiustalf. Toje series, moderately deep also located at the upper slope of the catena, was also classified as an Alfisol because it had an argillic horizon. It was an Ustalf at the suborder because it showed ustic soil moisture regime. At the great group level, it was a classified as a Kandiustalf because of the presence of a kandic horizon. At subgroup level, it was classified as a Rhodic Kandiustalf because it had hues redder than 2.5 YR and values (moist) of 3 or less and dry values notmore than 1 unit (Table 1). At the family level, the particle size class was sandy clay loam probably dominated by 1:1 clay minerals. Therefore, it was classified at the family level as a loamy kaolinitic isohyperthermic Rhodic Kandiustalf.

Adenta series located at the backslope was also classified as an Alfisol. It was an Ustalf at the suborder level because it had an ustic moisture regime. At the great group level, it was classified as a Kandiustalf. It met the requirements of a Typic Kandiustalf at the subgroup level because it has none of the qualities of other Kandiustalfs listed in *Soil Taxonomy* at the family level; it was classified as a loamy kaolinitic isohyperthermic Typic Kandiustalf.

Haatso series, deep and sandy and located at the lower slope of the catena was classified as an Alfisol; and an Ustalf at the suborder level because of its ustic moisture regime. It qualified as a Paleustalf at the great group level. It qualified as a Kandic Paleustalf at the sub group level. At the family level, the particle size class was sandy loam and it was probably dominated by 1:1 clay minerals. Haatso series, was therefore classified as a loamy kaolinitic isohyperthermic Kandic Haplustalf because it has a both CEC of less than 24 cmol(+)/kg clay (by 1N NH4OAc pH 7) in 50 percent and more of the argillic horizon if less than 100 cm thick and of its upper 100 cm.

Alajo series, located at the bottom slope position was deep and black in colour. It was classified as a Vertisol at the order level because its A horizons were more than 25 cm thick, with an upper boundary within 100 cm of the mineral soil surface, that had slickensides. It was classified as an Aquert at the suborder level because it had more than one horizon within 50 cm of the mineral soil surface with aquic conditions for some time in normal years. It met the requirements of a Natraquert at the great group level due to the presence of a natric horizon within 100 cm of the mineral soil surface. It was a Typic Natraquert at the subgroup level. The particle size class of Alajo series was very-fine as it had 60% or more clay content in the fine earth fraction. It most likely has a mixed mineralogy and superactive cation exchange capacity (Table 2). It had an isohyperthermic temperature regime (that is, mean annual soil temperature of 22°C or higher). Alajo series was therefore classified as a fine clay smectitic superactive isohyperthermic Typic Natraquert.

The soils were also classified according to the (WRB, 2007). Nyigbenya series was classified as Lixic Vetic Nitisol (Abruptic) Toje was classified as Lixic Vetic Nitisol (Rhodic) Adenta series was classified as Haplic Lixisol (Abruptic, Endoclayic) Haatso series was classified as Endogleyic Lixisol (Abruptic) while Alajo series was Natric Vertisol

DISCUSSION

Variations in the topographic positions and drainage status along the catena account for the term catena as used in describing these soils. The increase in depth of the profiles along the catena could be attributed to the deposition of materials (sediments) on the lower hill slopes by water, wind and/ or gravity. The accumulation of clay in the B horizons of Nyigbenya, Toje and Adenta series suggests either mechanical migration of clay particles from the surface horizon into the B - horizons or *in situ* weathering of parent materials. The coarse fragments found throughout Nyigbenya profile and in the last horizon of Toje series were predominantly iron oxide concretions.

The moderately acidic to slightly alkaline pH range in the soils of Haatso, Toje, Adenta and Nyigbenya series could be partly due to the chemical nature of the underlying parent materials, and also partly due to leaching of soluble salts in these soils (Fiagbedzie, 1989). The lower pH values in the subsoil horizons of Nyigbenya, Toje, Adenta and Haatso series indicate an advanced degree of soil development and leaching. The soils had pH ranges that would be suitable for the production of most arable crops. The ΔpH values were negative for all the soils ($\leq$ -0.9 in Nyigbenya, Toje, Adenta and Haatso series, but $\geq$ -1.0 throughout the Alajo series) indicating that their colloids are likely to possess net negative charges as explained by Tan (1982).

The organic carbon contents of all the soils were generally low. This could be attributed to small accretion of organic materials coupled with high rate of mineralization of organic matter in the soils (Lal et al., 2004). The relatively higher amounts of organic C content in the surface horizon of Alajo series might be due to slower rate of mineralization as a result the hypoxic and anaerobic conditions prevailing in this soil (Olk et al., 2006). The dark colour of Alajo series could however not be attributable to the level of organic C but rather to the parent material (Acquaye and Oteng, 1972). The low levels of exchangeable bases and effective cation exchange capacity (ECEC) in Nyigbenya, Toje, Adenta and Haatso series could be attributed to near complete absence of weatherable primary minerals under the prevailing tropical environment coupled with leaching of basic cations. On the contrary, the higher amount of exchangeable bases (18.89 - 27.70 $cmol_c$ kg^{-1}) in Alajo series indicates that it probably contained 2:1 clay minerals.

