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HYDRAULIC PROPERTIES IN RELATION TO MORPHOLOGY OF A TROPICAL SOIL WITH HARDENED PLINTHITE UNDER THREE LAND USE TYPES.

[PROPIEDADES HIDRAULICAS EN RELACIÓN A LA MORFOLOGÍA DE UN SUELO TROPICAL CON PLINTITA ENDURECIDA Y BAJO TRES TIPOS DE MANEJO]

O.J. Idowu[1*] and G.A. Oluwatosin[2]

[1]Department of Crop & Soil Sciences, Cornell University, Ithaca NY 14853.
E-mail: oji2@cornell.edu
[2]Institute of Agricultural Research and Training, Obafemi Awolowo University
P.M.B. 5029 Moor Plantation, Ibadan, Nigeria
[*]Corresponding Author

SUMMARY

Hydraulic and morphological properties of soils with hardened subsurface plinthite were investigated under three adjacent land use types, which were coconut plantation, continuous arable (maize-soybean rotation) and a pastureland. Apart from the description of soil morphology, measurements carried out included laboratory saturated hydraulic conductivity on the undisturbed soil core samples collected from the field, conductivity of the pan material and field infiltration capacity. The hardened plinthite layer under these adjacent land use types varied with thickness and structural characteristics. Hardened plinthite found under the coconut plantation was a petro-plinthite and spongy in nature, while those found under the arable and pasture management systems were petroferric contact. While the hardened plinthite under the arable land was very compact with unbroken sesquioxide sheet, the pan under the pasture was vesicular and less compact. The thickness of the pan was 0.56m under the coconut, 0.68m under the arable and 0.18m under the pasture land use types. The mean saturated conductivity of the soil layers above the pan did not differ significantly under the three land use types. While the petro-plinthite layer found in the coconut plantation allowed free water movement, the petroferric contact found in the arable and pasture management systems did not. The saturated hydraulic conductivity of the hardened plinthite was 2.15 x 10^{-6} for the arable land and 2.49 x 10^{-6} m s^{-1} for the pasture land. Coconut plantation had significantly higher final infiltration rate (1.11 x 10^{-4} m s^{-1}) than the continuous arable and pasture land use types. Generally, the arable land had lower soil quality compared to the pasture land and showed field evidences of degradation by soil erosion.

Keywords: Hardended plinthite, hydraulic conductivity, land use, infiltration.

RESUMEN

Las propiedades hidraúlicas y morfológicas de suelos con plintita endurecida fueron investigadas en tres tipos de uso suelo adyacentes, plantación de cocotero, labranza continua (rotación maíz-soya) y pradera. Además de la descripción de la morfología, las mediciones incluyeron conductividad hidráulica saturada de muestras no modificadas extraídas en campo, conductividad del material y capacidad de infiltración de campo. Las observaciones morfológicas mostraron que las capas de suelo en los diversos tipos de uso variaron en cuanto a su grosor y estructura. La plintita endurecida encontrada en la plantación de cocotero fue petroplintita y de naturaleza esponjosa, mientras que la encontrada en la tierra de cultivo y la pradera era una petroferrica. Mientras que la plintita en la tierra de cultivo era muy compacta y con una capa no alterada de sesquióxido, el horizonte C de la pradera era vesicular y menos compacto. El grosor del horizonte C era de 0.56 m debajo del cocal, 0.68 m en la tierra de cultivo y 0.18m en la pradera. La conductividad saturada no difirió en los tres tipos de uso del suelo. La petroplintita localizada en la plantación de cocotero permitió el libre movimiento del agua, mientras que el suelo petroferrico de la tierra de cultivo y pradera la restringió. La conductividad hidraúlica saturada de la plintita fue de 2.15 x 10^{-6} en la tierra de cultivo y 2.49 x 10^{-6} m s^{-1} en la pradera. La plantación de cototero tuvo una mayor tasa de filtración (1.11 x 10^{-4} m s^{-1}) en comparación con la tierra de cultivo y las praderas. En general, la tierra de cultivo era un suelo de menor calidad comparado con la pradera y mostraba evidencia de degradación y erosión.

Palabras clave: Plintita endurecida, conductivdad hidráulica, uso del suelo, infiltración.

INTRODUCTION

The occurrence of plinthite and associated forms within the soil layer can significantly impact the productivity of land, limiting its usefulness for crop production. Plinthite, which is a pedogenic pan within the soil, has been defined as a "highly weathered material, rich in secondary forms of iron, aluminium or both; poor in humus; depleted of bases and combined silica; with or without non-diagnostic substances such as quartz, limited amounts of weatherable primary minerals or silicate clays; and either hard or subject to hardening upon exposure to alternating wetting and drying" (Sivarajasingham *et al*., 1962).

