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PLINTHITE AND CONDITIONS FOR ITS HARDENING IN AGRICULTURAL SOILS IN GHANA

A thesis submitted to the Department of Crop Science, Faculty of Agriculture, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, in partial fulfilment of the requirements for the Degree of

DOCTOR OF PHILOSOPHY
IN
SOIL SCIENCE

By

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DECLARATION

I do hereby declare with sound mind that this thesis entitled "*Plinthite and conditions for its hardening in agricultural soils in Ghana*" was written by me and that it is the record of my own research works. It has neither in part nor in whole been presented for another degree elsewhere.

Works of other scientists cited and all assistance received are duly acknowledge.

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DEDICATION

This thesis is whole-heartedly dedicated to my two encouraging daughters:

Elsie Dankwaa Asiamah

Louisa Obenewaa Asiamah

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In order to maintain the productive capacity of soils in Ghana, practices which expose and predispose soils to dehydration and formation of petroplinthite should be avoided. These practices include deforestation, overgrazing, bush burning, charcoal production, clean weeding of farmlands, surface mining, improper tillage and soil erosion. In cultivating these soils, practices that maintain as much cover as possible all year round should be adopted.

Suggestions have been made on modifications of the existing definition of plinthite to include the findings of the study that plinthite also forms in well to moderately well drained upland soils. It has been recommended that levels of iron content in agricultural soils should be determined in routine physico-chemical laboratory investigations of soil samples and also that plinthite should be recognised as a diagnostic soil property in the Ghana soil classification system.

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CHAPTER ONE

INTRODUCTION

Agriculture plays a central role in the socio-economic development of Ghana. It is the mainstay of the national economy. Currently, the agricultural sector accounts for 45% of the gross domestic product (GDP), contributes 60% of export earnings, employs 70% of the rural labour force and provides over 90% of the food needs of the people (Ofori, 1998). It is also an important source of raw materials for the manufacturing industry. However, the present overall agricultural growth rate of 2.8% is far below the expected 5 to 6% needed to facilitate the transformation of Ghana from a poor - income to a middle - income nation by the year 2020 (GOG, 1995). The latter target can only be achieved through a more efficient agriculture based on the sustainable management of the country's soil resources which form the natural resource base for production.

While sustainable agricultural production depends primarily on productive soils, the soil resources of Ghana are being degraded as a result of the interaction of both natural and anthropogenic factors. Soil degradation, in its several forms, is evident in all the agro-ecological zones of Ghana. Amongst the major forms of degradation, soil fertility decline and soil erosion have been recognised as the major bio-physical constraints to agricultural production in Ghana (MOFA, 1998; Bonsu *et al.*, 1996; Quansah, 1999). However, one other major forms of soil degradation, which is often marginalized but poses the most serious threat to soil productivity is the insidious formation of petroplinthite (ironpan) within the rooting zone of plants.

Petroplinthite is formed as a result of an irreversible hardening of plinthite which is a soft subsoil material. The process is facilitated mainly by the removal of vegetation, soil erosion and exposure of the soil to the climatic elements. In Ghana, large tracts of land have undergone this process of degradation, especially, in the savanna zones where the scanty vegetation is burnt annually. The extent of soils with petroplinthite in Ghana has been found to be 96,920 km^2 (FAO, 1976). With the increase in the removal of vegetation for timber and farming purposes in the country since 1976, the present area covered by petroplinthite could be increased by several orders. Estimates of the distribution of plinthite, the precursor for petroplinthite formation, revealed that soils covering an area of 128,581 km^2 of the land area of Ghana, contain plinthite (SRI, 1998: Map 1). These soils can be transformed into petroplinthite and lost to agricultural production if mismanaged.

Once formed, petroplinthite restricts the movement of air, water and roots (Plates 1 & 2) in the soil and subjects the overlying soil to saturation and erosion during prolonged rainfall. The effective soil volume available for moisture and nutrient storage is also significantly reduced. The presence of petroplinthite in agricultural soils in Ghana has been found to cause poor crop yields and degeneration of cocoa and coffee plantations and food crops in several forest regions which once supported luxuriant growth of the crops (FAO, 1976).

Although petroplinthite has a lot of engineering uses and have received detailed studies in its physico-chemical and engineering properties, its continued formation and spread pose a threat to sustainable agricultural production and food security in Ghana. Sound natural resource management is therefore needed, more than ever, to reverse the on-going land degradation and to enhance the sustainable use of the soil resources of the country. In particular, there is the need to develop strategies to control the formation of petroplinthite. In order to be effective, such strategies should be based on sound knowledge of the nature of plinthite, the base material for the formation of petroplinthite, the processes involved in its hardening and the driving forces which engender its irreversible hardening.

Unfortunately, this research area has received very little detailed studies, yet such studies would be needed to provide the requisite data for developing strategies for preventing the transformation of productive tropical soils into barren lands.

In contributing to the latter data needs, this study was designed to investigate the behaviour of plinthite under different conditions that affect its hardening processes.

The following were the specific objectives of the study:

i. To identify soils occurring throughout the country that have plinthite material developed in them.

ii. To describe, classify and characterize some agricultural soils with plinthite.

iii. To assess the role of factors such as climate, burning, alternate wetting and drying and vegetative cover in the irreversible hardening of plinthite.

iv. To establish the threshold values of iron and moisture contents at which plinthite hardens irreversibly.

v. To verify the hypothesis that plinthite and petroplinthite form only on flat hydromorphic lands.

vi. To recommend practices that are necessary to prevent plinthite build-up and its irreversible hardening.

CHAPTER TWO

LITERATURE REVIEW

2.1 *Definition of Plinthite*

Plinthite is defined as an iron-rich, humus-poor mixture of clay with quartz and other diluents which commonly occur as dark red redox mottles, usually in platy polygonal or reticulate patterns and changes irreversibly to petroplinthite (ironstone hardpan) or to irregular aggregates on exposure to repeated wetting and drying (SSS, 1975, 1998; FAO, 1990b, 1998). In a moist soil, plinthite is usually firm but can be cut. When irreversibly hardened, the material is no longer considered plinthite but ironstone or petroplinthite (Sys, 1968; SSS, 1975; FitzPatrick, 1980; Sombroek and Camargo, 1982). In the past both the soft (plinthite) and hardened (petroplinthite) materials were designated as laterite, first by Buchanan (1807). Currently, the term laterite is used synonymously with petroplinthite and defined as iron rich materials either occurring in consolidated sheets or as concretions of variable sizes, formed by irreversible hardening of plinthite (Varghese and Byju, 1993; Aleva, 1994; Moormann, 1981). Obeng (1970) recommended that soils with petroplinthite formed in them be called Petrosol.

2.2 *Formation of Plinthite an its Hardening Process*

The formation of plinthite involves the accumulation of oxides of aluminium and iron (sesquioxides) through desilication with loss of silica and ferralization with removal of the more weatherable and soluble compounds. In some cases, sesquioxides which have been mobilized may come in from outside, as when they move downslope to lower soils, or from upper to a lower horizons to enrich the existing sesquioxide content of the soil. In the presence of a fluctuating watertable relatively near the soil surface, there is segregation of iron due to alternating reduction and oxidation with some iron translocation to form the red-and-gray mottled soft material called plinthite (Buol *et al.*, 1973; Ahn, 1970; Driessen and Dudal, 1991). Mohr *et al.* (1972) termed the process of plinthite formation as plinthization.

Ayetey and Castel (1970) and Alexander (1951) considered the presence of iron-rich rocks, alternating dry and wet conditions and topography of the land as the most predominant factors influencing plinthite formation. They stated that the chemical weathering of iron-rich rocks is initiated by the action of acidic rain which tends to dissolve rock minerals at tropical temperatures, leaving behind a concentration of hydrates of iron and aluminium. According to them, during wet periods the soluble minerals are eliminated, whereas in the dry season the iron is precipitated as ferric hydrate which finally hardens up by dehydration. Van Wambeke (1991) indicated that the main source of the iron hydroxides is groundwater which either receives the iron from the weathering of primary minerals containing bivalent iron (Fe^{+2}) or from the reduction of trivalent iron (Fe^{+3}) oxyhydrates at low oxydo-reduction potentials.

It is generally believed that stable land surfaces, a humid tropical climate with abundant rainfall and good drainage conditions, are the most important factors controlling the formation of plinthite. However, Sombroek and Camargo (1982) found that most soils with plinthite are imperfectly drained with a pale and relatively light textured A2 horizon overlying the plinthic B and/or C horizon. Driessen and Dudal (1991) found that plinthite develops in level to gently sloping areas with fluctuating water table and exhibits ABC and AEBC profiles.

Buol *et al.* (1973) observed that where large amounts of plinthite have accumulated, a continuous phase is formed in the soil. If subjected to repeated wetting and drying, especially when exposed by clearing of forests and erosion of the overlying material, the plinthite becomes hardened or indurated to ironstone or beads of irregular modular aggregates. Ahn (1970) has demonstrated the possible stages in the formation of plinthite and ironstone and the associated changes in the landscape.

On the hardening of plinthite, Gidigasu (1969) and Sivarajasingham *et al.* (1962) were of the view that a mere concentration of sesquioxides does not necessarily ensure the hardening process. Although alumina is known to crystallize and harden, iron, particularly goethite, is by far the most common and important agent in the hardening process.

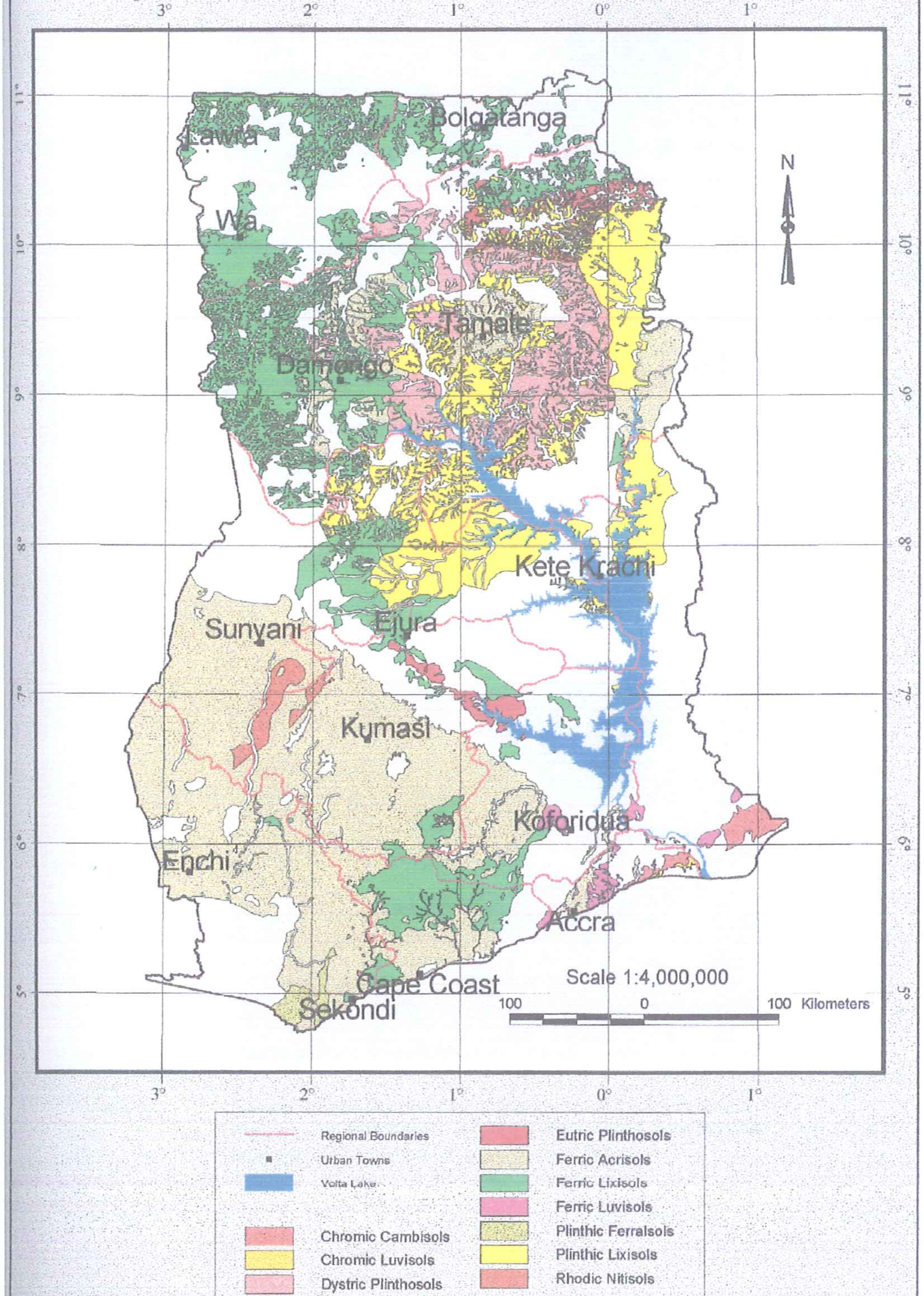
Gidigasu (1969) summarized the factors influencing the formation of plinthite and petroplinthite as climate (rainfall and temperature), vegetation, parent material, topography and time. Ahn (1970) observed that if the horizon containing plinthite is covered by a thick layer of soil, it may remain relatively soft or slightly hardened but can be penetrated by plant roots. However, if the horizon is exposed at or near the surface, a hardening process may set in. Ahn (1970) contended that the hardening or induration of plinthite appears to be partly a further oxidation and partly a reorganization and crystallization of the constituent iron compounds under the influence of wetting and drying. He stated that microscopic examination of thin sections of the hardened plinthite showed that it is the formation of interlocking goethite crystals and of a more or less continuous crystalline phase of iron oxides that causes the induration. Ahn (1970) further observed that there may be little or no difference in total iron content between the soft plinthite and its hardened form. When plinthite material is exposed to dry atmospheric conditions the material dries up. If the exposure is prolonged it irreversibly hardens to form petroplinthite (indurated ironpan). A number of authors including Ahn, (1970), Gidigasu (1974), and Lee (1996) have indicated that dehydration of plinthite is the major process that renders the material permanently hardened.

2.3 *Occurrence and Extent of Plinthite*

Plinthite is widely distributed in the tropical and sub-tropical regions of the world including Africa, Australia, India, South-East Asia and South America (FAO, 1991; Varghese and Byju, 1993; Raychanduri, 1981). It occurs mostly in the tropical belt between latitudes 30°N and 30°S where conditions for its formation are prevalent (McNeil, 1964; Eswaran *et al.*, 1990). Apart from the humid tropics, plinthite can also be found in both semi-arid and arid tropics (Maignien, 1966). It is common in areas of hot and humid climate with high annual rainfall and a short dry season as found in Western India, West Africa and some parts of South America (Driessen and Dudal, 1991).

