Variability in the properties of soils on two toposequences in northern Ghana

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SUMMARY

The variability in the properties of five Lixisols — Tingoli Tolon and Kumayili series on toposequence 1; Kpelesawgu and Changnalili series on toposequence 2 — was studied to ascertain the natural differences in the soils. The Tingoli and Tolon series accumulate more *in situ* formed nodules with greater bulk density. Moisture storage is greater in the toposequence 2 soils because of poor internal drainage. Kaolinite is the dominant clay mineral in the toposequence 1 soils. Illite is dominant in the toposequence 2 soils, especially in the Changnalili series, serving as K reserve source. The nodules have high concentrations of haematite and goethite, implying greater maturity. Soils on toposequence 1 are more weathered with more pronounced desilication. Organic carbon accumulation and effective CEC in the toposequence 2 soils are relatively greater because of poor internal drainage, which hinders organic matter decomposition. The toposequence 1 soils show reddish colouration because of better internal drainage.

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RÉSUMÉ

NARTEY, E., DOWUONA, G. N., AHENKORAH, Y., MERMUT, A. R. & TIESSEN, H.: *L'inconstance dans les propriétés de cinq séries Lixisols - Tingoli, Tolon et Kumayili sur la toposéquence (1) Kpelesawgu et Changnalili étaient étudiés pour s'informer les differences naturelles dans les terres.* Les séries Tingoli et Tolon s'accumulent sur place, et ils ont formé des nodules avec compacité en gros quantité. L'accumulation d'humidité est grande en toposéquence (2) à cause d'une systéme d'écoulement des eaux médiocre. La tene-végétale dominante dans toposéquence (1) est kaolinite. Illite est dominante dans toposéquence (2) particulièrement aux séries Changnalili qui serve comme source réserve de K. Les nodules ont une large concentration de haematite et goethite indiquant une haute maturité. Les terres sur toposéquence (1) sont plus désagrégés avec une desenvasement prononcée. L'accumulation de carbon organique et le CEC qui est efficace dans la toposéquence (2) sont relativement plus grands à cause d'une systéme d'écoulement des eaux médiocre qui empêche la décomposition des matières organiques. La terre toposéquence (1) montre une coloration rougeâtre à cause d'une meilleure systéme d'écoulement des eaux.

Introduction

A good soil management strategy requires a reliable estimate of soil properties for efficient prediction and control of crop yield. The application of soil properties to the efficient prediction of yield is beset by many difficulties including the variability of soil properties. Large differences exist among soils which are in close proximity.

Various factors may contribute to soil variability. These may include pedogenic processes (Wilding & Drees, 1978; van Wambeke & Dudal, 1978), topography (Buol, Hole & McCracken, 1989) and soil-borne pests (Germani & Reversat, 1982). Topographical effects on soil variability are reflected in the term "catena". Parent material as well as hydrology varies from one part of a landscape to another, giving rise to a topographic series (landscape) of soils (Russel, 1967). Soils on hill slopes differ from those on summits because of percolating water which tends to move laterally across a profile instead of vertically; particularly, if there is any layer of low permeability in the soil (Russel, 1967).

Variability occurs in the morphological, physi-

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cal and biochemical properties of soils formed from the same parent material on a toposequence. Even for a simple topography, the extent of variability in soil properties may be appreciable (Uehera, Trangmer & Yost, 1985). In many cases, however, the pattern of variability of soil properties is not apparent. Generally, owing to the variability in properties, soils tend to be heterogeneous.

The majority of soils in northern Ghana are made up of groundwater laterites (Lixisols) (Ahn, 1970) which, with the notable exception of some relatively deep variants, are highly concretionary. These ferruginous concretions, nodules and ferricretes represent a more extreme case of heterogeneity within the soils. They do not only affect root penetration and water movement, but also have substantially higher iron and aluminium oxide contents than the surrounding soil (Nahon *et al.*, 1977; Tiessen, Frossard & Nyamekye, 1987). These concretions, therefore, impose a severe limitation on the use and management of the soils in northern Ghana.

The problem of variability in the nature and properties of soils is more acute in tropical landscapes (Bonsu & Laryea, 1989). However, there is scanty information on variations in properties of soils on adjacent landscapes in the savanna zones of Ghana. For good management and use of soils for sustainable agricultural production, this gap in knowledge should be filled.

This study, therefore, examines the variability in the properties of some widely cultivated ferruginous soils on two different major landscapes in northern Ghana.

Materials and methods

Site characteristics

The study site is at 6° 25' N and 1° 00' W in the interior savanna zone of Ghana near the Savanna Agricultural Research Institute, Nyankpala. This zone is semi-arid with total annual rainfall of 1000 mm and mean daily temperature of 28 °C. The vegetation is dominantly grassland-woodland. The local geology comprises clay-shale with lenses of sandstone, siltstone and mudstone (Adu, 1957) which belong to the Lower Voltaian formations.