Eswaran et al. (1990) described the two distinct forms of hardened plinthite layer commonly found on the field which are “petroplinthite” and “petroferric contact”. When plinthite dries out, it may harden irreversibly to either petroplinthite or petroferric contact (Eswaran et al 1990; Soil Survey Staff. 2006). Active petroplinthite formations occur in areas where the groundwater table is high and rich in the supply of iron (Eswaran et al. (1990). According to Eswaran et al. (1990), petroplinthite is nodular or pisolithic material with a hard crust of closely crystallized goethite and/or hematite, enclosing iron enriched soil material; sometimes adjoining nodules may be joined or cemented together or the whole petroplinthic material may be dendritic in form. The petroplinthic materials often occur in the soil as loose or slightly cemented gravel. Though petroplinthite may constitute a zone of mechanical impedance within the soil, it does not necessarily restrict water movement in the soil. Petroferric contact on the other hand is a continuous layer of indurated material with iron playing an important role in the cementation process (Eswaran et al 1990; Soil Survey Staff. 2006). The occurrence of the petroferric contact within the soil constitute a significant management challenge to land users since they are dense, hard and severely restrict the movement of water. Petroferric contact is formed through the re-cementation of plinthite or petroplinthite by a rapid flux of iron. From micro-morphological observations, the cement of petroferric contact is laminated, indicating that the exposure of the materials to iron flux was short and cyclical with a very high amount of iron playing a dominant role in the enrichment and the cementation process (Eswaran et al. 1990).

Severe management problems that have been observed in soils with hardened plinthite include mechanical impedance (Adeoye & Mohammed-Saleem, 1990), intense nutrient leaching (Hubbard *et al*., 1991; Hubbard & Sheridan, 1983), acidity of the hardened layer (Perkins & Kaihulla, 1981; Ahmed & Jones, 1969) and restriction of downward movement of water (Guthrie & Hajek, 1979, Daniels *et al*., 1978 Blume et al., 1987; Bosch et al., 1994)

Guthrie & Hajek (1979) and Daniels *et al*. (1978) have observed perching of water above plinthic horizon during periods of high rainfall. In addition, Blume *et al*. (1987) in a study using bromide as a tracer observed that the subsurface flow downslope just above the plinthic pan was very rapid. Carlan *et al*. (1985) in studying the flow of water through a plinthic material noted that the plinthite layer was very dense, with a bulk density of 1.71 Mg m^{-3} and with very low water conductivity. This low conductivity of a plinthic pan layer may become very critical when it comes closer to the soil surface.

Ezeaku and Anikwe (2006) studied the water and solute movement in water restricting horizons in two landscapes in south-eastern Nigeria using a blue dye stain. They observed a reduced amount of water mobility in the horizon containing plinthite.

Despite the knowledge of the vulnerability of soils with hardened plinthite to degradation, information on long-term soil and crop management effects on hydraulic characteristics of soils underlain by plinthitic pan is scanty. Soils with plinthite and associated forms are found more extensively in the humid tropics characterized by high soil erodibility and rainfall erosivity. Improper soil management in many cases has led to accelerated erosion of the soil above the pan (Eswaran *et al*., 1990). The presence of hardened form of plinthite severely limits the soil quality, reducing the overall volume of soil available for plant and nutrient uptake (Yaro et al. 2006). As part of the efforts to address management concerns in tropical plinthic soil, this study therefore sets out with the goal to investigate the hydraulic characteristics of a soil with hardened plinthic layer under three adjacent land use types, relating the observed hydraulic differences to soil morphology. For the purpose of this study, we have used the term “hardened plinthite” to describe both petro-plinthite and petroferric contact that were observed on the field.

MATERIAL AND METHODS

The study was carried at the Institute of Agricultural Research and Training Moor Plantation Ibadan. This area is longitude 7° 35’N and latitudes 3 83’E and is 195 masl. Ibadan is characterised by humid tropical climate with mean annual rainfall of about 1500 mm.

The soil of the area belongs to Gambari series (Smyth & Montgomery, 1962) and is classified as Typic Kanhapludalfs according to US soil taxonomy (Soil Survey Staff. 2006).

Table 1: Morphological characteristics of the pedons.