The areal coverage of plinthite has been found to be very extensive. Matheis (1982) recorded that about one quarter of the earth's land surface is covered by lateritic soils. FAO (1991) estimated about 60 million hectares as the global extent of soils with plinthite. Although plinthite is widely distributed in Africa, not much has been reported on it. Bain (1952) first reported its occurrence in South Africa. Later, its presence was

Map 1 SOILS WITH PLINTHITE MATERIAL IN GHANA



Source: SRI (1998)

reported from several places in Nigeria, Sierra Leone, Guinea, Zimbabwe and Mozambique. An assessment by Tietz (1982) showed that lateritic soils covered more than 50% of the surface area of Nigeria.

In a study of representative toposequences on Basement Complex in Southern Nigeria. Moormann (1981) found concentrations of laterite occurring both in patches on summits and crests and in strips along the lower pediment slopes. He considered summit laterites as relicts from older land-surfaces which were originally formed as extensive groundwater laterites or more localized lacustrine laterites. Such formations were left 'suspended' in the higher parts of the present landscape because of their protective role during the general erosion of the land-surface in the Tertiary and the Pleistocene. He reported summit laterite in situ in the Isoya sequence.

In Ghana plinthite has been observed to occur in soils in all agro-ecological zones but it has not been described and characterized. It occurs on all slopes with gently to rolling topography and in soils developed from varied parent rocks especially Granitic, Birimian and Tarkwaian rocks (Asiamah and Dedzoe, 1999). In 1976, petroplinthite was found to cover an area of about 96,920 km^2 of Ghana (FAO, 1976). An assessment of the distribution of plinthite showed that soils covering an area of 128,581 km^2 (approximately 54%) of the land area of Ghana contain plinthite (SRI, 1998, Map 1). If this area is mismanaged it can potentially be transformed into petroplinthite to the detriment of agricultural production. The most vulnerable area is the Interior Savanna Zone of Ghana (Obeng, 1970).

The extensive coverage of plinthite and its potential transformation into petroplinthite pose a major threat to Ghana's future agricultural production and food security. For sustainable use of soils containing plinthite, management practices which are capable of mitigating the hardening process need to be developed and adopted (Eswaran *et al.*, 1990). As a guide to the choice of appropriate management practices, the presence of plinthite in the soil to be managed should be known. This can be facilitated if plinthite is used as a diagnostic property in the classification of soils in Ghana. Currently, it is petroplinthite which is used as a diagnostic property in delineating

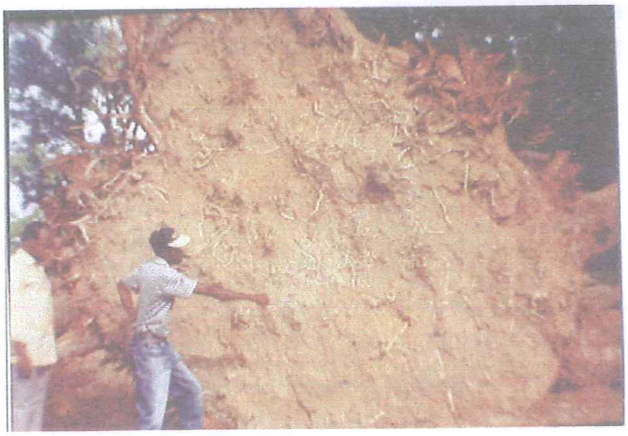


Plate 1. Blown down huge Mahogany tree (*Khaya senegalensis*) showing no vertical and tap roots. The tree was growing on massive plinthite near Navrongo (Upper East Region).

Plate 2. Laterally developed roots of Ficus plant on exposed petroplinthite at Abesewa (Ashanti Region). The site had been cleared of the topsoil to build a school after which the exposed subsoil hardened.

soils, such as *Wenchi, Changnalili* and *Kpelesawgu series*, in relation to their suitability for mechanized tillage.

2.4 . *Importance and use of Plinthite*

Interest in plinthite, either soft or hardened, the world over, has been expressed by pedologists, agronomists, geologists, mining and civil engineers and ore traders **(Buchanan, 1807; Obeng, 1960, 1970; Alexander and Cady, 1962, Gidigasu, 1972, 1974;** Eswaran *et al.*1990; Driessen and Dudal, 1991; Varghese and Byju, 1993). Plinthite has been and continues to be a very important and cheap material for the building and road construction industries (Gidigasu, 1974; Varghese and Byju, 1993). Because of its ability to harden irreversibly when exposed, plinthite is cut into blocks to harden and used for building purposes.

In Ghana and some parts of West Africa, many buildings, bridges and monuments constructed from plinthite in the early part of the 20th century are still in good condition (Plates 3 to 5). The material is still being used for building purposes in some parts of West Africa (Plate 6). Petroplinthite is also considered as sacred stone ("Bonsam buo") on which sacrifices are performed by chiefs in Ghana. According to Sanchez (1981) some scientists working in South America consider plinthite an asset rather than a liability to agricultural development. The material is considered as an asset because its hardened form is a cheap and excellent road building material and may occur as outcrops at scarps between erosion surfaces to provide slope stability. Moormann (1981) has stated that laterite formation acted as a control on land forms, and influenced general and local relief. Apart from the above uses, plinthite is an important source of iron and aluminium ores (Gidigasu, 1969; Alexander and Cady, 1962) and manganese (Eswaran *et al.*, 1990) because of its high content of iron, aluminium, silica and manganese. The presence of plinthite and its hardened form in soils has been heralded as a major impediment to agricultural development (Goodland and Irwin, 1975.; McNeil, 1964; Obeng, 1970). Sanchez (1981) and Ahn (1970) observed that plinthite in the subsoil is not a threat to plant growth unless it is exposed to the hardening process by the removal of the overlying topsoil material and the plinthite becomes hardened. However,

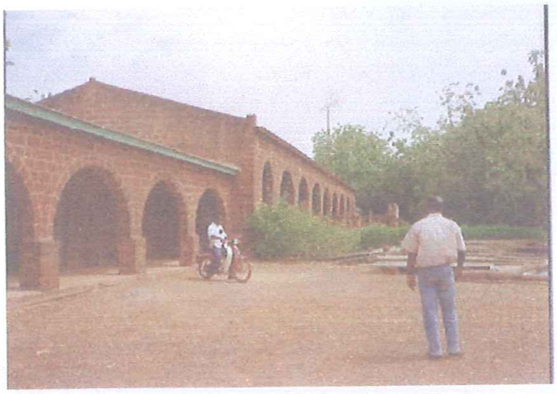


Plate 3. Church built with plinthite blocks at Nandom (Upper West Region)

Plate 4. Old post office building at Navrongo (Upper East Region) built with plinthite blocks in the colonial days.

Plate 5. Pillar remains of the defunct Nyange settlement built by the Gonjas with plinthite blocks near Sawla (Northern Region) between 1932 and 1935 as the Yabun-Wura Court during the reign of Yabun-Wura Mahama.

Plate 6. Active plinthite mine on upland soil at Hounde in Burkina Faso.
The plinthic layer is over 20 m thick.

when plinthite is hardened, it restricts the development of roots (Plates 1 and 2) and contributes to frequent water logging (Driessen and Dudal, 1991; Obeng, 1970). In the subsoil, petroplinthite may cause perching of water (Eswaran *et al*., 1990) which may lead to erosion and solifluction of the overlying soil. Obeng (1960) and Brammer (1962) also indicated that since soils containing plinthite are strongly leached and therefore poor in bases and most essential elements, they are low in fertility. The phosphorus in these soils is low and the little amount present is often fixed by the iron content making it unavailable to plants.

These adverse plant growth conditions, in addition to plinthite's firm consistence and low humus content constrain the sustainable use of soils containing the material for agricultural production (Plate 7). Because of these constraints, there is an upsurge of interest in finding out more about the process of plinthization. The objectives shall be to develop not only strategies for preventing the hardening and lateral extension of plinthite but better management practices where petroplinthite is already formed.

2.5 Characteristics of plinthite

2.5.1 *Physical Characteristics*

The important physical characteristics of plinthite are its form, colour and consistence. Plinthite has different forms which have been variously referred to as concretionary, pisolithic, slaylike, vesicular, cellular and vermicular. According to Vaghese and Byju (1993) the presence of these structures in the soil depends on the topography and position or horizon within the profile. The colours of plinthite vary considerably and the shades most frequently encountered are pink, ochre, red and brown. It is often mottled and streaked with violet and others have green colours (Maignien, 1966). The different colourations are due to the presence of oxides of iron, aluminium and manganese in various degrees of hydration.

2.5.2 *Chemical characteristics*

The major elements found in plinthite consist of silicon, aluminium, iron and manganese (Eswaran *et al*., 1990; Ahn, 1970). The richness of plinthite in these elements

Plate 7. Poor performance of upland rice on soil with plinthite at shallow depth

results from the weathering of the common felsic to fairly mafic igneous, metamorphic and sedimentary rocks (Aleva, 1994). The major chemical constituents of plinthite are the sesquioxides and their hydrated oxides followed by the kaolinitic substances.

While sesquioxides are the major components of plinthite there seems to be no general agreement as to their accumulation in the B-horizon. However two modes of accumulation which may occur simultaneously are suggested. In one case sesquioxides are considered as residual products in the decomposition of various minerals in rocks. In other situations accumulation of sesquioxides may be due to enrichment through capillary rise of groundwater during dry periods. Lee (1996) found plinthite to be generally well drained with acidic to neutral reaction. He observed that due to the dominance of kaolinitic clay mineralogy, plinthite is low in bases, nutrients and cation exchange capacity. It is also low in organic matter but contains high amounts of iron and alumina.

2.5.3 ***Mineralogical characteristics***

Plinthites with similar chemical properties may differ in their mineralogical characteristics. The minerals found in plinthites vary greatly both in type and mobility. Some are resistant while others are mobile under a variety of conditions. According to Buol *et al.* (1973), high temperatures and extreme leaching favour desilication (removal of silica) and accumulation of iron (ferritization) immobilized in ferric oxide forms under oxidizing conditions. The removal of the mobile constituents and the absolute enrichment of resistant ones contribute to different clay minerals in plinthite (McFarlane, 1976). Bampoe Addo *et al.* (1969) indicated that kaolinite is the dominant clay mineral in soils containing plinthite but lesser amounts of illite and montmorillinite are also found.

The iron content of plinthite occurs in various forms but the oxide, haematite, and the hydrated goethite are the commonest (McFarlane, 1976; Ayetey and Castel, 1970; Sivarajasingham *et al.*, 1962; Obeng, 1970). Other forms such as lepidocrocite, magnetite, ilmenite and limonite have also been detected. The aluminium contained in plinthite occurs in hydrates of alumina and aluminosilicates (Maignien, 1966). The alumina content occurs in the form of gibbsite, boehmite, diaspore and amorphous diachite. Variable quantities of aluminosilicates occur in plinthite (Maignien, 1966). Alumina content of kaolin, according to Grim (1953), is 39.5%.

Various mineralogical forms of manganese, such as lithiophorite, bixnessite, hallondite and tadorakile occur in plinthite. Titanium is present in plinthite in minute quantities of about 0.01%. The forms of titanium commonly found in plinthite are ilmenite, rutile, anatase and leucoxene.

2.6 Classification of soils with plinthite

2.6.1 *Ghana Interim Soil Classification System*

As indicated in Section 2.3, plinthite material has so far not featured as a diagnostic soil property in the Ghana Interim Soil Classification System (Brammer, 1962). However, a review of the system during this study showed that plinthic subunits can be used as lower level names for other reference soil groups.

The hardened form, ironpan or petroplinthite, is, however, considered diagnostic and soils with ironpan occurring at depths of less than 30 cm or exposed at the surface on upland areas named as *Wenchi series* and are found in all the ecological zones of Ghana. The gently undulating peneplain, with hydromorphic soils in savanna areas, have ironpan in the subsoils and the soils are named *Changnalili* and *Kpelesawgu series*. These form part of the extensive imperfectly to poorly drained groundwater laterite soils of the country. Plinthic horizons have been found during the study to occur in a number of soil series of the Forest and Savanna Ochrosols, Forest and Savanna Rubrisols, Forest and Savanna Brunosols and Forest Oxysols of the Great Soil Group of the System.

2.6.2 *World Reference Base for Soil Resources (WRB) of FAO*

The WRB, which was adopted at the 16th World Congress of the International Society of Soil Science (now International Union of Soil Sciences) at Montpellier, in France, in August 1998, replaces the FAO/UNESCO Soil (Revised) Legend (FAO, 1990b). The new system (FAO, 1998) recognizes plinthic and petroplinthic horizons as diagnostic properties of soils in the Plinthosols and eight other reference soil groups.

A plinthic horizon is defined as a subsurface horizon which constitutes an iron-rich, humus-poor mixture of kaolinitic clay with quartz and other constituents, and which changes irreversibly to a hardpan or to irregular aggregates on exposure to repeated wetting and drying with free access to oxygen. In addition, the material must have 2.5% (by weight) or more, citrate-dithionite extractable iron in the fine earth fraction, especially in the upper part of the horizon, or 10% in the mottles or concretions. The ratio between acid oxalate (pH 3) extractable iron and citrate-dithionite extractable iron should be less than 0.10. Such a horizon must have a thickness of 15cm or more and organic carbon content must be less than 0.6% by weight (FAO, 1998). The system recognizes Plinthosol as one of its 30 reference soil groups. Plinthosols are defined as soils having a plinthic horizon or petroplinthic horizon starting within 50cm from the soil surface or having a plinthic horizon starting within 100cm from the soil surface when underlying either an albic horizon or a horizon with stagnic properties (FAO, 1998).

In Ghana plinthic and petroplinthic subunits have been found in the following reference soil groups: Gleysols, Ferralsols, Alisols, Nitisols, Acrisols, Luvisols, Lixisols and Cambisols. The major lower level units of plinthosols encountered in Ghana were petric, acric, alic, stagnic, ferric, haplic and xanthic.

2.6.3 *Soil Taxonomy*

The Soil Taxonomy of the SSS (1975) and the Keys to Soil Taxonomy (SSS 1998) recognise plinthite as diagnostic soil characteristics mostly at Great Group and Subgroup levels of some of its Soil Orders. It is not considered diagnostic in the Orders Gelisols Vertisols, Mollisols, Spodosols, Andisols, Aridisols and Histosols. It is only considered diagnostic in subgroup level of Entisols as Plinthic Quartzipsamment and in the Order Inceptisols, the material is considered diagnostic at great group level as Petraquept and subgroup level as Plinthic Petraquept. The material is however considered in the classification of soils at Great Group and Subgroup levels of the Soil Orders Alfisols, Ultisols and Oxisols. In the Order Alfisols, three of its Great Groups, Plinthaqualfs, Plinthustalfs and Plinthoxeralfs, have the material used in the classification. There are plinthic subgroups of eight Great Groups, Plinthaquic

Subgroups in two Great Groups, an arenic plinthic Subgroup of Kandiudults and grossarenic plinthic subgroups of two great groups.