The Tingoli and Tolon series (Plinthic Lixisols according to FAO/UNESCO, 1990; Plinthustalfs according to Soil Survey Staff, 1994), and Kumayili series (Ferric Lixisol) (Haplustalf) are well-drained soils which occupy the summit, upper slope and midslope positions, respectively, on a toposequence. These three soils occur at approximately 186, 178 and 171 m above sea level, respectively. The Tingoli and Tolon series have developed from ironstone gravel and ferruginized brash and contain various amounts of ironstone nodules. The Kumayili series has, however, developed from local alluvium/hill wash and has very few amounts of ironstone concretions. The low-lying soils on the other toposequence (Kpelesawgu and Changnalili series) are all Plinthic Lixisols (Plinthaqualfs) which occur at 170 and 167 m above sea level, respectively. The Kpelesawgu series is formed from local alluvium and is imperfectly drained while the Changnalili series, which is shallow and poorly drained, has developed from massive ironstone deepened by soil wash.

Soil sampling

For all the profiles, undisturbed (for bulk density) and disturbed soil samples were collected from each genetic horizon for laboratory analyses. The disturbed soils were air-dried and passed through a 2-mm sieve to obtain the fine earth fraction. The nodules (less than 2 mm in diameter) in the samples were hand-picked after passing samples through an 0.5-mm sieve, washed, oven-dried at 105 °C and used for analysis. A portion of the fine earth from each horizon was fractionated into sand, silt and clay (Jackson, 1974) and used for mineralogical and chemical analyses.

Laboratory analyses

Particle size distribution was determined by the conventional hydrometer method (Day, 1965) while bulk density of the undisturbed samples was estimated by the core method (Blake, 1965). Moisture content of the soils was measured at 1/3 bar (33 kPa) and 15 bar (1500 kPa) by the pressure plate extraction method (Eilers, 1978). The difference in the moisture content at 33 and 1500 kPa was calculated as available moisture content (AMC) of the soil. Random-powdered samples of sand, silt and nodules and parallel-oriented clays were analyzed for their mineralogical composition. Treatment of the clay samples included K-saturation and heating at 25, 350 and 550 °C (Jackson, 1974).

The pH in both the fine earth and nodules was determined in 1M KCl and H_2O at a 1:2 soil: liquid ratio. Organic carbon was determined on both fine earth and ground nodules using a Lec Carbon determinator. Exchangeable cations were extracted from both the fine earth and nodules with unbuffered 1M NH_4Cl. Calcium and Mg in the extracts were measured by atomic absorption spectrometry, and K and Na by flame emission photometry. Exchangeable acidity was measured by the 1M KCl extraction method (McClean, 1965). Effective CEC was calculated by cation summation. Iron concentrations in the fine earth were determined by the Dithionite-citrate-bicarbonate (DCB) extraction method (Mehra & Jackson, 1960) and also by the ammonium oxalate extraction method (Mckeague & Day, 1966). Total elemental analysis was done on the fine earth, clay fraction and nodules using the closed vessel microwave technique (CEM, 1992).

Results and discussion

Physical properties

Table 1 shows the results of the analysis on the physical properties of the soils on the two toposequences. Nodules occur throughout the profiles in the upland Tingoli and Tolon series with a general increase in nodule content with depth. This increase is related to variations in the total Fe concentration in the fine earth. This is demonstrated by the significant correlation between the nodule content and total Fe concentration in the soils (r=0.78* for the Tingoli series and r=0.89* for the Tolon series). However, in the Kumayili series on toposequence 1 and the two low-lying soils on toposequence 2, nodule accumulation is low and largely confined to the subsoil because of transported material from upslope.

The two upland soils on toposequence 1 have the greatest accumulation of nodules, which are likely to have been formed *in situ*. For plinthite and nodule formation, a continuous supply of iron which usually comes from the weathering zone is necessary (Gallaher, Perkins & Tan, 1974). The iron-rich parent material of the Tingoli and Tolon series, therefore, serves as ready source of iron for the genesis of nodules.

The silt content is higher in the soils on toposequence 2 than soils on toposequence 1. This difference could be attributed to the relative elevation of the two toposequences and also to the influence of the different parent materials. The soils on toposequence 2 occur at a relatively lower elevation. Consequently, they may have accumulated silt transported from adjacent landscapes at higher elevations. The Kpelesawgu series has developed from local colluvium and the Changnalili series from massive ironstone deepened by soil wash (Adu, 1957). These soils may, in addition, have accumulated more silt from weathering of their respective parent materials.

The bulk density values increase, generally, with depth in all the soils and tend to be higher in the soils on toposequence 1 (Table 1). This increase in bulk density with depth is related to the variations in nodule content in the soils. In all the soils, the horizon of maximum nodule concentration also has the highest bulk density. This is supported by the significant correlation between bulk density and nodule content in the soils (r = 0.85* for the Tingoli series, r = 0.79* for the Tolon series, r = 0.92* for the Kumayili series, r = 0.99* for the Kpelesawgu series, and r = 0.84* for the Changnalili series). The higher bulk density in the toposequence 1 soils is due to the higher amount of nodules in the soils. A high percentage of nodules would lead to a lower proportion of pore space which would in turn result in high bulk density (Buol, Hole & McCracken, 1989).