Horizon Design	Depth (cm)	Colour	Boundary[1]	Texture[2]	Structure[3]	Consistence[4]	Quartz stone[5]	Concretions[6]	Roots[7] Concentration	Mottles[8]	Drainage[9]
Coconut											
Ap	0-17	7.5YR3/3	c,s	LS	1,f,cr	fr	A	f(Fe-Mn)	Fi Ab	A	WD
Bc1	17-41	7.5YR4/4	c,s	LS	1,f,cr	fr	m(qrt)	m(Fe-Mn)	Fi,wd,m	A	WD
Bc2	41-69	7.5YR5/6	g,i	SL	1,m,sab	hd,fr,st	m(qtz)	up(P) broken	Fi,wd,m	A	WD
Btc	69-97	10YR6/8	c,w	SCL	2,m,c,sab	hd,fm,mst	f(qtz)	lp(P) broken	Fi,wd,m	A	WD
Bt	97-180	10YR7/3	-	SC	2,m,c,sab	s,fm,mst	A	A	Fi,wd,f	7.5YR5/8	ID
Continuous cultivation											
Ap	0-18	7.5YR3/3	c,s	LS	1,f,cr	vfr	f(qtz)	f(Fe-Mn)	Fi Ab	A	WD
Bc1	18-30	7.5YR4/3	c,i	LS	1,f,cr	fr	m(qtz)	m(Fe-Mn)	Fi,m	A	WD
Bc2	30-66	7.5YR5/6	g,i	SL	1,m,sab	hd,fr,st	m(qtz)	up(P)compact	Fi,f	A	ID
Btc	66-98	10YR6/8	c,w	SCL	2,m,c,sab	hd,fm,mst	m(qtz)	lp(P)compact	A	A	ID
Bt	98-130	10YR7/3	-	SC	2,m,c,sab	s,fm,mst	A	A	A	7.5YR5/8	ID
Pasture											
A	0-18	7.5YR3/2	c,s	LS	1,f,cr	vfr	A	A	Fi Ab	A	WD
AB	18-35	7.5YR3/3	c,s	LS	1,f,cr	vfr	A	A	Fi,Ab	A	WD
Bc1	35-72	7.5YR4/3	c,i	LS	1,m,sab	fr	A	f(Fe-Mn)	Fi,f	A	WD
Bc2	72-107	7.5YR5/6	g,i	SL	2,f,sab	fr,st	f(qtz)	m(Fe-Mn)		A	WD
Btc	107-125	10YR6/8	c,w	SCL	2,m,c,sab	hd,fm,st	f(qtz)	P(vesicular)	A	7.5YR5/8	ID
Bt	125-170	10YR7/3	-	SC	2,m,c,sab	s,fm,st	A	A	A	7.5YR5/8	ID

Key to the notation

1. c,w=clear wavy; gi=gradual irregular; cs=clear smooth
2. LS=Loamy sand; SL=Sandy loam; SCL=Sandy clay loam; SC=Sandy clay
3. 1=weak; 2=medium; f=fine; m=medium; C=Coarse; Cr=Crumb; sab=subangular blocky
4. S=soft; vfr=very friable; fr=friable; fm=firm; mst=moderately sticky; st=slightly sticky; hd=hard
5. A=absent; m(qtz)=many quartz stone; f(qtz)=few quartz stone
6. A=absent; f(Fe-Mn)=few iron-manganese nodules; m(Fe-Mn)=many; P=iron pan; up=upper limit, lp=lower limit
7. A=absent; Fi=fibrous; wd=woody; m=many; f=few
8. A=absent
9. WD=well drained; ID=imperfectly drained

An area with three adjacent but different land use types occurring within the same mapping unit was used for this study. The three major land use types were coconut plantation, continuous arable and pasture land. The mean slope of these fields was 8%. The coconut plantation had been in place for 35 years with cassava (*Manihot esculenta*) being cultivated under the coconut canopies. The continuous arable land had been conventionally tilled (disk plowing followed by disk harrowing) for the past 20 years with maize-soybean rotation. The pasture land had been in place for 35 years sown to a mixture of *Cynodon dactylon* and *Centrosema pubescens*.

Representative soil profiles were dug in each of the different land use type and morphologically described. Morphological descriptions of the soil profiles found in different land use types are given in Table 1, while selected physical and chemical characteristics of the surface soil are given in Table 2. Five sampling spots were located within each land use types.

Cylindrical cores of 0.05 m in diameter and 0.1 m in height were used to sample the soils incrementally by depth until the hardened plinthite layer beneath the soil was reached. For example, the arable land use system with a hardened plinthite layer located at about 0.3 m beneath the soil surface had three 0.1 m long soil cores taken from the field. These soil cores from the field were carefully trimmed and covered with a cheese cloth at the bottom end and saturated in a water bath for about 24 hours. Hydraulic conductivity was then determined on the core samples after saturation using a constant head permeameter according to the method described by Klute and Dirksen (1986). After the conductivity measurement, the samples were broken up to determine the gravel concentration within the soil cores. The mean conductivity of the soil for a given sample location was taken to be an average of the conductivity measurements of all layers incrementally sampled by the core. In addition, the pan material beneath each sampling location was subjected to conductivity test after saturation. At each sampled location, the depth of the soil to the pan was noted.