The Order Ultisols have the materials considered in four Great Groups of Plinthaquults, Plinthohumults, Plinthudults and Plinthustults. Plinthic subgroups are found in fifteen Great Groups, plinthaquic subgroups in four great groups, arenic plinthic subgroups in seven great groups and plinthudic subgroups in fragiaquult great group. The material is expressed in Great Group - Plinthaquox, in the Order - Oxisols. There are plinthic subgroups in fifteen Great Groups and plinthaquic Subgroups in nine Great Groups of this Order.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 *Field Visits*

Seventy five soil profiles within the various agro-ecological zones of the country were examined based on their subsoil colours, mottlings, texture and consistence to establish the occurrence of plinthite materials in their subsoils by the use of auger and chisel borings, existing pits and roadcuts along some major roads. Soils developed on different parent materials and soils at different topographical sites were examined. Observations were made on roadcuts, excavated and eroded sites where the plinthite material has been exposed and/or hardened in Ghana and some other countries of the West African subregion including Benin, Burkina Faso, Cote d'Ivoire, Mali and Nigeria. Buildings and bridges built with the material long ago and old and active plinthite block mines were also visited. Photographs of some of these are presented (Plates 3, 4, 5, 6, 8 and 9).

3.2 *Soil description and classification*

Nine soil series with well developed plinthite horizons were selected for detail studies. Profile pits, each measuring 2m x 3m, were dug to the parent rock or to 200cm depth on the selected soils. The genetic horizons of the profiles were delineated and each described in detail using the FAO (1990a) methods. The horizons were then sampled for routine laboratory physico-chemical investigations. The dominant matrix colours and mottlings were determined using the Munsell (1994) Colour Charts. The soils were classified based on FAO (1990b, 1998) and SSS (1998) Systems.

3.3 *Plinthite Exposed in Open profile pits*

A number of investigators including Sivarajasingham *et al.* (1962), Gidigasu (1969), Ahn (1970), Buol *et al.* (1973), FitzPatrick (1980) have indicated that plinthite when exposed, may harden irreversibly to ironpan. The study determined the rate of hardening of the material and the changes in some of its chemical composition when exposed to the atmosphere.

The major factors influencing the hardening of plinthite include its moisture and iron contents and their temporal variations. In order to assess the effects of the latter parameters on the hardening process, plinthite in five soil pits were exposed to atmospheric conditions under variable vegetative cover. Three pits (CPU2, CPM2 and CPL2) were sited in an open field of short and sparse vegetation designated as no-cover. The remaining two pits (APU and APM) were under a cover of cocoa plantation with a closed canopy. The hardness, moisture and the total and species of iron (i.e. Fe(II) and Fe(III)) were determined monthly for a period of 14 months.

3.4 *Burning effect on plinthite*

Heating of soils through bush fires and burning of vegetative matter on farmlands are common features in farming systems in Ghana. Charcoal production for household energy is a widespread practice in all the agro-ecological zones. These practices result in heating of the soils with plinthite material, thus speeding up petroplinthite formation to degrade the land. This study determined the effect that burning has in changing plinthite into petroplinthite using soils of sites near pits CPU2, CPM2 and CPL2. A land area, measuring 2m x 2m, was demarcated and the topsoil dug out to reach the surface of the plinthite layer. The plinthite was subjected to regular heating by burning vegetative materials over it at two-weeks intervals. The state of hardness of the plinthite was monitored after each burning treatment using the penetrometer. The heated plinthite materials were sampled for their iron contents after each burning. Thermometers were inserted into the plinthite layer at 3cm and 5cm depths to determine heat transmission in the layer. The temperature values were read at 5 minute intervals up to 35 minutes.

3.5 *Alternate Wetting and Drying Studies*

Four galvanised tanks of dimensions 1.0m x 0.5m x 0.5m were constructed with inlet and outlet valves to control the amount of water in the tanks. The tanks were filled with washed coarse river sand.

Four rectangular blocks of plinthite materials, measuring 40cm x 10cm x 5cm, were taken from each of the three profile pits - CPU2, CPM2, CPL2. 3 blocks of plinthite, one each from the above three pits, were embedded deep in the sand fill of each tank. The tanks with the plinthite blocks, were filled with water and allowed to stand for two weeks. The tanks were then completely drained for the following two weeks in a cycle. The first tank was subjected to four cycles, the second to five cycles, the third to six cycles and the fourth tank to seven cycles. At the end of each cycle the plinthite blocks were removed from the sand-fill, exposed to atmospheric conditions and immediately sampled for the determination of their Fe(II) and Fe(III) and moisture contents in the laboratory. The hardness of each block was also measured with penetrometer. The sampling of the blocks for laboratory analysis and the determination of their hardness were repeated at two weeks intervals. The effluent from the tanks at the end of each cycle was sampled and analysed for their Fe(II) and Fe(III) contents.

3.6 *Laboratory physico-chemical Analyses*

The following laboratory analyses were carried out on the 79 samples taken from the genetic horizons of the ten profile pits.

3.6.1 *Soil Reaction (pH)*

The pH of soil was potentiometrically measured in the supernatant suspension of a 1:1 soil : water mixture using a pH meter with glass-calomel combination electrodes after shaking the suspension in a reciprocating shaking machine for two hours (Black, 1965).

3.6.2 *Organic Carbon*

Soil organic carbon was determined using the Walkley and Black (1934) procedure involving wet combustion of the organic matter with a mixture of 10 ml of 1M potassium dichromate and 20 mi concentrated sulphuric acid at about 125°C. The residual dichromate was titrated against 1M ferrous sulphate.

The percentage carbon of the soil was calculated as:

$$\%C = \frac{M\ (V_1 - V_2)}{s} \times 0.39$$

where

M	=	molarity of ferrous sulphate solution (from blank titration)
V1	=	ml ferrous sulphate solution required for blank
V2	=	ml ferrous sulphate solution required for sample
s	=	weight of air-dry sample in gram
0.39	=	$3 \times 10^3 \times 100\% \times 1.3$ (3 = equivalent weight of carbon)

Organic matter content was calculated by multiplying the percent organic carbon values by 1.724 (van Bemmelen factor).

3.6.3 *Total Nitrogen*

This followed the micro Kjeldahl procedure (Bremner and Mulvaney, 1982) involving digestion of 1 g soil sample in 5ml concentrated sulphuric acid and few drops of 30% hydrogen peroxide with selenium as catalyst. By this method organic nitrogen is converted to ammonium sulphate and the resultant solution made alkaline by adding 5 ml of 40% sodium hydroxide and ammonia distilled into 2% boric acid and titrated with standard hydrochloric acid.

3.6.4 *Cation exchange capacity and base saturation*

The exchangeable bases were determined by the ammonium acetate (NH_4OAc) method described by Jackson (1967) using neutral 1M NH_4OAc solution. Calcium and magnesium in the leachate were determined by EDTA titration, while sodium and potassium were determined by flame photometry.

The total acidity was determined by shaking the sample in 1M KCl and the resultant filtrate titrated with 0.1M NaOH.

The effective cation exchange capacity (ECEC) was obtained by the sum of the exchangeable bases and the total acidity. Base saturation was calculated as the percentage of the effective CEC occupied by the exchangeable bases.

3.6.5 *Particle size analysis*

Particle size distribution was determined by the Bouyoucos hydrometer method modified by van Reeuwijk (1995) using sodium hexametaphosphate (calgon) as a dispersing agent.

The mineral part of the soil was separated by wet sieving into various fractions and their proportions determined. The samples were pretreated with hydrogen peroxide to remove organic matter (cementing material) before shaking with the dispersing agent. Sand fraction was separated from silt and clay with a 50µm sieve. The clay and silt fractions were determined using a hydrometer.

3.7 *Laboratory analysis of treated plinthite*

It has been detected by a number of authors that plinthite is composed principally of iron, aluminium, clay and water, whose behaviour affect the hardening of plinthite (Eswaran *et al.*,1990; Vaghese and Byju, 1993; Aleva, 1994; Lee, 1996). Other chemical constituents are silica, manganese and titanium. Most authors have, however, indicated that iron is the most common and important agent in the hardening process of plinthite.

At various stages of hardening, the treated plinthic materials were sampled and analysed for their contents of moisture and oxides of iron. Pieces of sampled plinthite materials were put in glass of water to stand for 24 hours in order to find out whether they had reached irreversible hardening stage. The material had reached irreversible hardening stage if they did not flake in the water.

The laboratory investigations were carried out on samples of plinthite materials that were subjected to the following treatments:

i. Exposed plinthite in pits
ii. Heated plinthite material in the field
iii. Plinthite subjected to wetting and drying conditions.

3.7.1 *Iron determination (Phenanthroline method)*

Both Fe(III) and Fe(II) contents of the plinthite samples were determined using Phenanthroline method described by Jackson (1967).

Fe(II) extraction

Twenty grams of freshly taken plinthite sample was quickly weighed into a shaking bottle, and 100ml of 1.0M NH_4OAc solution at pH 7.0 added. The suspension was shaken vigorously for 1 hour and filtered through Whatman's filter paper No. 42.

The filtrate, containing exchangeable ferrous iron, was freed of NH_4OAc by evaporation on a steam hot plate. The last traces of organic matter were removed by treatment of the residue with 10ml of aqua regia, and then the solution was again brought to dryness. The residue was dissolved in 10 ml of 0.1M HCl.

Two millilitres of 10% hydroxylamine hydrochloride and 1 ml of 1.5% orthophenanthroline solutions were added and transferred into 100ml volumetric flasks and made up to the volume with distilled water. A ferrous complex of orthophenanthroline compound of intense red colour was formed. The intensity of the red colour of the solution is proportional to the concentration of the Fe(II) in the solution. The absorbance was measured on spectrophotometer at 490nm to give the value of the Fe(II) concentration in the fresh sample which was read from calibration curve of standard ferrous solution.

Fe(III) extraction

The same plinthite sample, part of which was used for the above Fe(II) extraction, was spread and air-dried to oxidize all Fe(II) to Fe(III). Twenty grams of the dried sample were extracted with 100 ml of 1M NH_4OAc solution at pH 3 to give solution containing Fe(III), representing total Fe in the exchangeable sites. The Fe(III) was then reduced to Fe(II) and following the procedure described above, the Fe(II) concentration in the sample was read from a calibration curve of standard ferrous solution.

The difference between this value and that of the initial Fe(II) extraction above, gave the value of the Fe(III) content of the sample.

3.7.2 *Moisture Content Determination*

The moisture content of the soil samples was determined gravimetrically. Five grams of fine earth was weighed into a moisture can, and oven dried at 105°C for 24 hours overnight. The can was removed from the oven and cooled in a dessicator.

The can containing the dried soil sample was weighed.

Per cent moisture content was obtained by:

$$\%M = \frac{A-B}{B} \times 100$$

where:

A = wt of moist soil - wt of can

B = wt of dried soil - wt of can

3.7.3 ***Measurement of hardness values***

The hardness of the plinthite materials exposed in the pits were determined monthly for fourteen months using the hand penetrometer. Five readings were taken at a time and averaged for the value of the month.

Hardness values were also determined every two weeks for the plinthite blocks subjected to wetting and drying conditions and the heated plinthite in the field using the hand penetrometer.

3.7.4 *Statistical Analysis of Results*

Results obtained were analysed using Microsoft Excel Spreadsheet and Statistix for Windows (R) Version 4 (SAS, 1989). Statistical analyses done included calculation of means, standard deviations and standard error of the means for the various parameters measured.

The formula for mean is given by

$$\bar{x} = \frac{\sum_{i=1}^{N} Y_i}{N}$$

Where	=	mean,
Y_i	=	variates or observations of the sample, and
i	=	summation index, which indicates that the values of Y_i go from the value of Y_1 to that of Y_N (Y_1 and Y_N are the 1st and Nth variates, respectively), and
N	=	number of variates or observations.

The standard deviation, s, is calculated as

$$s = \sqrt{\frac{\left(\sum Y_i^2 - \frac{(\sum Y_i)^2}{N}\right)}{N-1}}$$

while the standard error of the means, SE, is given by

$$SE = \frac{s}{\sqrt{N}}$$

The standard error of the mean was used to determine significant differences among the means. Regression between hardness values and parameters measured [Fe(II), Fe(III), Total Fe and moisture contents of the plinthite] were calculated. Simple correlation matrices were also calculated for measured parameters for samples from the pits and tanks.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 *Occurrence of Plinthite and Petroplinthite*

Field visits and observations showed that soils with plinthite are widely distributed in all the agro-ecological zones of Ghana (Map 1). While plinthic horizons are frequent in the forest, extensive sheets of flat petroplinthite are more common in the savanna and forest-savanna transition zones. Many of these are considered very old (Tertiary age) and therefore as "*fossil formations*" inherited from a previous period (Ahn, 1970). According to the latter author, this distribution of plinthite and petroplinthite has led some observers to suggest that plinthic horizons form under a forest or forest-type vegetation but rather harden irreversibly as the forest disappears during a subsequent dry period and erosion exposes the mottled hardened layers at the surface.

However, examination of fresh roadcuts, pits and eroded sites in this study revealed active plinthite and petroplinthite formations to be on-going processes in most agro-ecological zones and at various toposites ranging from summits through upper to lower slopes (Plates 8 and 9). Moormann (1981) reported the presence of active plinthite formation in the lower parts of some toposequences in Southern Nigeria where certain seepage levels were characterized by the accumulation of Fe and manganese. Apart from these recent formations, Moormann (1981) encountered summit petroplinthite *in situ* which were relicts from older landsurfaces originally formed as extensive groundwater laterites or more localised lacustrine laterites. Such formations were left 'suspended' in the higher parts of the present landscape because of their protective role during the general erosion of the land surface in the Tertiary and the Pleistocene. Some workers, including Brammer (1962), Obeng (1960) and Driessen and Dudal (1991), believed that plinthite and petroplinthite occur only on flat or gentle relief sites characterised by a fluctuating water table. This belief was apparently based on the fact that flat topography favours the concentration of sesquioxides in certain well defined horizons (Ahn, 1970). Thus, Alexander (1951) considered a relatively flat surface to be necessary for the formation of plinthite, and Sombroek and Carmago (1982) reported that plinthite occurred in hydromorphic or imperfectly drained soils of flat terrains.