TABLE 1

Some Physico-chemical Properties of the Soils

Depth (cm)	*Particle size (%)*			*BD† (Mg/m³)*	*Nodule content (%)*	*AMC‡ (mm)*	*pH (fine earth)*		*pH (nodules)*	
	Sand	*Silt*	*Clay*				H_2O	*KCl*	H_2O	*KCl*
Toposequence 1										
Tingoli series										
0-16	70.0	8.1	21.9	1.56	11.0	0.35	6.0	4.4	5.8	5.4
16-32	59.9	7.9	32.2	1.62	9.3	0.49	6.1	4.5	5.9	5.5
32-48	43.3	7.7	49.1	1.76	43.5	0.52	6.2	4.6	5.8	5.6
48-67	52.7	10.6	36.7	1.74	84.0	0.31	5.9	4.9	6.3	6.0
67-98	46.2	8.9	44.9	1.88	82.8	0.28	5.6	4.4	5.5	5.6
98+	40.6	8.8	50.6	1.51	17.5	0.73	5.9	4.3	6.1	5.4
Tolon series										
0-14	70.5	7.9	21.5	1.58	4.2	0.83	6.6	5.1	6.3	5.5
14-30	62.4	12.4	25.2	1.64	12.2	0.82	6.3	4.6	6.3	5.4
30-54	48.4	15.4	36.3	1.70	70.0	1.13	6.3	4.7	6.1	5.6
54-76	46.4	6.3	47.2	1.70	80.3	1.35	6.3	4.6	6.0	5.5
76-100	60.8	7.3	31.9	1.95	91.3	0.46	6.3	5.0	6.2	5.6
Kumayili series										
0-18	72.8	8.0	19.2	1.52	0.5	0.44	5.8	4.1	nd	nd
18-36	64.3	11.8	23.9	1.63	0.3	0.52	6.0	4.5	nd	nd
36-57	54.7	15.9	29.5	1.59	1.4	0.81	6.2	4.5	nd	nd
57-90	45.5	15.5	39.0	1.60	3.2	0.55	6.1	4.4	6.0	5.2
90+	36.9	13.8	49.3	1.80	65.8	0.91	6.3	4.9	6.1	5.4
Toposequence 2										
Kpelesawgu series										
0-15	63.4	15.0	21.5	1.48	0.7	0.92	5.7	4.0	nd	nd
15-34	51.2	18.5	30.3	1.46	0.1	0.91	5.8	4.0	nd	nd
34-64	34.6	22.6	42.9	1.52	0.6	1.06	6.0	4.0	nd	nd
64-100+	42.0	25.9	32.1	1.99	61.1	0.57	6.2	4.1	6.0	4.8
Changnalili series										
0-12	57.0	22.7	20.3	1.41	0.7	0.87	5.9	4.7	nd	nd
12-24	50.9	20.9	28.2	1.65	0.5	0.83	6.0	4.3	nd	nd
24-37	44.6	22.0	33.4	1.62	3.9	0.79	6.1	4.4	6.1	5.6
37-57	34.9	24.6	40.5	2.03	76.3	1.09	6.4	4.6	6.2	5.5
57-100+	26.4	12.6	61.0	1.69	51.5	1.22	6.0	3.6	5.7	4.3

† BD=Bulk density; nd=Not determined (due to very low amounts of nodules).
‡ AMC=Available moisture content.

Available moisture content in the toposequence 2 soils are generally higher than in the toposequence 1 soils (Table 1). The soils on toposequence 2, which occur at low-lying sites, are predisposed to poor internal drainage due to discharge of water from upland sites. Moreover, clay accumulation and the presence of illite may account for the relatively higher AMC in these soils. It is noteworthy that among all the soils, the Changnalili series shows a significant correlation between AMC and clay content ($r = 0.86^*$). The greatest accumulation of nodules in the Changnalili series are at depths with high clay content and AMC. This implies that enrichment of iron (Fe III) and subsequent formation of nodules in the subsoil are facilitated by high moisture and clay contents, which confirm the redoximorphic features of the Changnalili series (Nartey, 1994).

Total water storage which is related to toposite in the soils is as follows: Tingoli series, 44.8 mm/m; Tolon series, 67.9 mm/m; Kumayili series, 93.2 mm/m on toposequence 1; and Kpelesawgu series, 83.4 mm/m; Changnalili series, 104.9 mm/m. The greater moisture storage in the low-lying soils makes them suitable for the cultivation of water-loving crops, especially rice, in the wet season and vegetables in the dry season with sound management practices.