Field infiltration was carried out close to each sampled spot using double ring infiltrometers with 0.3 m inner diameter and 0.6 m outer diameter. The rings were carefully driven into the soil with a sledgehammer and a driving plate centered over the rings, to a depth of 0.15 m. A device consisting of a float and measuring rod was placed inside the inner ring to monitor the downward entry of water. For the first 1800 s, water levels were taken at 60 s interval after ponding of water in the infiltrometer. This interval was increased to 180 s up to a period of 3600 s. Beyond 3600 s, readings were taken every 600 s until a steady state was attained, which corresponded to a total time period of about 10,800 s.

One-way ANOVA was performed on the measured properties and the means were separated using Scheffe's method after a significant F-ratio. Correlations between some of the measured variables were computed to study the significance of linear relationships.

RESULTS

The types of hardened plinthite materials found under the different land use types varied. Under the coconut, the hardened layer was a petro-plinthite, while under the pasture and arable land management, it was a petroferric contact. There was no significant difference in the mean saturated conductivity of the soil above the pan under the three different land use types (Table 3).

However the mean conductivity of the soil under the coconut plantation was highest at 3.5 x 10^{-5} (Table 3). Although the mean conductivity of the entire profile was not significant for each land use types, there were distinct contrasts in saturated conductivity when individual soil layers were considered. The highest saturated conductivity was measured at 0-0.1m for the arable land, 0.1-0.2m for the pasture land and 0.4-0.5m for the coconut plantation (Figure 1).

Table 2. Some soil physical and chemical properties of the surface soil (0-0.15m)

Soil properties (0- 0.15 m)	Pasture land*	Arable land	Coconut Land
Sand (20-2000 μm) (g kg^{-1})	768	880	838
Silt (2-20 μm) (g kg^{-1})	150	71	100
Clay (<2 μm) (g kg^{-1})	82	49	62
Bulk Density (Mg m^{-3})	1.22	1.65	1.31
Organic Carbon (g kg^{-1})	15.5	10.6	24.3
pH in water	5.2	5.8	6.2

* permanent grass/legume

Table 3. ANOVA results and mean separation for measured variables under the three land use types.

Measurements↓	Coconut land	Arable land	Pasture land	F-Ratio	LS*
Saturated hydraulic conductivity of soil above pan ($m\ s^{-1}$)	3.54 x 10^{-5}	3.01 x 10^{-5}	2.31 x 10^{-5}	1.5	ns
Final infiltration rate ($m\ s^{-1}$)	11.2 x 10^{-5}a	0.82 x 10^{-5}b	2.83 x 10^{-5}b	46.5	1%
Depth to pan from soil surface (m)	0.40b	0.32b	0.63a	11.5	1%
Gravel concentration (%)	20.0a	17.3a	7.9b	6.3	5%
Saturated hydraulic conductivity of the hardened plinthite materials ($m\ s^{-1}$)	no restriction	2.16 x 10^{-6}	2.49 x 10^{-6}	-	-

a,b: values followed by the same alphabets are not significantly different
*LS: level of significance

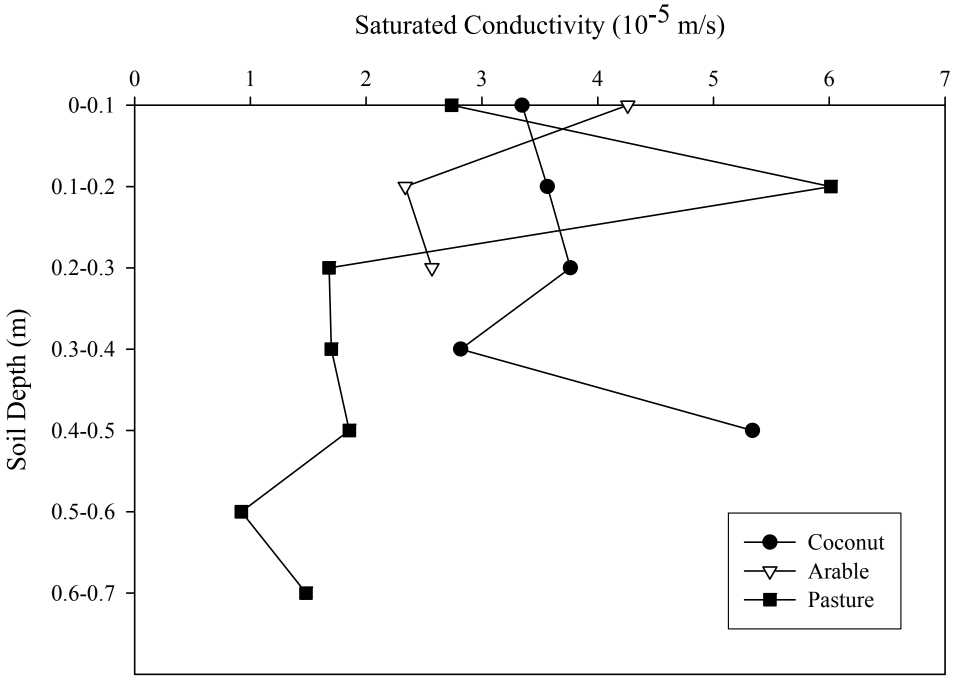

Figure 1. Saturated hydraulic conductivity with depth under different land use types