Plate 8. Petroplinthite formed on the surface of a road cut through upland soils near Duayaw Nkwanta (Brong Ahafo Region)

Plate 9. Petroplinthite hardened from a dugout on Kpelesawgu series (Plinthosol) in the Guinea Savannah Zone (Northern Region).

In this study, however, plinthite was found in old, matured and moderately developed soils on varied parent materials and on all topographical sites.

The soil units and soil series found to have the plinthite material developed in them were Plinthosols (*Sirru, Chagnalili series*), Lixisol (*Ejura, Damango series*), Luvisol (*Dorimon, Varempere series*), Acrisols (*Kumasi, Asikuma series*), Alisols (*Bompata, Koforidua series*), Nitisols (*Atewa, Atukrom series*), Ferralsols (*Boi, Abenia series*), Cambisols (*Murugu, Nta series*). It was however not found in Fluvisols, Planosols and Regosols.

It must be pointed out that plinthite formation is an active process in soils of the tropical environment and whenever subjected to conditions that favour hardening, such as wetting and drying cycles and dehydration, it is transformed into petroplinthite.

4.2 *Depth and thickness*

Plinthite materials were found deep within the profiles of normal uneroded soils (Appendices 8.1 - 8.10) Most of them occur below 70 cm of the soil surface, and appear to be deeper on middle and lower slope soils. The thickness of the plinthite layers of the soils examined varied from 60 cm to over 200 cm. Elsewhere, as found in a plinthite mine in Burkina Faso, the material was over 10m thick (Plate 6). The thickness of the plinthite material seems to depend on the length of the plinthization process, the stability and age of the landscape. It was also established that the plinthite layers coincided in most cases with the illuvial clay accumulated layers, the Argic B (Argillic) horizon.

4.3 *Colouration of Plinthite*

The major colours of plinthite observed in well drained soils (CPU1, UPU2 and APU) of upper slopes were mostly red to dark red (10R 4/6 to 2.5YR 4/6) with faint strong brown to reddish yellow mottles (7.5YR 5/6 to 7.5YR 6/8) (Plate 10, Appendices 8.1, 8.2, 8.6, and 8.9). The moderately well drained soils (CPM1, CPM2, APM) of the middle slopes had mainly yellowish red to dark red colours (5YR 4/6 to 2.5YR 4/6) with common yellow, reddish yellow and red mottles

Plate 10. Typical profile of well-drained reddish upland soil whose subsoil can harden to form petroplinthite when exposed. Bekwai series (Ferric Acrisol) in semi-deciduous forest zone (Ashanti Region)

(10YR 7/6, 7.5 YR 6/8 to 2.5 YR 5/8, Appendices 8.3, 8.4, 8.7 and 8.10).

Matrix colours of the plinthite in imperfectly drained lower slope soils (CPL1, CPL2) were varied and were mostly yellowish brown to pale olive (10YR 5/4 to 5Y 6/4). This is the result of shorter periods of oxidation and longer periods of reduction processes because of the presence of moisture within the zone for a longer period (Plates 8 and 9). The mottlings are numerous and range from prominent grey, yellowish red, red, light brownish grey, light yellowish brown, light olive grey to very pale brown (5Y 6/1, 5YR 5/6, 2.5YR 5/8, 10YR 6/2, 10YR 6/4, 5Y 6/2 to 10YR 7/3 respectively, Appendices 8.5, 8.9). In all the soils examined it was observed that mottlings increased in abundance, size and contrasted with depth.

The above colours of plinthite, which accord with those reported by FitzPatrick (1980), Sombroek and Carmago (1982) and Daniel *et al.* (1978) are indicative of the degree of drainage and the hydration of the constituent Fe oxides. The red, reddish brown or brownish red colours, characteristic of the well drained soils of the upper slopes, denote the predominance of non-hydrated Fe oxides (haematite, Fe_2O_3) as indicated by Ahn (1970) and Hughes (1981). The Fe oxides remain red only so long as it is non-hydrated (hematite, Fe_2O_3) as detected in CPU1 and APU. In the middle slope soils where drainage is slower than the upper slope and summit soils, the Fe oxides become hydrated into goethite (FeOOH) and limonite ($2Fe_2O_3.3H_20$) to give brown to orange brown to yellow brown and brownish yellow colours as determined in CPM1 and APM. As drainage becomes poorer in the lower slope soils (CPL1, CPL2) the reduced condition of the Fe oxides gives soil matrix colours of grey with yellowish, brownish or reddish mottles or yellowish brown matrix colour with shades of grey, bluish or white mottles.

The sequence of colourations observed from the upland soils to bottomland soils is in line with colour catenas described by Milne (1935) indicating a sequence of red upland soils that change into yellowish soils on adjacent slopes which in turn may grade into gray bottomland soils. The colour changes usually correspond to hematite-geothite ratios, in soils at various toposites.

4.4 *Types of Plinthite*

The field observations on the occurrence of plinthite were made in relation to its position in the soil profile and at the toposite, drainage conditions and sources of moisture for the wetting process. The variations observed in these parameters made it necessary to classify plinthite into three types, namely: stagnic, gleyic and pseudo-plinthite.

4.4.1 *Stagnic Plinthite*

Most of the soils observed on the summits, upper and middle slope sites had plinthic materials wholly in the B horizon occurring below 70 cm from soil surface. The upper limits of the plinthic horizons in the upland soils were found to coincide almost with those of the argic B. Plinthite formation in these upland soils is influenced by rainfall. This type of plinthite significantly affects agricultural production since it occurs within the exploitable volume of the solum for nutrients and moisture.

Its position in the profile, underlying light textured and easily erodible material, makes it more susceptible to be exposed at the surface after the overlying soil is eroded. The plinthic material usually contains Festone concretions and gravels which form breccias when hardened. As a result of the influence of atmospheric rainfall on its formation, this type of plinthite may be classified as "*stagnic plinthite*"(Plate 11.1). Examples of soils that have stagnic plinthite were *Ejura, Damango, Bompata and Bekwai* series.

4.4.2 *Gleyic Plinthite*

This type of plinthite occurs within the profile in the BC horizon with partly weathered rock materials. Its formation is influenced mostly by the fluctuating movement of groundwater. Because of the regular presence of water, this type of plinthite is characterized by more prominent colourations. It seldom gets hardened unless the soil is exposed to that depth. The plinthic materials occur at such great depths within the profile - below the exploitable soil volume - that they do not threaten agricultural production. This type can be termed "*gleyic plinthite*" due to the influence of groundwater in its formation (Plate 11.2). *Lapliki, Chagnalili, Kpelesawgu series* are examples of soils with gleyic plinthite.

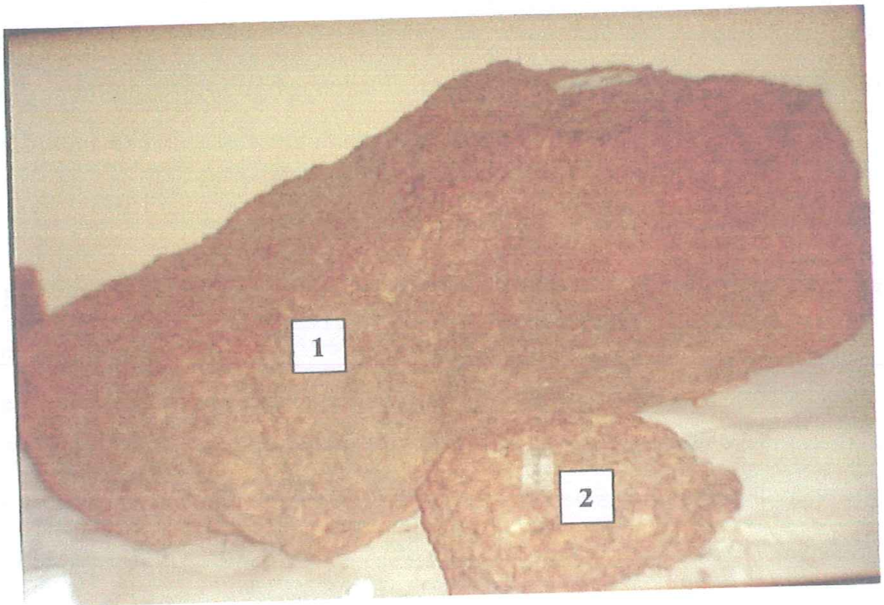


Plate 11. Petroplinthite (ironpan) boulders hardened from well drained upland soil (1) and imperfectly drained lowland soils (2)

4.4.3 *Pseudo-Plinthite*

In some depressional bottom, lower slope and valley bottom soils, colourations develop which are similar to those found in middle and lower slope plinthitic materials. This is due to seepage soil solution enriched with oxides of Fe, aluminium and manganese from the upslope sites. The colouration gives a false impression of the presence of plinthite. Such materials do not harden under any conditions to form petroplinthite and are therefore termed "*pseudo-plinthite*". It occurs in some Cambisols, Gleysols and Fluvisols. Pit APL (Appendix 8.9), which had pseudo-plinthite material, caved in soon after it was dug because the material had not been impregnated enough with Fe(III) and was therefore not massive and stable.

4.5 *Texture*

High clay content in the subsurface horizons was found to be ideal for plinthite formation (Alexander and Cady, 1962; FitzPatrick, 1980; USDA, 1975, 1998). All the plinthite materials of the soils examined were of high clay contents (Appendices 8.1-8.10). The average clay contents of the material of the upper and middle slope soils were all over 50% while those of the lower slope soils had average clay contents of nearly 40%. Plinthite layers of the five soils subjected to the experimental treatments had average clay contents between 39.6% and 57.9%. The upper slope soils, CPU2 and APU, had average clay contents of 57.7% and 55.9% respectively within their plinthite layers. The middle slope soils, CPM2 and APM, had 50.9% and 56.7% respectively while the lower slope soil of CPL2 had 39.6%.

The relatively lighter textures of the lower slope soils were found to be due to the coarse-textured nature of the saprolites since the plinthite materials occurred within the BC horizons. The clay minerals within which plinthite forms are mostly kaolinitic (Eswaran and Raghu Moham, 1973). Plinthite does not form in montmorillonitic clays.

4.6 *Organic Carbon and Total Nitrogen contents*

One characteristic of plinthite noted by a number of authors is its low humus content (Alexander and Cady, 1962; Fitz Patrick, 1980; USDA, 1975, 1998; Eswaran *et al.*, 1990). The low-humus content of plinthite makes it a poor medium for crop production. The plinthic materials of the soils examined were found to have low organic carbon contents ranging from 0.59% in CPM2 (Appendix 8.4) to 0.24% in CPL1 (Appendix 8.5). The laboratory results of the plinthic materials indicated low nitrogen contents with values ranging from 0.02 to 0.07%. These results confirmed that plinthite is humus-poor, making it a poor soil material for plant growth.

4.7 *Exposed Plinthite in Soil Profile Pit*

In the following sections, the results of the hardness, moisture and Fe content determinations on the plinthite material are presented and discussed.

4.7.1 *Moisture contents and Hardness of Plinthite*

The results of the moisture and hardness measurements for the five pits are presented in Figures 1 - 5.

The moisture content of the material in pit CPU2 (Fig. 1) increased gradually from 16.6% in March, 1998, decreased slightly in the following month and increased significantly to the highest value of 21.6% in June, the wettest month. There-after, there was a significant decrease in moisture content to 16.4% in September. The October value of 17.6% continued to decrease till the end of the observation period.

Significant decreases in moisture content were observed between October and December, and between December and January. From February to April 1999, the monthly decreases were significant. The value fell below 10% in January 1999 and even though the total rainfall of the months of March and April 1999 were higher than the previous eight months the moisture content of the materials continued to decline to 4.6% level in April 1999. Similar fluctuations in moisture content were observed in pits CPM2 (Fig. 2) and CPL2 (Fig. 3), except that in the latter two pits the peak moisture content of 22.5% was recorded in July 1998. The low-high-low moisture content recorded during the period of experimentation tended to coincide with the dry-wet-dry seasons.

In the case of the pits APU and APM under cover (Figs. 4 and 5) the initial moisture content of plinthite in March, 1998 decreased in the following two months. Thereafter the moisture content of plinthite increased and remained fairly uniform at 23% till September, 1998 in APU and November, 1998 in APM. The moisture content decreased again but gradually to a minimum of 10.6% in APU and 16.1% in APM in April, 1999.

The plinthite under cover exhibited less fluctuations in its moisture content and recorded a higher minimum moisture retention at the end of the experiment than that under no-cover. The tendency of vegetative cover to even out atmospheric conditions may account for the observed lower variations in moisture content. The higher moisture retained in the plinthite under cover may be due to the attribute of vegetative covers in attenuating ambient temperature and increasing humidity with a consequent reduction in evaporative losses.

The fluctuations in the moisture content of plinthite significantly influenced its hardness as shown in Figures 1 - 5. In the pits under no-cover, the initial hardness of 447 N/cm^2 for CPU2 (Fig. 1) in March, 1998 decreased to a minimum of 174 N/cm^2 in June 1998 when its moisture content was at a peak of 21.6%. Hardness then increased as the moisture content of plinthite decreased to attain a maximum value of 713 N/cm^2 in March, 1999. In the case of CPM2 (Fig. 2) the initial hardness of 459 N/cm^2 decreased to a minimum of 140 N/cm^2 in June 1998 and increased again to reach a peak of 513 N/cm^2 in April, 1999. Pit CPL2 (Figs. 3) started with a hardness of 457 N/cm^2 in March 1998, decreased to 100 N/cm^2 in June and then increased to a maximum of 610 N/cm^2 in February and March, 1999.

A similar trend in hardness was observed for the pits under cover. However, the magnitude of hardness under cover was significantly lower than that under no-cover. The initial hardness of 220 N/cm^2 in March, 1998 for pit APU decreased to a low of 95 N/cm^2 in October, 1998 and increased again to a peak of 400 N/cm^2 in April, 1999 (Fig. 4). In the case of pit APM (Fig. 5) the initial value of 160 N/cm^2 decreased to a minimum of 96 N/cm^2 in October, 1998. This was followed by an increase in hardness to a maximum of 367 N/cm^2 in April, 1999. The results further showed that beyond a certain level of hardness the moisture content of plinthite progressively decreased irrespective of the amount received through rainfall. Thus, in spite of the high amounts of rainfall received in March, 1999 (149.2mm) and April, 1999 (267.3mm), the February moisture content of plinthite in pits CPU2 (8.7%) and CPM2 (10.9%) continued to decrease to a minimum of 4.6% and 4.7% respectively.