Mineralogy

The mineralogical composition of the sand fraction is similar for all the soils. The x-ray diffraction pattern of the sand fraction shows quartz as the dominant mineral. Peaks referable to other minerals are absent (Table 2). In the silt fraction, quartz again constitutes the dominant mineral although there are minor quantities of feldspar and kaolinite. The two imperfectly and poorly drained soils on toposequence 2 also contain minor quantities of mica (illite) in addition to quartz and feldspar. The clay fraction of all the soils is dominated by kaolinite and quartz with illite, in addition, also being dominant in the Changnalili and the Kpelesawgu series. There are also traces of feldspars, goethite and haematite in the clay fraction of all the soils. The presence of illite in the two soils on toposequence 2 may be due to poor internal drainage which may suppress its transformation to other secondary minerals.

The dominance of kaolinite and illite in the clay fraction, especially in the Changnalili soil on toposequence 2, is consistent with previous observations in similar soils elsewhere in the interior savanna zone of Ghana (Obeng, 1975). The formation of kaolinite in the soils might be related to the weathering of feldspars, a primary mineral in the silt fraction of the soils. Dowuona *et al*. (1994) noted a diminution in feldspar content with increase in kaolinite in similar soils of the ecological zone.

TABLE 2

Mineralogical Composition of the Soils†

Profile	*Sand*	*Silt*	*Clay*	*Nodules*
Toposequence 1				
Tingoli series				
0-16	Q	Q, f, k, i	K, Q, f, i	Q, G, H, k
16-32	Q	Q, F	K, q, i, g, h	Q, G, H, k
32-48	Q	Q, f	K, q, i, g, h	Q, G, H, k
48-67	Q	Q, k	K, q, i, g, h	Q, G, H, k
67-98	Q	Q, k, f	K, q, i, g, h	Q, K, G, H
Tolon series				
0-16	Q	Q, f, k	K,Q i,f,g,h	Q, G, H, k
14-30	Q	Q, f	K,Q,i,f,g,h	Q, G, H, k
30-54	Q	Q, f, k	K,Q,i,g,h	Q, G, H, k
54-76	Q	Q, f, k	K,Q,i,g,h	Q, G, H, k
76-100	Q	Q, f, k	K,Q,i,f,g,h	Q, G, H, k
Kumayili series				
0-18	Q	Q, f	K, Q, i, f, g	nd
18-36	Q	Q, f	K, Q, i, f, g	nd
36-57	Q	Q, f	K, Q, i, f, g	nd
57-90	Q	Q, f	K, Q, i, f, g	Q, G, H, k
90+	Q	Q, f	K, Q, i, f, g	Q, G, H, k
Toposequence 2				
Kpelesawgu series				
0-15	Q	Q, f	Q,k, i, f, g	nd
15-34	Q	Q, F, i	Q, I, f, k, g, h	nd
34-64	Q	Q, F, i	Q, I, f, k, g, h	nd
64-100+	Q	Q, f, i	Q,I,F,k,g,h	Q,G,H,k
Changnalili series				
0-12	Q	Q,f,i	K,I,Q,f, g,h	nd
12-24	Q	Q,F, i,k	K,I,Q,f, g,h	nd
24-37	Q	Q,f,i,k	K,I,Q,f,g,h	Q, G, H, k
37-57	Q	Q, f, i, k	K,I,Q,f,g,h	Q, G, H, k
57-100+	Q	Q, f, i, k	K, I, Q, f	Q, g, h, k

†Q = Quartz; K= Kaolinite; F=Feldspar; I=illite; G = Goethite; H = Haematite; Lower case = minor component. nd = Not determined (due to very low amounts of nodules).

The absence of weatherable minerals in the profiles shows that all the soils are highly weathered which agrees with the assertion by Daugherty & Arnold (1982) that soils containing plinthite or ferruginous nodules are often at an advanced stage of weathering. Moreover, the absence of illite in the silt fraction of the soils on toposequence 1 shows that they are relatively more matured than the poorly drained soils on toposequence 2. Similar observations have been made in soils of other landscapes (Stumm & Morgan, 1981). The small amounts of illite in the clay fraction of the Tingoli, Tolon and Kumayili series on toposequence 1 are supported by the low K_2O concentrations (Table 3) in these soils which also conform to the absence of illite in their sand and silt fractions. These soils are, therefore, likely to have limitations in the supply of K nutrient.

The mineralogy of the nodules shows large amounts of goethite, haematite, and quartz with moderate to minor amounts of kaolinite. The dominance of goethite and haematite in the nodules is consistent with the mineralogical composition of similar lateritic soils elsewhere (Shadfan, Dixon & Calloun, 1985) and shows the nodules to be at an advanced stage of weathering relative to their associated soil matrix. The very weak peaks referable to kaolinite coupled with the high levels of goethite and haematite may be attributed to the hardening process during nodule formation. This is because hardening of nodules has been found to be accompanied by loss of kaolinite and dominance of goethite and haematite (Alexander & Cady, 1962). In the hardening process during nodule formation close packing of goethite crystals, which is necessary for rigidity of the nodule crust, often slows down the formation of kaolinite (Schwertmann, 1988).