The final infiltration rate differed significantly with management systems. Infiltration rate under the coconut was significantly higher than those of the arable and pasture land. Though the pasture had higher infiltration than the arable land, the difference was not significant (Table 3). While the hardened plinthite under coconut did not restrict water flow, the pan material under the arable and pasture land use types severely restricted water movement with conductivity values of 2.16 x 10^{-6} $m\ s^{-1}$ and 2.49 x 10^{-6} $m\ s^{-1}$ respectively. The depth of soil to the hardened plinthite layer differed significantly between the management systems, with pasture land having the pan located deeper in the soil than both the arable and the coconut land (Table 3).

The gravel concentration was significantly different among the land use types. The coconut and arable land use types had significant higher gravel content compared to the pasture land (Table 3). While the gravel concentration had a significant positive correlation with mean saturated conductivity (Figure

2), it was significantly negatively correlated with depth of soil to the pan (Figure 3).

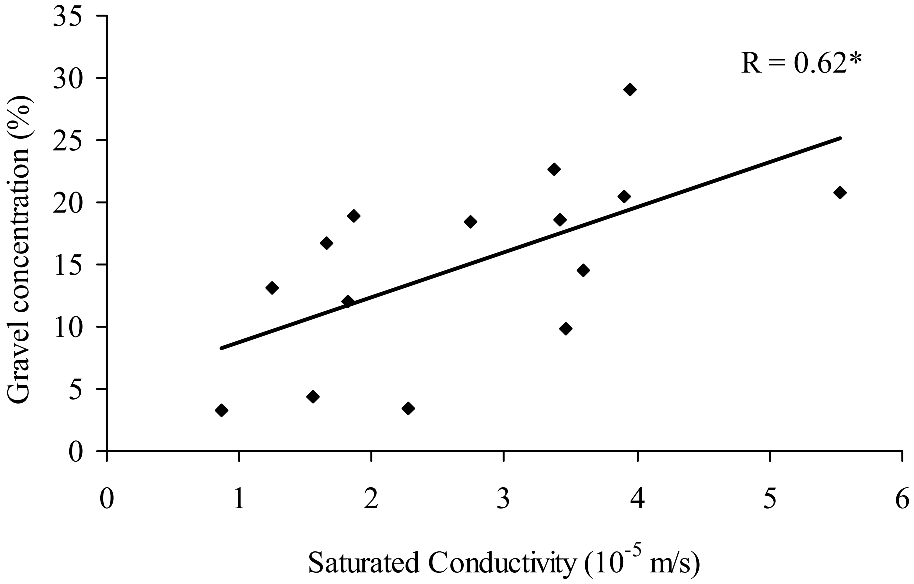

Figure 2. Relationship between gravel concentration and saturated hydraulic conductivity of the soil.

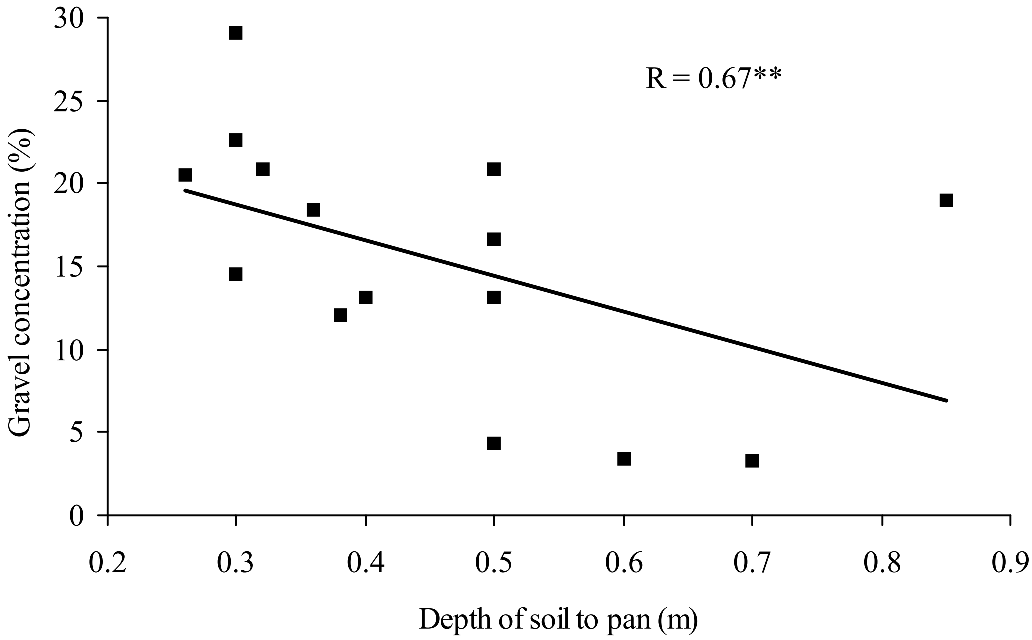

Figure 3. Relationship between gravel concentration and depth of soil to the pan.