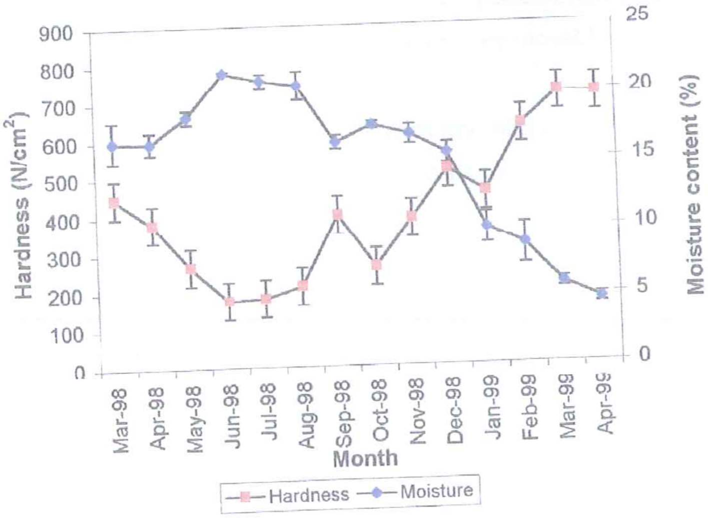


Fig 1. Changes in hardness and moisture contents of exposed plinthite in Profile Pit CPU2. *Error bars represent standard errors of the means. Two means are significantly different if their error bars do not overlap in this and subsequent figures.*

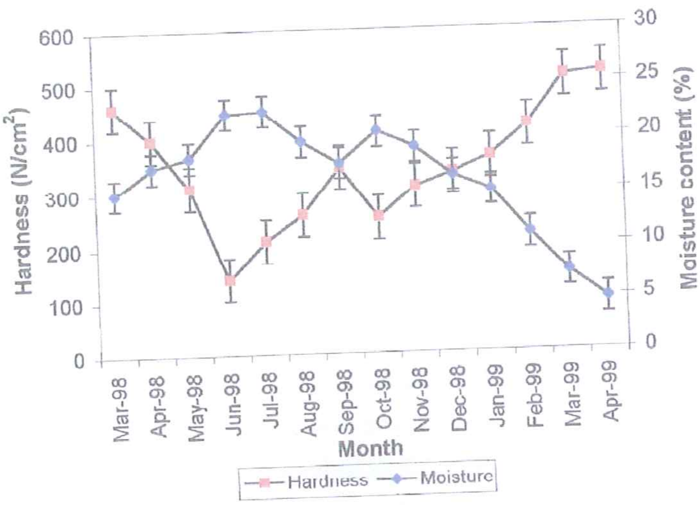


Fig 2. Changes in hardness and moisture contents of exposed plinthite in Profile Pit CPM2. *Error bars represent standard errors of the means.*

The implication is that beyond a certain level of hardness, plinthite becomes so massive that it is almost impermeable to rain water but is capable of losing moisture into the atmosphere due to increased matric suction at its surface caused by evaporation (Hillel, 1998).

The results presented in Figs 1 - 5 indicate that, whether under cover or no-cover, the hardness of plinthite is inversely related to its moisture content. This became quantitatively explicit through the correlation analysis of the data (Table 1), which showed a highly significant negative correlation between hardness and moisture content. The coefficient of correlation (r) ranged from -0.91 to -0.94 for the pits under no-cover and -0.78 to -0.88 for those under cover. It is therefore not surprising that the hardness of plinthite increased as its moisture content decreased and vice versa.

The effect of moisture on hardness may be due to its role in soil aggregate formation. Presumably, in a dry state, a high degree of particle to particle bonding and interlocking is attained. This increases the internal friction of the material which is reflected in a high penetrometer reading. On the other hand, as the moisture of plinthite increases, the films of moisture weaken the interparticle bonds and apparently reduce the internal friction of the material to give lower penetrometer readings.

4.7.2 ***Dynamics of Fe content of plinthite***

The Fe content of plinthite in the pits are presented in Figures 6 - 10. There was a steady increase in both Fe(III) and total Fe contents of plinthite in all the pits as the experiment progressed through the 14 months of observations.

With an initial value of 17.43 mg/kg in pit CPU2, March, 1998 the Fe(III) content increased steadily to a peak of 90.90 mg/kg in April, 1999 (Fig. 6). Following the same pattern, the total Fe content increased from an initial value of 33.76 to 92.77 mg/kg.

In pit CPM2 (Fig.7), the initial values of 23.10 and 33.37 mg/kg reached maximum values of 88.57 and 90.55 mg/kg for Fe(III) and total Fe respectively at the end of the experiment. The range of values for CPL2 (Fig. 8) were 22.70 to 89.93 mg/kg and 39.37 to 91.78 mg/kg for Fe(III) and total Fe respectively. In the case of pits APU (Fig. 9) and APM (Fig. 10) Fe(III) content ranged from 16.45 - 47.67 mg/kg and 21.10 - 51.12 mg/kg respectively. The total Fe varied from 29.31 to 50.20 mg/kg for pit APU and 31.10 to 54.19 mg/kg for pit APM.

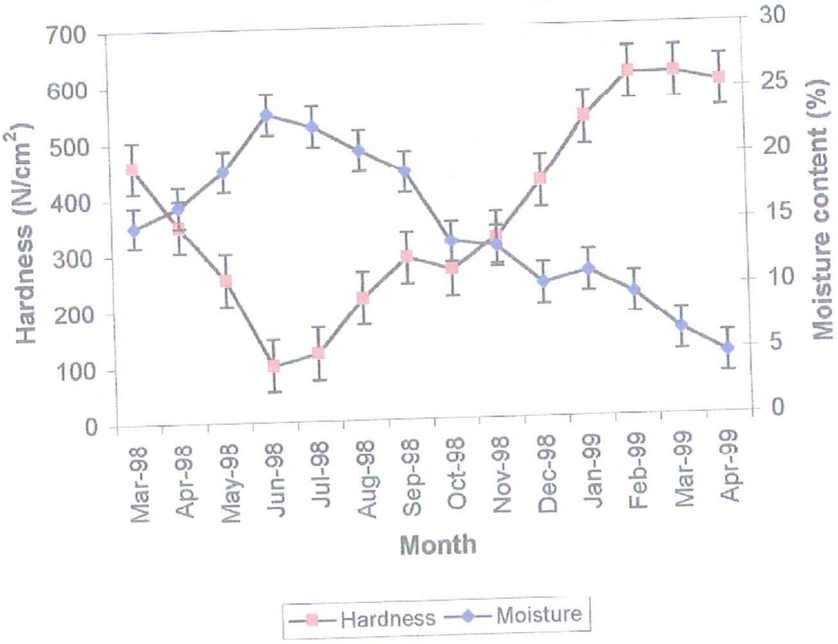


Fig 3. Changes in hardness and moisture contents of exposed plinthite in Profile Pit CPM2. *Error bars represent standard errors of the means.*

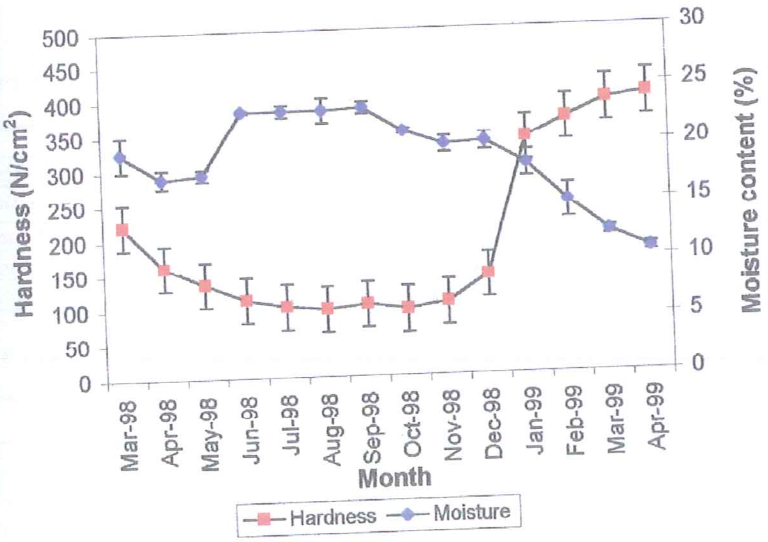


Fig. 4 Changes in hardness and moisture contents of exposed plinthite in profile Pit APU
Error Bars represent standard errors of the means.

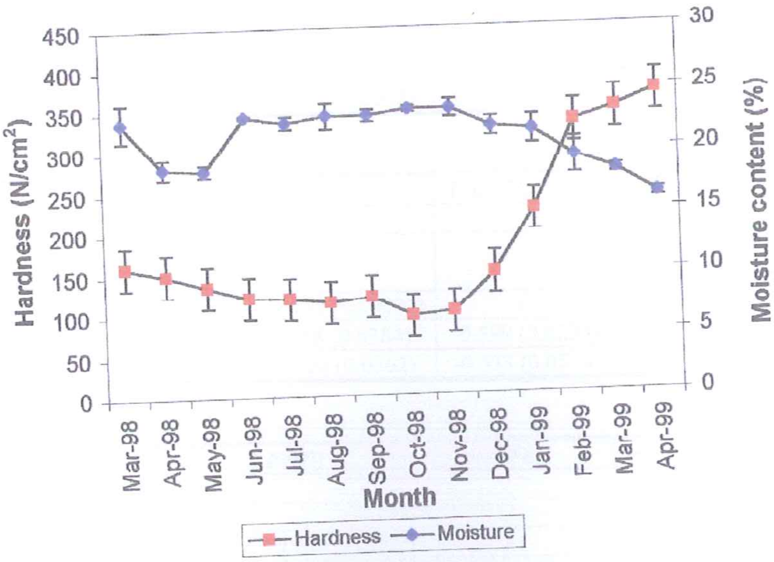


Fig. 5 Changes in hardness and moisture contents of exposed plinthite in profile Pit APM
Error Bars represent standard errors of the means.

Table 1.0: **Correlation matrices of Fe(III), Fe(II) and Fe contents, moisture contents and hardness for plinthite samples in the exposed pits. Figures in brackets represent levels of significance.**

CPU2

	Fe(III)	*Fe(II)*	*Total Fe*	*Hardness*	*Moisture*
Fe(III)	1				
Fe(II)	-0.908 (<0.0001)	1			
Total Fe	0.994 (<0.0001)	-0.857 (0.0001)	1		
Hardness	0.827 (0.0003)	-0.644 (0.0133)	0.850 (0.0001)	1	
Moisture	-0.897 (<0.0001)	0.710 (0.0045)	-0.919 (<0.0001)	-0.943 <0.0001)	1

CPM2

	Fe(III)	*Fe(II)*	*Total Fe*	*Hardness*	*Moisture*
Fe(III)	1				
Fe(II)	-0.951 (<0.0001)	1			
Total Fe	0.999 (<0.0001)	-0.933 (<0.0001)	1		
Hardness	0.591 (0.0259)	-0.457 (0.1000)	0.609 (0.0209)	1	
Moisture	-0.822 (0.0003)	0.663 (0.0098)	-0.842 (0.0002)	-0.908 <0.0001)	1

CPL2

	Fe(III)	*Fe(II)*	*Total Fe*	*Hardness*	*Moisture*
Fe(III)	1				
Fe(II)	-0.900 (<0.0001)	1			
Total Fe	0.990 (<0.0001)	-0.840 (0.0002)	1		
Hardness	0.804 (0.0005)	-0.623 (0.0173)	0.848 (0.0002)	1	
Moisture	-0.876 (<0.0001)	0.771 (0.0012)	-0.893 <0.0001)	-0.919 <0.0001)	1

APU

	Fe(III)	*Fe(II)*	*Total Fe*	*Hardness*	*Moisture*
Fe(III)	1				
Fe(II)	-0.978 (<0.0001)	1			
Total Fe	0.989 (<0.0001)	-0.935 (<0.0001)	1		
Hardness	0.594 (0.0256)	-0.558 (0.0384)	0.599 (0.0238)	1	
Moisture	-0.542 (0.0490)	0.524 (0.0562)	-0.533 (0.0516)	-0.878 (<0.0001)	1

APM

	Fe(III)	*Fe(II)*	*Total Fe*	*Hardness*	*Moisture*
Fe(III)	1				
Fe(II)	-0.982 (<0.0001)	1			
Total Fe	0.998 (<0.0001)	-0.967 (<0.0001)	1		
Hardness	0.672 (0.0199)	-0.613 (0.0199)	0.688 (0.0066)	1	
Moisture	-0.318 (0.2707)	0.248 (0.3946)	-0.341 (0.2356)	-0.780 (0.0010)	1

In contrast to the increase in Fe(III) content over the period of experimentation, the more mobile Fe(II) decreased. From an initial value of 16.33 mg/kg in March, 1998, the Fe(II) content of pit CPU2 decreased to a minimum of 1.87 mg/kg in April, 1999.

The changes in the amount and form of Fe in plinthite over the experimental period may be linked with the alternate oxidation - reduction cycles of the component Fe compounds due to changes in soil moisture content. The oxidation-reduction process results in the mobilization of Fe as Fe(II), transportation of Fe(II) by diffusion or mass flow due to gravity or capillarity, immobilization of Fe(II) by precipitation as solid Fe(II) oxides and adsorption on clays, and oxidation of Fe(II) by oxygen or other oxidants to Fe(III) oxides (Eswaran *et al.*, 1990; van Breeman, 1988). While high soil moisture enhances the reduction process to mobilize Fe in the Fe(II) form, low moisture favours the oxidation process to give the more stable Fe(III).

As a result of the oxidation-reduction process the initial Fe(III) contents of plinthite in all the pits increased through the additional Fe(III) gained from the oxidation of the Fe(II). The progressive oxidation of the Fe(II) coupled with its possible leaching from plinthite horizon to other horizons may account for the decreases observed in its content. However, the magnitude of the decrease in Fe(II) content was significantly lower than the increase in Fe(III). This implies that the Fe(III) content of the plinthite was enriched from other sources. A similar observation was reported by Eswaran and Raghu Mohan (1973), Driessen and Dudal (1991) and Lee (1996). The mobilization and translocation of Fe in the Fe(II) form from adjacent and overlying horizons and their subsequent oxidation and precipitation as Fe(III) in the plinthite may account for the observed enrichment. This accords with the observations of Fanning and Fanning (1989), Driessen and Dudal (1991) and Lee (1996). Because of this enrichment, the original Fe content of plinthite in all the pits also increased over the period of experimentation.