Elemental composition

The results of the total elemental analysis show that silicon is the dominant element in the fine earth and clay fraction of all the soils (Table 3). The high concentration of Si may generally be due to the fact that after oxygen, Si is the second most abundant element in the earth's crust, in addition to the large amounts of quartz (SiO_2) in the soils. There is a decrease in the concentration of Si in the fine earth and clay fraction and an increase in Fe and Al concentrations with depth in each profile which can be attributed to desilication (Nartey, 1994). It is likely that silica is being removed from the various profiles with the consequent accumulation of sesquioxides. The high temperatures and leaching, which occur in soils of northern Ghana, tend to favour this process. The desilication process is also more intense in the soils on toposequence 1 than in the soils on toposequence 2. This suggests that the Tingoli, Tolon and Kumayili series on toposequence 1 are more weathered than the Kpelesawgu and Changnalili series on toposequence 2.

The contents of total Ca, Mg, K and Na can be used to infer the relative abundance of primary minerals and weathering intensity in soils (Parker, 1970). The low levels of these elements in all the soils, therefore, confirm the absence of weatherable minerals in the soils. The relatively large content of K in the imperfectly and poorly drained soils on toposequence 2 is consistent with the greater accumulation of illite. This inherent property may serve as medium- and long-term K reserve source to satisfy the K nutrient requirements of growing crops.

The relatively low levels of Si, Ca, Mg and K in the nodules in each profile may also be the result of the higher degree of desilication. This confirms that the nodules reflect a more advanced stage of weathering than the rest of the soil matrix. The low concentration of Si, in particular, coupled with the relatively high Fe contents in the nodules is consistent with observations made in other ferruginous tropical soils elsewhere (Brooks, 1965; Sokoleva & Polteva, 1968).

Chemical properties

*p*H *and organic carbon.* There is no apparent difference in *p*H values of the soils and their respective associated nodules (Table 1). It is, therefore, likely that the nodules have been formed *in situ*, thus confirming the observation on the genesis of nodules in the previous section. The change in *p*H values, that is, $\Delta p\mathrm{H} = p\mathrm{H}\ \mathrm{KCl} - p\mathrm{H}\ \mathrm{H_2O}$ is negative for both the fine earth fraction and the nodules. These negative ΔpH values indicate that the soil colloids possess net negative charges (Juo, Moormann & Maduakor, 1974) and therefore exhibit cation exchange. The fine earth fraction has higher ΔpH values than the nodules suggesting better colloidal properties for the fine earth. This is supported by the higher CEC values for the fine earth (Nartey, 1994). The higher ΔpH values for the fine earth could be due to the fact that the nodules are not as reactive (more inert) as