DISCUSSION

Table 1 contains selected morphological properties of the pedons under the three land use types. The pedons belong to the same soil type. The pedons have grayish brown to brown colour, loamy sand topsoil but become sandy clay loam at the lower limit of the pan. The pan led to mottled sandy clay at depth. The profiles contain variable amounts of quartz gravel and stones and few to frequent iron-manganese nodules/concretions overlying a layer of almost impenetrable iron pan sheet. However, striking differences were observed in the depth to iron pan, the structure of the iron pan and the thickness of the pan.

The depth to upper limit of the hardened plinthite was 0.41 m under the coconut plantation, 0.30 m under continuous arable cultivation and 1.07 m under the pasture (Table 1). The variation in the depth to hardened plinthite probably reflects the effect of cropping management on the overall formation and transformations of plinthite. The rates of soil erosion varied under different management systems. From observations, the arable and coconut land seem to be experiencing high levels of soil erosion due to the bare soil surface created by land preparation for farming. Intense storms at the onset of the tropical rainy season often lead to high soil erosion rates; and this mostly coincides with the time period when soil surface is bare after land preparation. Structurally, the hard pan under the coconut is a broken structure with iron rubbles and iron stone boulders found within the pan layer. This pan has macropores probably created by dead roots through which water drains to the lower horizon and breaks more easily than those found in arable and pasture lands. This pan type fits the description of a petroplinthite as described by Eswaran et al. 1990. However, under continuous arable cultivation, the pan material was hard and formed a continuous sesquoxide sheet with compact unbroken structure. Under the pasture, the pan was vesicular in structure and without rubbles but not as compact as under continuous cultivation. The hard pans under both the arable and pasture land management systems are petroferric contact. This is a striking contrast especially that the management systems being compared occupy similar slope positions. We expected the plinthic pan formed to have been similar in these adjacent land units.

Our observations may be a reflection of the significant effects of management systems in the formation and transformations of hardened plinthite. This however needs to be further investigated. The thickness of the pan also varies with land use type. Under coconut, the thickness was 0.56 m while it was 0.68 m under arable and only 0.18 m under the pasture (Table 1). In all the land use types, the pan abruptly led downwards to very pale brownish clay with coarse reddish mottles. The color and the mottling of the clay reflect the poor drainage under the pan layer due to the rising water table at this position (middle slope) of the toposequence. The clay layer also led to the saprolite which suggest that the poor drainage was due to lateral seepage from the upper part of the toposequence and because of the nature of the clay, water could not drain properly thus creating a reduced condition favorable for mottling.

The presence of roots (fibrous and woody) within the pan as well as below the pan also reflected the nature of the pan. Both fibrous and woody roots were common with the pan under coconut (Table 1). The petroplinthite pan found under the coconut was weakly cemented, relatively porous and could be fractured more easily than those found under the arable and pasture lands. The nature of the pan under coconut therefore made it easier for roots to penetrate and explore compared to the pan found under arable and pasture lands. Few roots were found within the upper limit of the pan but virtually absent at the lower limit of the pan under arable cultivation (Table 1). Due to the nature of the roots of the grass/legumes mixture making up the pasture and the hardness of the pan, very few fibrous roots were observed within the pan layer under the pasture (Table 1).

The high saturated conductivity values observed for the soils in this study (Table 3 & Figure 1) were expected since the major textures of the soil found above the pan were either loamy sands or sandy loams (Table 1). Both of these textures are normally associated with high saturated conductivity (Soil Survey Division Staff, 1993). A breakdown according to soil layers showed that the saturated conductivity of 0-0.1m depth of the arable land was at least 1.5 times higher than the lower layers (Figure 1). The mean saturated hydraulic conductivity of 0.1-0.2m layer in the pasture land was more than twice that of the surface 0-0.1m and more than thrice the conductivity of the layers beneath it (Figure 1). For the coconut, the most conductive layer was 0.4-0.5m with saturated conductivity that was almost twice the surface 0-0.1m (Figure 1). These variations in the maximum conductive layers observed under these land use types may be related to zones of intense root activities. Generally, the soil above the pan of the three land use types does not present any significant problem to water movement.

Significant correlation between gravels and saturated hydraulic conductivity observed in this study (Figure 2) was also similar to observation made by Sauer and Logsdon, (2002), who reported the tendency for gravels to increase the saturated conductivity. The gravel encountered in the soil was mostly relics of broken iron pan materials and iron/manganese nodules/concretions.