The accumulation of Fe compounds, especially Fe(III) oxides, under fluctuating soil moisture content is very important for the transformation of the soft plinthite into the hard petroplinthite (Fanning and Fanning, 1989). The onset of the irreversible hardening of plinthite can therefore be delayed by any factor which slows down the oxidation of Fe(III) into Fe(III) and its accumulation. The results of the study showed that increases in the Fe(III) and decreases in the Fe(II) contents of plinthite were more gradual in soils under cover (Figs. 9, 10) than those under no-cover (Figs. 6 - 8)

The relatively higher and more uniform moisture content of the plinthite under cover might have favoured the reduction process at the expense of oxidation and thereby reduced the rate of Fe(III) formation and accumulation. This observation derives from the negative correlation between the moisture and Fe(III) content of plinthite (Table 1.0) with coefficient of correlation (r) ranging from -0.82 to -0.90 (P<0.0003 to 0.0001) for the pits under no-cover (CPU2, CPM2 and CPL2) and -0.32 to -0.54 (P<0.2707 to 0.0490) for those under cover (APU and APM).

On the other hand, the moisture content of plinthite was positively correlated with the Fe(II) content with the coefficient of correlation values varying from 0.66 to 0.77 (P< 0.0098 to 0.0012) and 0.25 to 0.52 (P< 0.3946 to 0.0652) for the pits under no-cover and cover respectively.

4.7.3 ***Hardness and Fe Content of Plinthite***

The correlation analysis of the results (Table 2) showed that while the correlation of the hardness of plinthite with its Fe(III) content was positive, it was negative with the Fe(II) content. In both cases the correlation was highly significant. The coefficient of correlation ranged between 0.59 and 0.83 (P<0.026 and 0.0003) for Fe(III) and -0.46 and -0.64 (P<0.100 and 0.013) for Fe(II). The results in Figs 6 - 10 however, revealed that the increase in the hardness of plinthite with its increasing Fe(III) content became more explicit after a certain level of its content was attained. In the case of the pits under no-cover, the Fe(III) levels were 44.63, 45.57 and 45.60 mg/kg for CPU2, CPM2 and CPL2 respectively. The corresponding hardness were 259, 250 and 265 N/cm^2. In the pits under cover, the Fe(III) levels with their corresponding hardness were 37.93 mg/kg and 95 N/cm^2 for APU and 38.33 mg/kg and 96N/cm^2 for APM.

The hardness of plinthite was also positively correlated with its Fe content. The positive correlation suggested that a greater percentage of the Fe was made up of Fe(III). The coefficient of correlation ranged from 0.61 to 0.85 (P<0.021 to 0.0001).

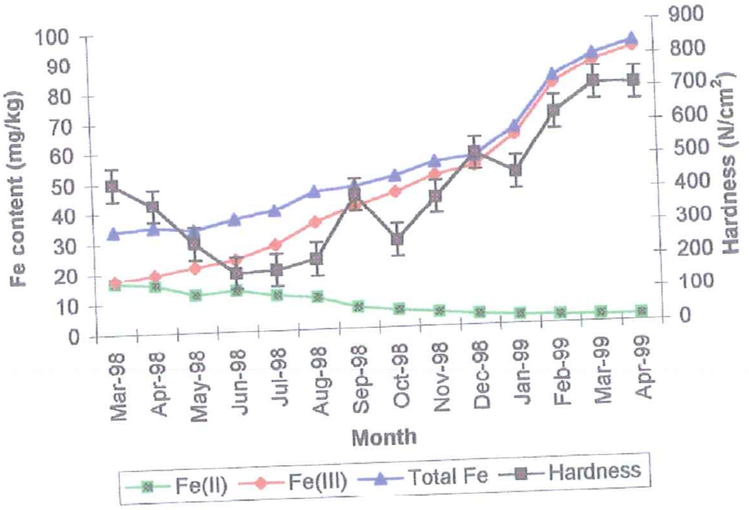


Fig.6 Changes in Fe(II), Fe(III), Total Fe contents and hardness of exposed plinthite in Profile Pit CPU2. *Error bars represent standard error of the means*

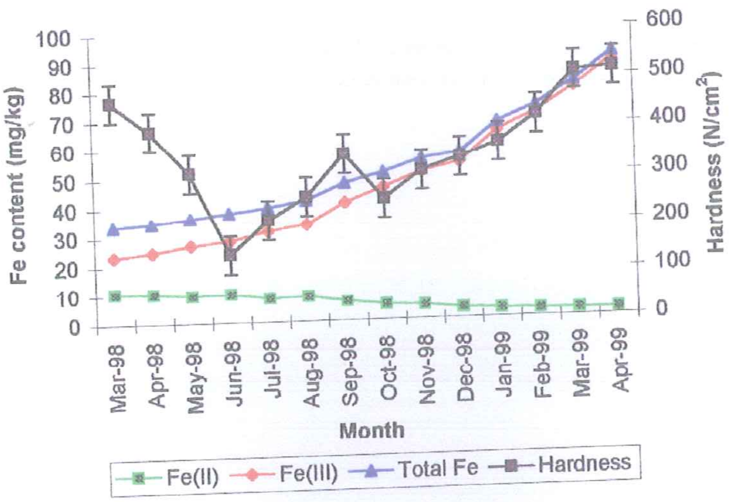


Fig. 7 Changes in Fe(II), Fe(III), Total Fe contents and hardness of exposed plinthite in Profile Pit CPM2. *Error bars represent standard error of the means*

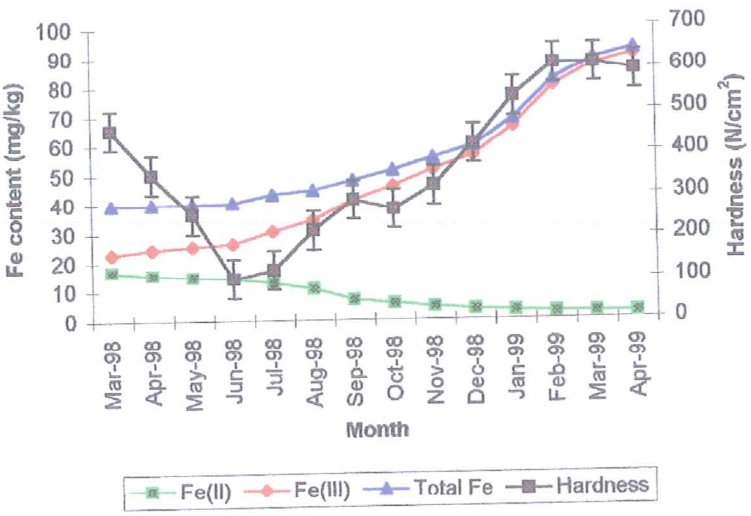


Fig. 8 Changes in Fe(II), Fe(III), Total Fe contents and hardness of exposed plinthite in Profile Pit CPL2. *Error bars represent standard error of the means*

At the initiation of the experiment, the percentage contributions of Fe(III) to the Fe content of plinthite were 56 and 68 for pits APU and APM respectively. The values for CPU2, CPM2 and CPL2 were 52, 69 and 58% respectively. As the experiment progressed, the Fe(III) component of Fe increased in all the pits. At the point where the positive correlation between Fe(III) and hardness became clear, the percentage of Fe(III) in the Fe content had increased by a range of 88 - 90% in all the pits.

At the onset of irreversible hardening of plinthite, as observed in pits CPU2, CPM2 and CPL2 in February, 1999, Fe(III) (79.40 mg/kg) constituted 97% of the Fe content of the plinthite from the latter three pits which were under no-cover. At the end of the experiment, the onset of irreversible hardening could not be attained in any of the pits (APU and APM) under cover. In these pits the final Fe(III) content was 47.67 mg/kg for APU and 51.12 mg/kg for APM forming 95 and 94% of the Fe content of the plinthite. These observations appear to suggest that irreversible hardening of plinthite occurs when it attains certain threshold values in its Fe(III) and moisture content.

4.7.4 *Correlation of Plinthite hardness with moisture and Fe contents*

The correlation coefficients for plinthite hardness with moisture and Fe contents are presented in Table 2.0. Plinthite hardness negatively correlated with moisture and Fe(II) contents, but positively with Fe(III) and Fe. The high and significant correlation of hardness with Fe(III) contents in all the pits show that Fe(III) was a major contributory factor to the formation of petroplinthite. The importance of Fe content in the hardening processes of plinthite had been stressed in the earlier findings of Sivarajasingham *et al.* (1962), Ayetey and Castel (1970), USDA (1975, 1998) and Eswaran *et al.* (1990). The very high and negative correlation of hardness with moisture content was indicative of the fact that the formation of petroplinthite resulted from dehydration of the plinthite material.

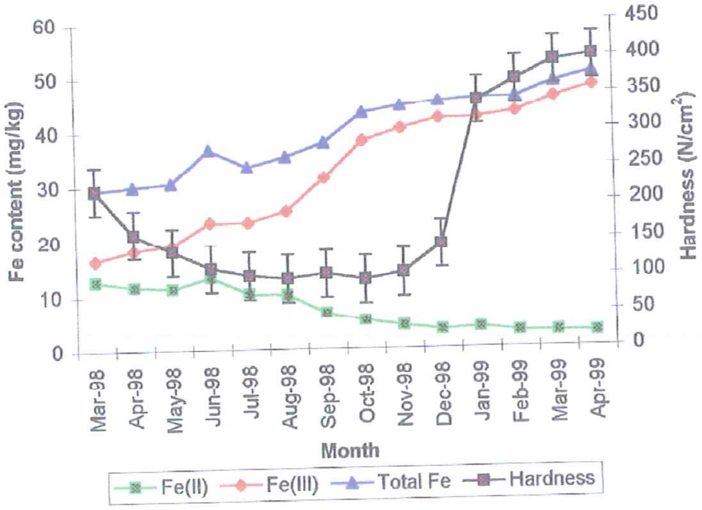


Fig. 9 Changes in Fe(II), Fe(III), Total Fe contents and hardness of exposed plinthite in Profile Pit APU. *Error bars represent standard error of the means*

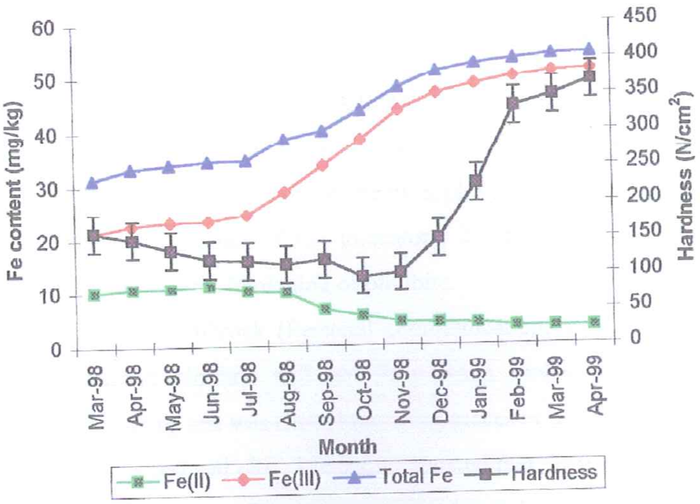


Fig. 10 Changes in Fe(II), Fe(III), Total Fe contents and hardness of exposed plinthite in Profile Pit APM. *Error bars represent standard error of the means*

Table 2.0 *Correlation coefficients (r) between hardness and moisture, Fe(II), Fe(III) and total Fe of plinthite in exposed profile pits*

Pit	Moisture	Fe(II)	Fe(III)	Total Fe
CPU2	-0.943(<0.00001)*	-0.644 (0.013)	0.827 (0.0003)	0.850 (0.0001)
CPM2	-0.908(<0.00001)	-0.458 (0.100)	0.591 (0.026)	0.609 (0.021)
CPL2	-0.919(<0.0001)	-0.624 (0.017)	0.804 (0.0005)	0.848(0.0001)
APU	-0.878(<0.0001)	-0.557 (0.038)	0.594 (0.025)	0.598 (0.024)
APM	- 0.780(0.001)	-0.612 (0.02)	0.671 (0.0086)	0.687 (0.0066)

*Values in brackets represent p-values

4.7.5 *Indicators and their threshold values at the onset of irreversible hardening of Plinthite*

The transformation of soft plinthite into petroplinthite presents an irreversible stage of soil degradation which results in land abandonment (Cassel and Lal, 1992). It is therefore necessary to develop and adopt management practices which are capable of mitigating the hardening process (Eswaran *et al*., 1990).

In contributing to the latter needs, this study presents some indicators and their threshold values for the onset of the irreversible hardening of plinthite. The indicators are the Fe(III) and Fe(II)s and moisture contents of plinthite and its hardness. In order to establish the threshold values of the indicators, it was necessary to pin-point the beginning of the irreversible hardening of plinthite.

According to Sombroek (Personal communication, 1999) and FAO (1998), irreversibly hardened plinthite will not flake when soaked overnight in water. Consequently, a flaking test was carried out using pieces of plinthite at different stages of hardness from the test soil pits. The results showed that the plinthite from APU and APM under cocoa plantation (Figs. 4, 5) continued to flake in water throughout the 14 months of observation. Although the plinthite from these pits were hard, irreversible hardening of plinthite could not be attained even at their peak Fe(III) content of 47.67 mg/kg for APU and 51.12 mg/kg for APM.

However, in pits CPU2, CPM2 and CPL2, irreversible hardening commenced in February and March, 1999, i.e. thirteen months of exposure to atmospheric conditions (Figs. 1-3). During these periods, flaking of the hard plinthite ceased to indicate the beginning of permanent hardening. The conditions of plinthite when permanent hardening began were:

Pit CPU2: 79.4 mg/kg Fe(III); 2.30 mg/kg; Fe(II); 8.7% moisture; and 629 N/cm^2 hardness

Pit CPM2: 78.77 mg/kg Fe(III); 2.13 mg/kg Fe(II); 7.3% moisture; and 507 N/cm^2 hardness

Pit CPL2: 79.33 mg/kg Fe(III); 2.17 mg/kg Fe(II); 9.4% moisture; and 610 N/cm^2 hardness

These findings show that for plinthite to begin hardening irreversibly under atmospheric conditions, the Fe(III) has to impregnate the material to levels not below 79 mg/kg at a moisture content below 10% and hardness of more than 500 N/cm^2. Fe(III) constituted 97% of the Fe content in all the three pits at the time of beginning of irreversible hardening.

4.8.0 *Alternate Wetting and Drying Effect on Plinthite*

The hardening of plinthite has traditionally been considered to be caused by or related to repeated wetting and drying (SSS, 1975, 1998; Alexander and Cady, 1962; Eswaran *et al*., 1990). Based on this assumption, the effects of alternate wetting and drying on plinthite were studied in a simulation experiment in the laboratory. The results are presented and discussed below.