TABLE 3

Total Elemental Composition of the Soils†

Depth (cm)	Fine earth SiO_2	Fe_2O_3	Al_2O_3	MnO	CaO	K_2O	MgO	Na_2O	Nodules SiO_2	Fe_2O_3	Al_2O_3	MnO	CaO	K_2O	MgO	Na_2O
	%															
Toposequence 1																
Tingoli series																
0-16	89-54	4.30	4.12	0.04	0.07	0.41	0.24	0.05	49.59	37.28	10.23	0.06	0.06	0.48	0.19	0.10
16-32	73.25	10.81	12.58	0.05	0.12	0.69	0.27	0.15	40.95	42.97	13.19	0.06	0.07	0.48	0.22	0.02
32-48	71.05	12.28	13.53	0.05	0.11	0.65	0.27	0.04	33.04	49.28	14.76	0.05	0.06	0.52	0.19	0.04
48-67	58.91	22.84	15.42	0.13	0.07	0.48	0.19	0.04	32.06	49.99	14.86	0.10	0.05	0.58	0.23	0.05
67-98	54.53	28.04	13.91	0.07	0.04	0.77	0.24	0.13	37.32	43.56	16.18	0.04	0.08	0.57	0.23	0.05
98+	55.85	20.71	20.11	0.06	0.11	0.68	0.30	0.06	32.44	48.56	15.91	0.04	0.07	0.66	0.26	0.05
Tolon series																
0-14	90.77	2.03	4.29	0.04	0.12	0.93	0.18	0.05	61.91	26.28	8.67	0.06	0.11	0.84	0.25	0.06
14-30	88.69	2.96	5.20	0.04	0.08	1.02	0.21	0.05	47.07	38.73	11.34	0.05	0.07	0.61	0.24	0.05
30-54	80.11	7.10	8.85	0.06	0.13	1.32	0.30	0.05	37.97	45.82	13.29	0.04	0.12	0.61	0.23	0.03
54-76	65.02	17.56	12.91	0.08	0.15	1.45	0.30	0.07	40.98	41.74	14.55	0.05	0.08	0.45	0.26	0.06
76-100	61.07	22.19	12.88	0.14	0.09	1.20	0.25	0.03	39.06	45.27	12.54	0.06	0.06	0.72	0.23	0.03
Kumayili series																
0-18	94.17	1.11	2.53	0.02	0.04	0.58	0.10	0.03	nd	nd	nd	nd	nd	nd	nd	nd
18-36	90.32	2.42	4.49	0.03	0.07	0.84	0.16	0.02	nd	nd	nd	nd	nd	nd	nd	nd
36-57	88.70	2.52	5.88	0.02	0.08	0.88	0.19	0.02	nd	nd	nd	nd	nd	nd	nd	nd
57-90	84.50	3.95	8.28	0.03	0.09	1.01	0.29	0.02	75.35	11.71	9.30	0.05	0.11	1.05	0.29	0.04
90+	72.79	10.51	12.87	0.08	0.14	1.17	0.35	0.05	44.42	41.19	11.00	0.07	0.09	1.07	0.27	0.02
Toposequence 2																
Kpelesawgu series																
0-15	91.97	1.19	3.78	0.02	0.07	1.12	0.21	0.19	nd	nd	nd	nd	nd	nd	nd	nd
15-34	88.27	1.91	5.90	0.02	0.07	1.60	0.33	0.21	nd	nd	nd	nd	nd	nd	nd	nd
34-64	87.04	2.34	6.43	0.02	0.12	1.73	0.37	0.23	nd	nd	nd	nd	nd	nd	nd	nd
64-100+	80.67	5.75	8.64	0.10	0.03	2.08	0.38	0.19	53.80	31.13	10.81	0.25	0.14	1.45	0.38	0.09
Changnalili series																
0-12	92.18	1.13	3.58	0.03	0.10	1.11	0.20	0.20	nd	nd	nd	nd	nd	nd	nd	nd
12-24	88.61	2.04	5.46	0.04	0.14	1.51	0.33	0.25	nd	nd	nd	nd	nd	nd	nd	nd
24-37	87.85	2.03	6.32	0.03	0.11	1.53	0.32	0.19	67.55	19.96	8.54	0.10	0.14	1.37	0.36	0.10
37-57	81.51	4.66	8.70	0.16	0.14	2.05	0.36	0.23	60.06	26.79	9.24	0.39	0.08	1.29	0.34	0.06
57-100+	93.48	1.54	2.47	0.05	0.07	0.72	0.17	0.08	66.74	13.63	14.33	0.21	0.20	2.18	0.69	0.14

† nd = Not determined (due to very low amounts of nodules).

the fine earth.

The organic carbon content in all the soils is generally very low (< 8 g/kg) (Table 4). This low level is due to the low biomass turnover from the predominantly grass vegetation and the destructive bush fires characteristic of the savanna environment. Consequently, the amount of organic matter returned to the soil from the vegetation is low. However, the organic carbon accumulation in the Changnalili series on toposequence 2 is relatively greater due to the poor drainage which hinders the decomposition of litter. Characteristically, the nodules have lower organic carbon content than their respective associated soils. This may be explained by the fact that at sites where nodule formation takes place, organic carbon content is generally low (Eswaran, DeConnick & Varghese, 1990).

Exchangeable bases and effective cation exchange capacity (ECEC). The exchangeable bases and acidity are generally very low; consequently, the ECEC is also very low (Table 4). The exchangeable Ca and Mg concentration is relatively high in the Changnalili series on toposequence 2 and this could be due to the relatively large amount of organic carbon in that soil. In addition, the relatively high levels of exchangeable Ca and Mg are consistent with the age of the Changnalili series. It is the least weathered of all the soils and, as a result, depletion of bases will not be pronounced compared to the other soils.

The very low ECEC in all the soils is reflected by the very low levels of total Ca, Mg, K and Na; it is also the result of the near complete removal of weatherable primary minerals under the prevailing tropical environment. The low ECEC is consistent with the dominance of the low-activity kaolinitic clays. The comparatively higher ECEC values in the Changnalili series are consistent with the large amounts of non-expandable 2:1 (illitic) clays in the soil. This further confirms the toposequence 1 soils as more weathered than their counterparts on toposequence 2.

The base saturation in the soils and their associated nodules is very high (> 60 %) and this is due to the very low exchangeable acidity. Soils in the savanna areas of West Africa have been known to exhibit very low exchangeable acidity because of their very low free aluminium contents (Ahn, 1970). The high base saturation in the soils can also be attributed to a constant replenishment of bases from annual harmattan storms which have been found to increase the CEC (Tiessen, Hauffe & Mermut, 1991).