The occurrence of these gravels was more prominent where the pan is closer to the soil surface as evident by significant negative correlation between soil depth and gravel concentration (Figure 3). The reason for this is not clear. Daniels et al., (1978), found few to many irregularly shaped hardened nodules with a maximum diameter less than 30 mm above the horizons with plinthite.

The conductivity of the pan material presented in Table 3, show that vertical movement of water will be limited by the indurated plinthic pan in both the arable and pasture soils, while the hardened plinthite under the coconut will not restrict flow. The flow rates of the hard pan encountered in the arable and pasture land compares favorably with those measured by Blume *et al*., (1987) and Carlan *et al*., (1985) which ranged from 2.78 x 10^{-7} to 4.17 x 10^{-6} m s^{-1}. From visual observations, the hardened plithite formed under the coconut was brown in color, coarse in nature, with fine roots found within the pan matrix. This coarse and spongy pan under the coconut allowed water to flow unhindered. The plinthite formation under the coconut is similar to the "nodular" plinthite described by Daniels et al. (1978). In contrast, the pan materials found under the continuous arable land and pasture were reddish in color, smoother in texture and more densely packed, without any fine roots found within them. This is also similar to "platy" plinthite described by Daniels et al. (1978). From hydraulic point of view, Daniels et al. (1978) described nodular plinthite as not restricting water movement while platy plinthite led to perched water table. The hardened plinthite found in the arable and pasture soil has a serious consequence for soil management in relation to runoff generation and soil erosion. From field observations, the continuous arable land normally showed evidences of intense soil erosion especially during the early part of the season. The rills formed in the arable land have often led to dislocation of young seedlings during the early part of the cropping season.

The results from ponded infiltration measurement showed that the water intake of the coconut land was 13 times higher that the continuous arable and 4 times higher than the pasture land (Figure 4). The cumulative infiltration over a period of 3 h was about 1.1 m for soil in the coconut plantation, 0.14 m for the arable soil and 0.4 m for pasture land. This is an indicator of the amount of water that these soils will take in before runoff builds up. Evidently, runoff will be generated more quickly in the continuously cropped arable land. Apart from the nature of the pan, the depth of the pan also had significant influence on the water movement in these soils.

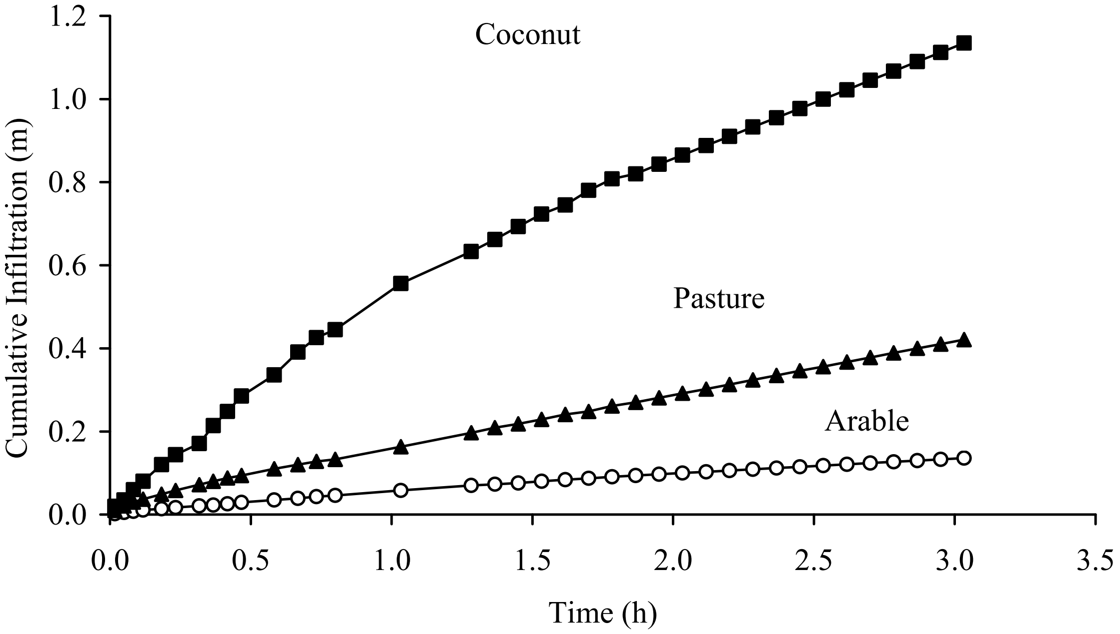

Figure 4. Cumulative infiltration rate as a function of time under the three land use types.