4.8.1 *The Fe Contents of the Effluent*

The results showed the cumulative contents of Fe(III), Fe(II) and total Fe in the effluent to increase with increasing cycles of wetting and drying (Table 3). The results for the 4 to 7 cycles ranged from 0.092 to 0.200, 0.572 to 1.074 and 0.664 to 1.274 mg/L for Fe(III), Fe(II) and total Fe respectively. The enhanced level of total Fe may be due to the reduction process and the release of the more mobile Fe(II). The wet cycles created reduced conditions which favoured the production and leaching of Fe(II) into the effluent to increase its Fe content. Consequently, the increasing wet conditions associated with the increasing wetting and drying cycles provided a greater opportunity for more Fe(II) to get into the effluent.

It is therefore not surprising that Fe(II) constituted a greater percentage (84-87%) of the Fe content of the effluent. These findings confirm the observation that under wet conditions, the Fe held in the wet zone is mainly in the reduced Fe(II) form.

Table 3.0 ***Cummulative Fe Content of the Effluent from plinthite samples during wetting and drying cycles***

Parameter	Wetting and Drying Cycles			
	4	5	6	7
			mg/L	
Fe(III)	0.092	0.134	0.174	0.200
Fe(II)	0.572	0.726	0.878	1.074
Total Fe	0.664	0.870	1.052	1.174
% Fe(II) in Total Fe	86.1	83.4	83.5	91.5

The analyses further showed that the changes in the Fe(II) and Fe(III) content of the plinthite over time followed a logarithmic pattern (Figs. 11 - 13). The equations presented in Figs 11 to 13 indicated that the dynamics of Fe in plinthite is highly correlated with the length of exposure of the plinthite to atmospheric conditions. The coefficient of determination (R^2) showed that, in all cases, the length of exposure accounted for 98 - 99% of the decreases in Fe(II) and 88-99% of the increase in the Fe(III) contents in the plinthite columns. The negative gradient in the equations for the Fe(II) implies that the longer the plinthite is exposed to the atmosphere, the greater the rate of reduction in its Fe(II) content presumably through its oxidation into Fe(III). Consequently the Fe(III) content of plinthite increases with increasing length of exposure as indicated by the positive gradient. The intercepts, however, represent the initial Fe(II) and Fe(III) contents in the plinthite before exposure to atmospheric conditions. These values correspond to the Fe(II), Fe(III) and total Fe contents of the plinthite after being subjected to the different cycles of wetting and drying. In the case of the Fe(II), the values of the intercept decreased as the wetting and drying cycles increased. As indicated earlier (Section 4.8.2) the increasing cycles of wetness and dryness enhanced the production and leaching of Fe(II) through the process of reduction. On the other hand, while the initial Fe(III) content of plinthite remained stable, its content gradually increased through the reoxidation and precipitation of Fe(II) in the form of Fe(III).

The total Fe content of the plinthtie blocks (Fig. 14) showed that there were no significant changes in the initial Fe content of all the test plinthite samples over the period of observation. This is in contrast with the observations made on samples of the plinthite in the open pits analysis where significant increases in the Fe content were recorded (Section 4.8.2). The source of the additional Fe was alluded to enrichment from adjoining soil horizons. However, under controlled conditions where the plinthite blocks had no contact with any adjoining soil, enrichment of Fe from the surrounding soils was not possible. The controlled experiment thus lends credence to the theory of Fe enrichment from surrounding soil bodies as discussed by Eswaran and Raghu Mohan (1973); Driessen and Dudal (1991) and Lee (1996).

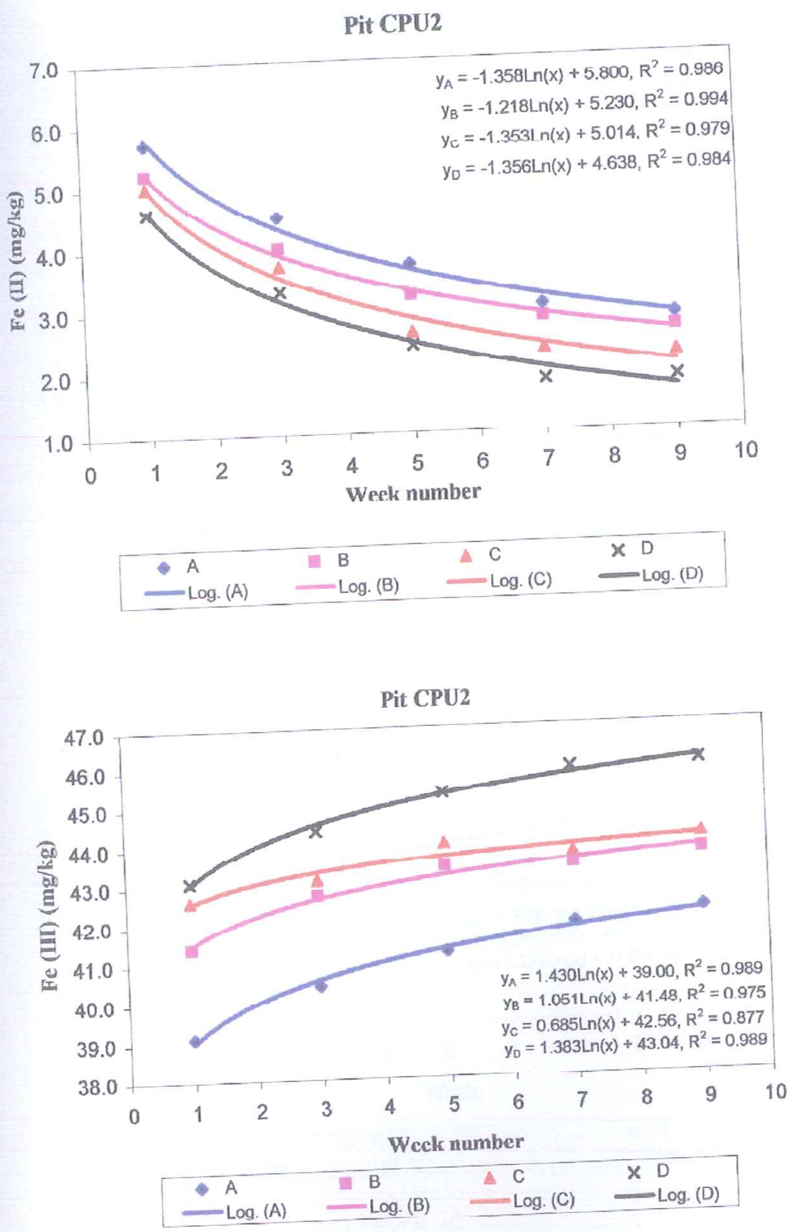
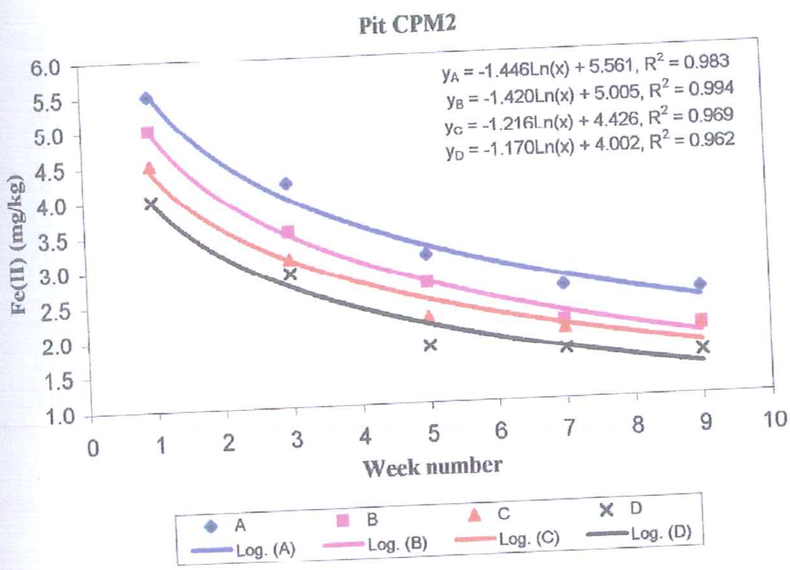


Fig. 11 Changes in Fe (II) and Fe(III) contents of Pit CPU2 plinthite samples after variable wetting and drying cycles

A = 4 wetting and drying cycles; B = 5 wetting and drying cycles
C = 6 wetting and drying cycles; D = 7 wetting and drying cycles
(One cycle was 2 weeks wetting followed by 2 weeks drying)



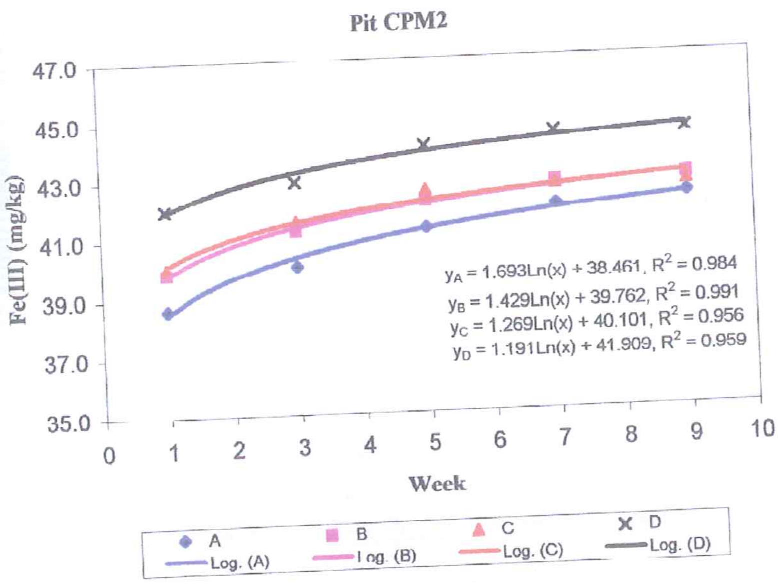
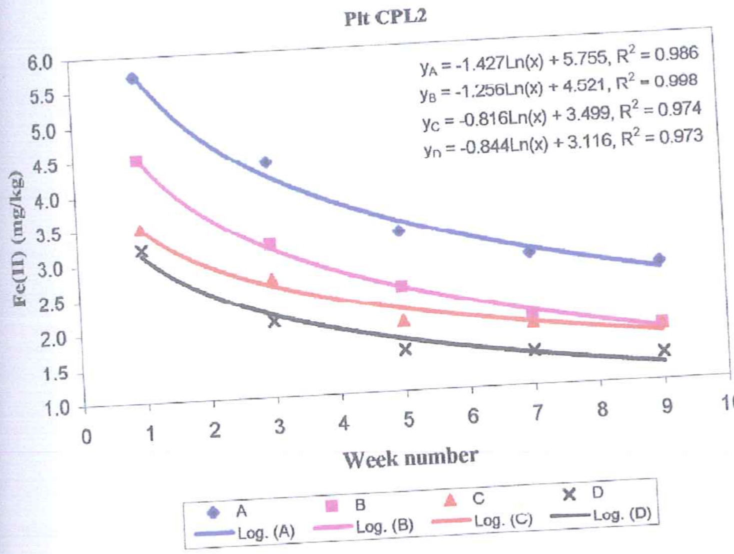


Fig. 12 Changes in Fe(II) and Fe(III) contents of Pit CPM2 plinthite samples after variable wetting and drying cycles
A = 4 wetting and drying cycles; B = 5 wetting and drying cycles
C = 6 wetting and drying cycles; D = 7 wetting and drying cycles
(One cycle was 2 weeks wetting followed by 2 weeks drying)



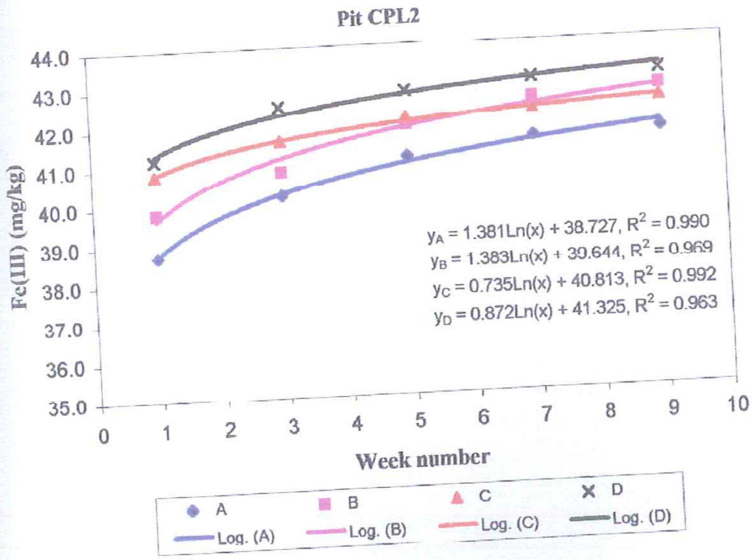


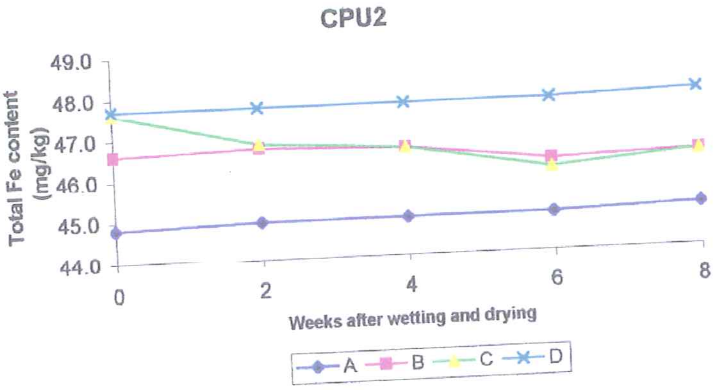
Fig. 13 Changes in Fe(II) and Fe(III) contents of Pit CPL2 plinthite samples after variable wetting and drying cycles

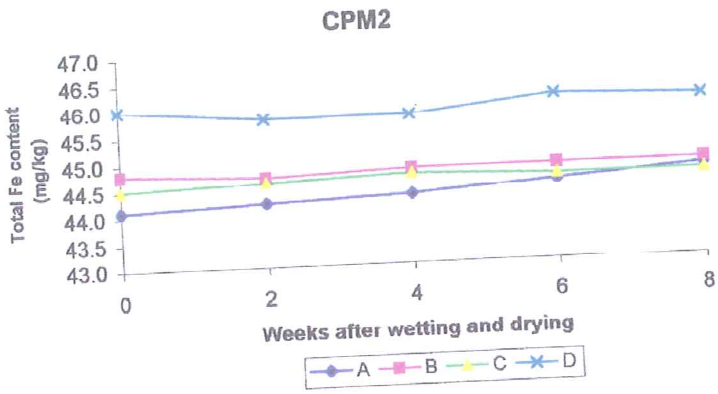
A = 4 wetting and drying cycles; B = 5 wetting and drying cycles
C = 6 wetting and drying cycles; D = 7 wetting and drying cycles
(One cycle was 2 weeks wetting followed by 2 weeks drying)

4.8.2. *Dynamics of Fe(III) and Fe(II) in Plinthite blocks*

The results of the Fe content of the plinthite blocks are presented in Figures 11-13. In all cases, the results showed that while the Fe(II) content decreased with increasing period of exposure there was a corresponding increase in the Fe(III) content. For example, the initial Fe(II) content of the plinthite from pit CPU2 (Fig. 11) after 4 cycles of wetting and drying, decreased gradually from 5.7 mg/kg to a minimum of 2.8 mg/kg over the period of observation. This corresponded to a decrease of 2.9 mg/kg or 51% in the initial Fe(II) content. On the other hand, the initial Fe(III) content of 39.1 mg/kg increased by 3.1 mg/kg or 7% over the 8 week period of observations. A similar pattern was observed for the 5, 6 and 7 cycles of wetting and drying. The increase in the initial Fe(III) content of the plinthite over the period of experimentation was due to the additional Fe(III) produced through the oxidation of the Fe(II). Thus as the more stable Fe(III) in the plinthite increased with increasing period of exposure to atmospheric conditions, the Fe(II) content decreased.