Free iron and colour

The amount of DCB extractable Fe (Fed) in soils is used to depict the weathering intensity of soils. High amounts of Fed indicate advanced weathering (Blume & Schwertmann, 1969). This is in accord with the view that the intensity of soil development can be determined by the amounts of sesquioxides and their distribution in soil profiles (Gorbunov, Dzadevich & Tunick, 1961). On the basis of the Fed contents and distribution (Table 5), therefore, the weathering intensity of the soils on toposequence 1 follows a decreasing maturity sequence of Tingoli series > Tolon series > Kumayili series. For the soils on toposequence 2, Kpelesawgu series is more matured than the Changnalili series. Consistent with the observation in previous sections, the toposequence 1 soils are more matured than those on toposequence 2.

There is an obvious relationship between soil colour and concentration of free Fe-oxide in the soils at the different toposites of the two landscapes. There is also an increase in redness of soil colour as the active Fe ratio (Feo/Fed) decreases (Table 5). This trend is found both within and between profiles. The soils with more yellowish hues (7.5 and 10 YR) generally have higher Feo/Fed ratios than those with reddish hues (2.5 YR). Ibanga *et al.* (1983) found a similar trend in some old tropical soils of Nigeria and Brazil. The Tingoli series, which is the most well-drained and matured among the soils, has the highest redness rating followed by the Tolon and Kumayili series (toposequence 1), and then Kpelesawgu and

TABLE 4

Some Chemical Properties of the Soils†

	Fine earth								Nodules							
Depth (cm)	*OC (g/kg)*	*Ca*	*Mg*	*K*	*Na* *cmol(+)/kg*	*Ex Ac.*	*ECEC*	*BS* *%*	*O C (g/kg)*	*Ca*	*Mg*	*K* *cmol(+)/kg*	*Na*	*Ex Ac*	*ECEC*	*BS* *%*
								Toposequence 1								
								Tingoli series								
0-16	6.5	1.47	0.64	0.39	0.28	0.15	2.78	94.9	4.7	1.49	0.68	0.39	0.28	0.15	2.78	94.9
16-32	5.4	1.94	1.24	0.09	0.02	0.10	3.29	97.1	5.1	1.43	0.03	0.13	0.02	0.25	1.61	86.6
32-48	6.1	2.35	1.94	0.19	0.03	0.25	4.34	94.8	5.7	1.25	0.99	0.15	0.03	0.25	2.42	90.1
48-67	6.7	2.09	1.39	0.21	0.01	0.15	3.70	96.1	4.6	1.27	0.71	0.19	0.04	0.20	2.21	91.7
67-98	4.4	2.40	1.37	0.16	0.02	0.55	3.95	81.7	4.0	1.44	0.72	0.15	0.02	0.15	2.33	93.9
98+	2.8	2.85	1.54	0.17	0.01	0.70	4.57	86.7	4.4	1.64	0.78	0.16	0.03	0.15	2.61	94.6
								Tolon series								
0-14	6.3	2.60	0.92	0.19	0.00	0.15	3.71	96.1	7.5	2.06	0.74	0.22	0.01	0.15	3.03	95.3
14-30	3.4	2.01	0.73	0.10	0.01	0.20	2.85	93.4	4.6	1.35	0.56	0.17	0.01	0.20	2.14	91.3
30-54	6.4	2.73	1.18	0.19	0.01	0.20	4.11	95.4	5.5	1.10	0.56	0.22	0.01	0.20	1.89	90.4
54-76	7.0	3.52	1.97	0.29	0.01	0.20	5.49	96.7	3.4	1.44	0.84	0.24	0.07	0.15	2.59	94.5
76-100	4.9	2.62	1.58	0.28	0.02	020	4.49	95.7	5.0	1.37	0.91	0.29	0.19	0.20	2.76	93.2
								Kumayili series								
0-18	3.6	0.87	0.24	0.08	0.00	0.40	1.19	74.8	nd	nd	nd	nd	nd	nd	nd	nd
18-36	3.3	1.44	0.39	0.07	0.00	0.20	1.90	90.5	nd	nd	nd	nd	nd	nd	nd	nd
36-57	3.4	1.68	0.68	0.08	0.01	0.20	2.45	92.5	nd	nd	nd	nd	nd	nd	nd	nd
57-90	3.6	2.18	1.37	0.11	0.02	0.25	3.68	93.6	4.2	2.14	1.42	0.17	0.19	0.15	3.92	96.3
90+	2.9	3.36	2.67	0.19	0.07	0.20	6.29	96.9	4.2	1.15	0.92	0.20	0.11	0.15	2.38	94.1
								Toposequence 2								
								Kpelesawgu series								
0-15	4.3	0.93	0.64	0.13	0.00	0.45	1.70	79.1	nd	nd	nd	nd	nd	nd	nd	nd
15-34	4.5	1.23	0.81	0.09	0.04	1.00	2.17	68.5	nd	nd	nd	nd	nd	nd	nd	nd
34-64	5.2	1.01	1.02	0.14	0.09	1.30	2.26	63.5	nd	nd	nd	nd	nd	nd	nd	nd
64-100+	4.0	1.16	1.58	0.18	0.09	1.05	3.01	14.1	3.7	0.89	1.23	0.28	0.12	0.30	2.52	89.4
								Changnalili series								
0-12	6.4	1.98	1.14	0.26	0.00	0.10	3.38	97.1	nd	nd	nd	nd	nd	nd	nd	nd
12-24	6.2	2.78	1.31	0.09	0.02	0.35	4.20	92.3	nd	nd	nd	nd	nd	nd	nd	nd
24-37	6.1	2.98	1.51	0.12	0.02	0.25	4.63	94.9	4.47	2.41	1.26	0.20	0.06	0.15	3.93	96.3
37-57	6.8	3.70	2.22	0.29	0.02	0.20	6.23	96.9	3.54	1.84	1.22	0.27	0.04	0.20	3.37	94.4
57-100+	5.3	3.99	6.87	0.31	0.28	2.00	13.45	87.1	2.39	4.70	5.46	0.39	0.36	0.60	10.90	94.7