The arable land with significantly shallower pan compared to the pasture (Table 3), presents a severe limitation to the growth and development of crop. The volume of soil explorable will be limited by the shallow depth of the pan since the roots are essentially restricted to the soil above the pan which is just 0.3m below the surface. The reduced soil volume can affect crops growth during short term drought which can occur during the growing season. Another problem normally created by water restricting plinthite pan is the intense shallow subsurface flow which can lead to intense nutrient leaching losses (Blume *et al.* (1987). Although the subsurface flow at the soil/pan interface was not quantitatively assessed, observations made along drainage ditches at the down slope end of continuous arable land, showed a rapid discharge of water at this interface after major rainfall events. Visual observations showed that the runoff from pasture land was less muddy compared to the continuous arable field. Generally, the continuous arable soil had low amounts of organic carbon, clay and silt contents (Table 2). The bulk density and total sand content were also higher in the continuous arable land than the other land use types (Table 2). The relatively shallow depth of soil to the pan occurring under the continuous arable land use may also be related to higher rates of soil erosion due to plow and harrow tillage being practiced on this land. Disk harrowing in tropical soils has been shown to promote accelerated soil erosion (Ambassa and Nill, 1999). The shallow plinthic pan found under the coconut (Table 3) may be reflecting the effect of under-sowing the coconut land with cassava. Some evidences of soil erosion were also seen in the soil with coconut plantation, though not as severe as those seen in the continuous arable land. This might have been due to removal of surface cover under the coconut to allow for cassava cropping. The ground was normally left bare at the early part of the rainy season during the land preparation for cassava. The presence of a ground cover to prevent aggregate breakdown and surface sealing is very crucial for minimizing soil erosion in the tropics. As shown in Table 3, the pasture with continuous ground cover had the plinthic pan located deepest within the soil profile. This may be related to lower rate of erosion in the pasture soils. The pasture which contained a mixture of *Cynodon dactylon* and *Centrosema pubescens* provides a less erodible soil surface compared to the arable and coconut land use types. Both of these plants have been shown to reduce soil erosion when planted as cover crops (Chheda *et al*., 1981; Obi, 1982).

An earlier study suggested the use of subsoiler to break the hardened plinthic layer to reduce soil density and to improve water storage of the soil for crop growth (Adeoye & Mohamed Salem, 1990). These same authors observed an increase of 24% in maize yield through subsoiling of a soil with hardened plinthite. This option may however be limited by the nature and thickness of the hardened plinthite layer since they vary in hardness and thickness. If the pan is too hard or too thick, the energy requirement to break this layer might not be justifiable from agronomic viewpoint. Often, the marginal soils with hardened plinthite are being cultivated by resource poor farmers in the developing world who may not have access to mechanized tools such as subsoilers. Any management option being proposed must be realistic and easily adoptable by the resource poor farmers using such marginal lands for farming.

From this study, it is evident that arable cultivation of soils with hardened plinthite may be unsustainable in the tropics especially when mechanized soil tillage is practiced. Utilizing these soils as pasture seems to be more sustainable than putting them into intensive mechanized, arable crop production. As earlier pointed out, less soil erosion was observed in the pasture land compared to the arable land and the hardened plinthite of the pasture land was located deeper in the soil than in the continuous arable land. For sustainable arable crop production in soils with shallow hardened plinthite, minimum or no tillage with well managed cover crops need to be considered.

Although the hardened plinthite under the coconut did not restrict water, nevertheless, good groundcovers are needed to protect the soil from surface sealing and soil erosion.

CONCLUSIONS

Significant morphological differences were observed in adjacent soils with hardened plinthite layers but under different land use types. Different hardened plinthite pans were formed under different management systems. Under the coconut land, a petroplinthite which was weakly cemented was formed while a petroferric contact formed under the arable and pasture lands. Important differences observed included the depth of the pan within the soil, the thickness of the pan and the characteristics of the pan. The saturated conductivity of the soil above the pan did not prove to be a limitation to water flow in the study area, however, the plinthic pan layers under two of the land use types (pasture and arable land) proved to be a zone of reduced water conductivity. The hardened plinthite under the coconut plantation was porous and did not restrict water flow. Ponded infiltration measurements showed that the coconut plantation had a high water intake rate compared to the pasture and the arable land. Despite the high water intake rate, the plinthic pan under the coconut was located relatively shallow with no significant difference in depth from the arable land. The pan in the pasture was located at significantly deeper layers than both the arable and the coconut land. The difference in pan depth reflected the erosion rates under these land use types. Arable land and cassava farming under the coconut canopies may have led to accelerated soil erosion compared to reduced erosion in the pasture which had permanent ground covers of legume/grass mixture. Mechanized tillage practised in the arable land was unsustainable and produced a lower soil quality and a higher soil erosion risk. Careful management of soils with hardened plinthite is essential for sustainability. Such management should include the use of minimum tillage and adequate ground cover to reduced soil erosion.

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