Low levels of P-retention in all the soils studied except the C horizon of Alajo series indicate that the exchange complex of the soils could possibly have contained negligible amounts of amorphous materials (noncrystalline minerals or Al/ Fe – humus complexes). Perhaps, the very high level of $CaCO_3$ nodules in the C horizon of Alajo series could be partly responsible for the high P- retention. The correlation of P-retention and clay content is stronger for the upper 30 cm of the profiles (Figure 2a) where organic matter were higher suggesting organo-clay chelation could help in increasing P-retention in soils. However, more work, including clay mineralogy, needs to be done to elucidate its origin of the high P-retention in the C horizon of Alajo series.

Due to the low organic carbon contents of the soils, the CEC might be controlled mainly by the clay content. Apart from Haatso series which contained the highest amount of sand, the level of CEC of the soils tended to correlate positively with the amount of clay, especially in Alajo series which tended to have higher levels of clay and also showed a higher CEC (>30 $cmol_c$ kg^{-1}). Similarly high CEC values were reported by Acquaye and Oteng, (1972) for some cracking soils from the Accra Plains. The relatively higher CEC values of Alajo series also indicate that it is less weathered than the other soils. Higher CEC/clay ratio indicates less weathering of soils with weatherable primary minerals (Buol et al., 1989). Down the profiles, CEC and clay content retention did not vary much (Figure 2b) suggesting that the clay mineralogy species were possibly uniform in the soils.

This study indicates clearly that the differences in parent material, topography, drainage and age (stage of weathering) have played important roles in the genesis of these soils and consequently their morphological, physical and chemical properties. Nyigbenya series at upper slope was shallow and predominantly gravelly due to the continuous removal of finer surface soil materials by mainly water and to a lesser extent wind and gravity. It had an iron-rich parent material that had undergone