† OC= Organic carbon; Ex Ac.=Exchange acidity; ECEC= Effective cation exchange capacity; BS = Base saturation; nd=Not determined (due to very low amounts of nodules).

TABLE 5

DCB Extractable Fe, Active Iron Ratios and Soil Colour

Depth (cm)	*Fed (g/kg)*	*Feo/Fed (fine earth)*	*Colour (dry)*
		Toposequence 1	
		Tingoli series	
0-16	21.3	0.03	5YR 4/6
16-32	53.1	0.02	2.5YR 3/6
32-48	55.1	0.02	2.5YR 3/6
48-67	55.0	0.02	2.5YR 4/6
67-98	95.2	0.01	2.5YR 3/6
98+	87.8	0.01	2.5YR 3/6
		Tolon series	
0-14	10.5	0.04	5YR 5/6
14-30	12.5	0.03	5YR 5/6
30-54	29.4	0.02	7.5YR 5/4
54-76	65.3	0.02	5YR 5/4
76-100	74.6	0.01	5YR 5/6
		Kumayili series	
0-18	5.8	0.07	5YR 5/6
18-36	8.2	0.06	5YR 5/6
36-57	11.3	0.05	7.5YR 6/6
57-90	17.8	0.03	7.5YR 5/6
90+	52.5	0.01	7.5YR 5/6
		Toposequence 2	
		Kpelesawgu series	
0-15	5.4	0.21	7.5YR 7/4
15-34	7.5	0.12	7.5YR 7/4
34-64	8.5	0.11	7.5YR 7/4
64-100+	24.7	0.05	7.5YR 7/4
		Changnalili series	
0-12	5.3	0.18	10YR 6/4
12-24	6.0	0.18	7.5YR 6/2
24-37	7.4	0.16	7.5YR 6/2
37-57	14.4	0.10	7.5YR 6/2
57-100+	7.6	0.07	7.5YR 6/4

Changnalili series (toposequence 2).

Red colouration in soils is due to the influence of Fe^{3+} and free iron oxides. On the contrary, Fe^{2+} contributes to yellowish colouration (Buol, Hole & McCracken, 1989). Consequently, reddish colouration of the well-drained soils on toposequence 1 can be attributed to greater Fe^{3+} and free iron oxide contents. The toposequence 2 soils have hues on the yellow side because of their poor internal drainage which promotes the formation of Fe^{2+} and less free iron oxides.

Conclusion

The well-drained upland Plinthic Lixisols (Tingoli and Tolon series) on toposequence 1 have accumulated more nodules than their respective counterparts on toposequence 2 because of the prevailing favourable environmental conditions within the landscape. These nodules have influenced the bulk density which is higher in the soils on toposequence 1 than those on toposequence 2. Moisture storage in the soils on toposequence 2 is higher and is influenced by their relatively lower elevations.

The soils on toposequence 1 lack weatherable minerals due to the intense weathering, and as a result kaolinite is the dominant clay mineral. The poor internal drainage of the soils on toposequence 2 has preserved illite which, together with kaolinite, constitutes the major clay minerals in these soils. Haematite and goethite are the major minerals in the nodules; the nodules are therefore at a relatively more advanced stage of weathering. Silicon is the dominant element in the soils with very low total Ca, Mg, K and Na contents, suggesting a general maturity of the soils studied. In each profile, the *p*H values and CEC of the soils and their respective associated nodules are similar, indicating that all the nodules may have formed *in situ*.

It is apparent from the study that distinct differences exist between the soils in the two toposequences, particularly in the Fed contents. The sequence of Fed distribution follows a decreasing order of Tingoli series > Tolon series > Kumayili series on toposequence 1, and Kpelesawgu series > Changnalili series on toposequence 2. Iron oxide crystallinity, which relates to stage of maturity, is also higher in the soils on toposequence 1 than in those on toposequence 2. There is also a drainage-related increase in redness of colour which also corresponds to decreases in the active Fe ratios. The two groups of soils, therefore, need different management practices to ensure their sustainable utilization.

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