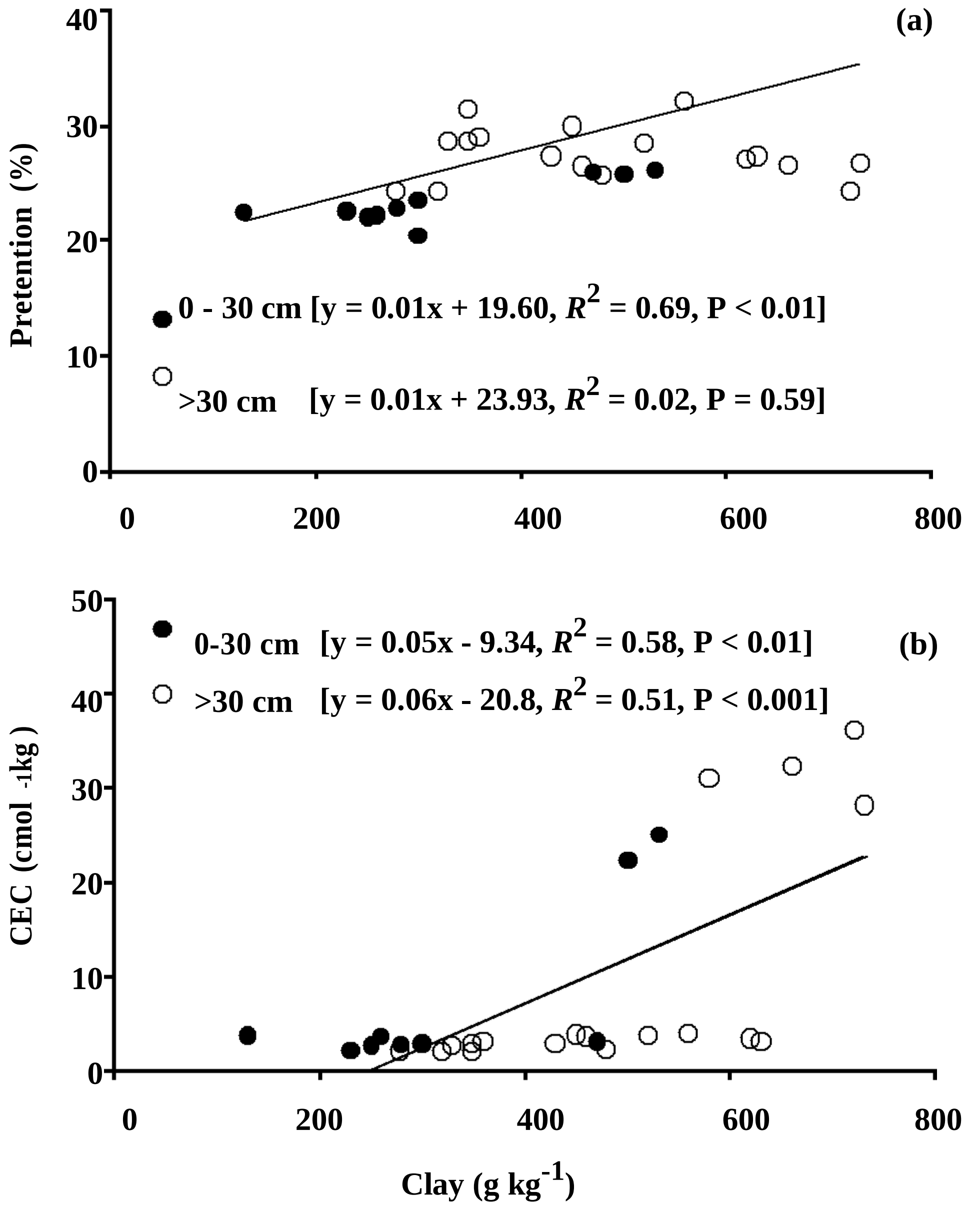

Figure 2. Relationship between (a) phosphorus (P) retention and clay content; and (b) cation exchange capacity (CEC) and clay content of the soils on the Legon hill catena.

intermittent reduction and oxidation cycles and subsequently formed ironstone concretions. Nyigbenya showed a good internal drainage condition hence the uniformly reddish colour shown throughout the profile – an indication of predominant oxidizing condition. The red sandy clay soils of Toje series at upper slope had a shiny clay-rich subsurface horizon of relatively high stable structure. The deep pedon indicates that intense weathering had taken place on a stable geomorphic surface where lessivage was running concurrently with other pedogenic processes like in situ formation of clay and weathering of primary minerals. In Adenta and Haatso series at the middle slope and foot slope positions respectively, deep and intensive weathering had probably resulted in a residual concentration of resistant primary minerals (e.g. quartz) alongside the development of sesquioxides and kaolinitic clays (judging from the CEC data). This mineralogy and the relatively low pH explain the stable microstructure (pseudo-sand) and the yellowish (goethite) soil colours could be inferred from the internal drainage conditions (moderately well drained). Pedogenic processes such as illuviation and eluviation resulted in lower clay content in the surface horizons and higher amounts in the sub-surface horizons. These subsurface horizons with distinct higher clay content than the overlying horizons might have been brought about by pedogenic processes which could have included illuvial accumulation of clay, sedimentary differentiation, pedogenetic formation of clay in the subsoil, destruction of clay in the surface horizon and selective surface erosion of clay.

Alajo series had sediments that contained a high proportion of shrinking-swelling clays that might have been produced by neoformation from rock weathering. Alternate swelling and shrinking of expanding clays resulted in deep cracks in the dry season, and formation of slickensides and wedge-shaped structural elements in the sub-surface horizons. The distribution of carbonates in the sub-surface horizons indicates translocation up and down the horizons (Phillips and Lorz, 2008). Calcification was also evident in the pedon.

All soils studied had the largest organic matter concentration in the surface horizons, decreasing uniformly with depth in the profile. The differences in the amount of organic matter in the soils were probably due to the differences in biomass production and litter mineralisation rate, both of which are affected by soil moisture content. All the soils were deep; with Haatso and Alajo series showing the deepest profiles. They all had a high sand content except for Alajo series. Hence, their texture ranged from sandy clay loam to sandy clay except for Alajo series which was clay throughout the entire profile. All the soils were also slightly acidic except for Alajo series which was slightly alkaline. The slightly alkaline pH of Alajo series could be attributed to the high amounts of extractable base, especially Ca, and the presence of $CaCO_3$ nodules. The large difference in CEC between Nyigbenya and Toje series, at the upperslope position, and that of Alajo series at the bottom slope was due to the higher clay and organic matter contents of Alajo series. The relatively large clay content of Alajo series could be due to *in situ* formation in the nature of its parent material and/or sedimentary differention.

All soils on the catena contained mainly quartz (SiO_2) in the fine earth fractions due to their quartzite schist or sandstone parent materials. Alajo series, however, contained relatively smaller amountas of SiO_2, a refletion of the fact that it had different parent material. Sandstone contains small amounts of other primary minerals, particularly ferromagnesian. Quartz is a highly resistant mineral in soils (Cornu et al. 1999; Stiles et al., 2003)

The soils tended to contain moderate amounts of Al and Fe oxides. The C-horizon of Alajo series contained exceptionally higher amounts of Ca-oxide and relatively higher levels of exchangeable Ca which are further indications that this soil had a different parent material. On the other hand, the elemental compositions of the soils located at upper slope showed very little variations in their chemical compositions which could be due to the fact they fact similar parent materials.

The small variations were probably due to different degrees of weathering of the same parent rock. Expectedly, all the other soils located at higher hillslope positions were classified as Alfisols whereas Alajo series was a Vertisol. Under the World Reference Base, Nyigbenya and Toje series were Nitisols and Adenta and Haatso series were Lixisols. On the other hand, Alajo series was classified again as a Vertisol. Thus, the elemental compositions, the hillslope positions and parent materials of the soils influenced their classifications.

Conflict of Interest

The authors have not declared any conflict of interest.

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