The dynamics of Fe(III) and Fe(II) in the plinthite from CPM2 and CPL2 (Figs. 12 and 13) followed the above pattern described for CPU2.





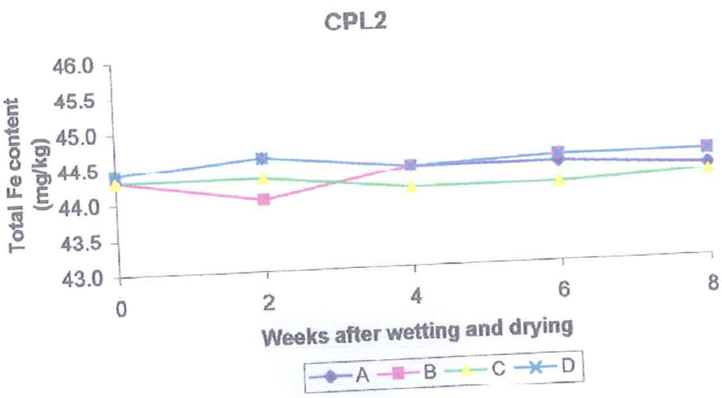


Fig. 14 Changes in total iron contents of Pits CPU2, CPM2 and CPL2 plinthite samples after variable wetting and drying cycles
A = 4 wetting and drying cycles; B = 5 wetting and drying cycles
C = 6 wetting and drying cycles, D = 7 wetting and drying cycles
(One cycle was 2 weeks wetting followed by 2 weeks drying)

4.8.3 ***Hardness of Plinthite blocks***

The plinthic material from pit CPU2 in Tank A had initial hardness value of $80N/cm^2$ (Fig. 15). After two weeks of exposure to the atmosphere the value rose to $260N/cm^2$ and then increased gradually to $320N/cm^2$ after exposure for eight weeks.

The same material from Tank D (Fig. 15) had an initial hardness value of $100N/cm^2$, rose to $295N/cm^2$ after two weeks exposure and then to $400N/cm^2$ when exposed for eight weeks. The values for the other materials from the other tanks followed the same pattern. However, the longer the materials were subjected to repeated wetting and drying as in Tank D the higher their initial hardness values and the higher the increases in their values over longer periods of exposure to the atmosphere (Figs.15). Similar trends were observed for samples from CPM2 and CPL2 (Figs. 16-17). The results confirmed the belief that plinthite would harden faster when subjected to repeated wetting and drying conditions. The longer the material was subjected to wetting and drying, the harder it became after exposure to the atmosphere.

Pit CPU2

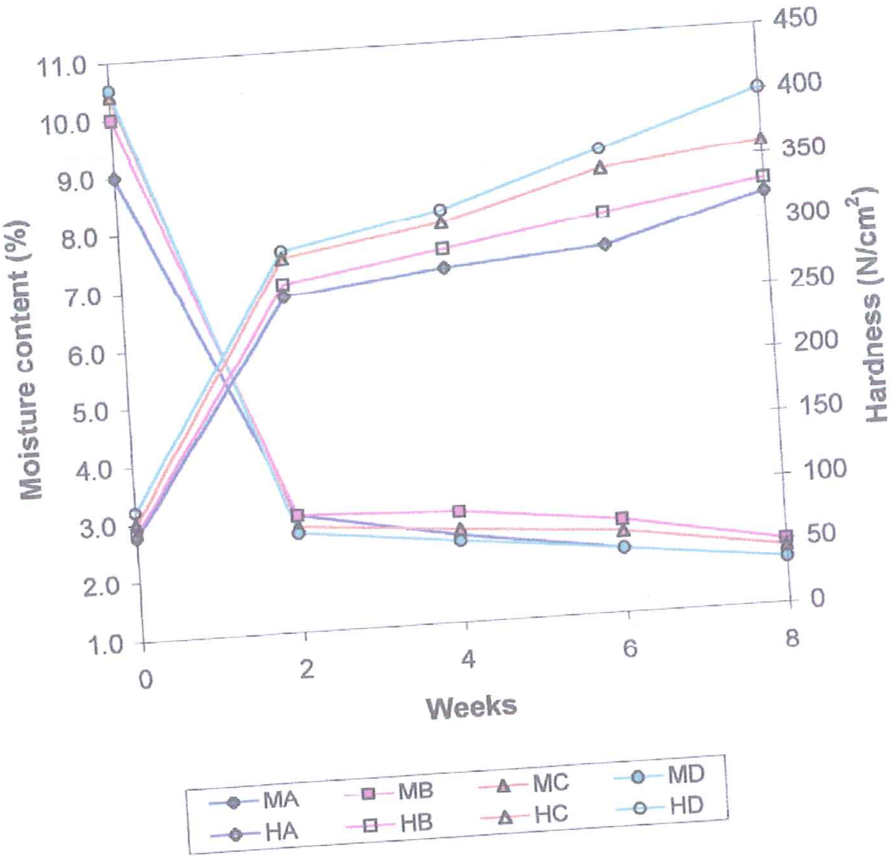


Fig. 15 Changes in hardness and moisture contents of plinthite samples from Pit CPU2 exposed after variable wetting and drying cycles in tanks A to D
A = 4 wetting and drying cycles; B = 5 wetting and drying cycles
C = 6 wetting and drying cycles; D = 7 wetting and drying cycles
(One cycle was 2 weeks wetting followed by 2 weeks drying)

Pit CPM2

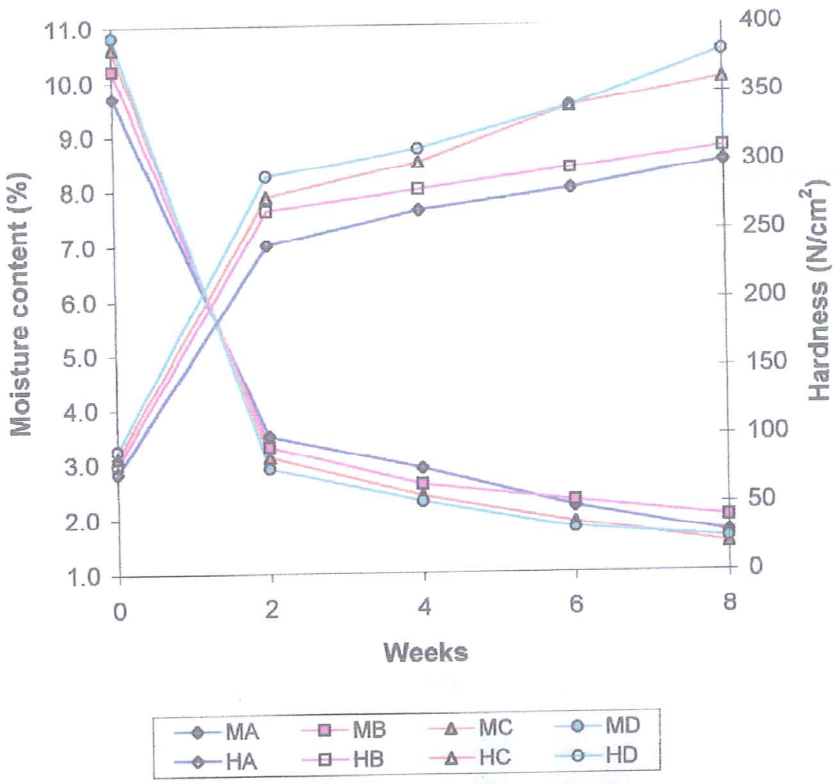


Fig. 16 Changes in hardness and moisture contents of plinthite samples from Pit CPM2 exposed after variable wetting and drying cycles in tanks A to D
A = 4 wetting and drying cycles; B = 5 wetting and drying cycles
C = 6 wetting and drying cycles; D = 7 wetting and drying cycles
(One cycle was 2 weeks wetting followed by 2 weeks drying)

Pit CPL2

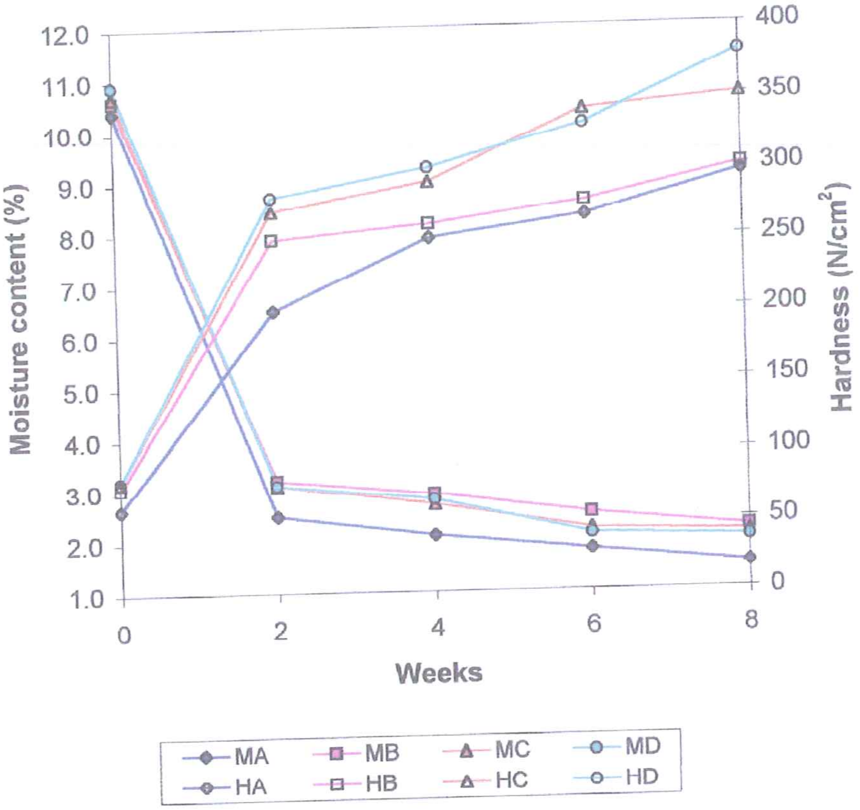


Fig. 17 Changes in hardness and moisture contents of plinthite samples from Pit CPL2 exposed after variable wetting and drying cycles in tanks A to D

A = 4 wetting and drying cycles; B = 5 wetting and drying cycles
C = 6 wetting and drying cycles; D = 7 wetting and drying cycles
(One cycle was 2 weeks wetting followed by 2 weeks drying)

4.8.4 *Moisture content of Plinthite blocks*

The moisture content of the plinthite blocks, exposed to the atmosphere decreased sharply within two weeks to below a third of their initial values and thereafter decreased further gradually to about 20% of the original values after eight weeks exposure (Figs. 15-17). It appeared that the initial moisture contents were higher in blocks subjected to longer periods of wetting and drying but after eight weeks of drying their values dropped to nearly 2%.

The rates of drying of the materials followed the rates of increases in their hardness (Figs. 15-17). They also showed a direct relationship with the rates of increases in Fe(III) and decreases in Fe(II). The correlation of hardness of plinthite with all the parameters were highly significant ($P<0.01$). Hardness negatively correlated with moisture and Fe(II) contents, but positively with Fe(III) (Table 4.0). These confirm the observation that increase in Fe(III) contents as well as dehydration and the accompanying reduction in Fe(II) contents result in hardening of the plinthite material.

Table 4.0 ***Correlation coefficients (r)* between hardness and moisture, Fe(II) and Fe(III) of plinthite blocks from profile pits CPU2, CPM2 and CPL2 subjected to variable wetting and drying conditions.***

Pit	Moisture	Fe(II)	Fe(III)
CPU2	-0.956	-0.931	0.678
CPM2	-0.972	-0.923	0.792
CPL2	-0.925	-0.847	0.834

* All the coefficients were significant at $P<0.01$

4.9 *Burning Effect on Plinthite*

Burning of vegetation results in high soil temperature, dehydration of soil, combustion of soil organic matter, transformation of oxides of Fe and increased hardness of plinthite. Because bush burning is pervasive in most farming systems in Ghana, its effects on plinthite were examined in this study.

4.9.1 *Heat transmission through Plinthite*

The results of the experiment on the effect of burning on plinthite indicated that heat was transmitted through the material. Temperature measurements within the plinthite at 3 cm and 5 cm depths indicated gradual increase in temperature of the material to maximum values before decreasing (Appendix 7). The initial temperature of 42°C at 3 cm depth in pit CPU2 increased to 47°C after 15 minutes before decreasing to 40°C within 35 minutes and remained constant for 10 minutes before decreasing. The pattern was observed to be almost the same in the other two pits - CPM2 and CPL2. The results indicated that burning of vegetative cover of soils caused heat transmission through the soil to dehydrate the plinthite material resulting in its permanent hardening.

The burning temperature was 250°C while the ambient air temperature before the burning was 33°C.

4.9.2 *Hardness of Plinthite*

The burning effect on the hardness of plinthite in pits CPU2, CPM2 and CPL2 (Figs. 18-20) was irregular within the first 8 weeks of observation. Thereafter, there was a progressive increase in hardness till the end of the study. In general, the initial hardness of plinthite in all the pits increased with time with a range of 350-570, 220-600 and 116-520 N/cm^2 for CPU2, CPM2 and CPL2 respectively.

A comparison of the hardness of plinthite in the pits under atmospheric conditions (Appendix 2) with that under burning clearly shows that burning accelerates the hardening of plinthite. Whereas a hardness of 500 N/cm^2 was attained after 11-13 months of exposure under atmospheric conditions, this value was recorded within 10-12 weeks under burning.

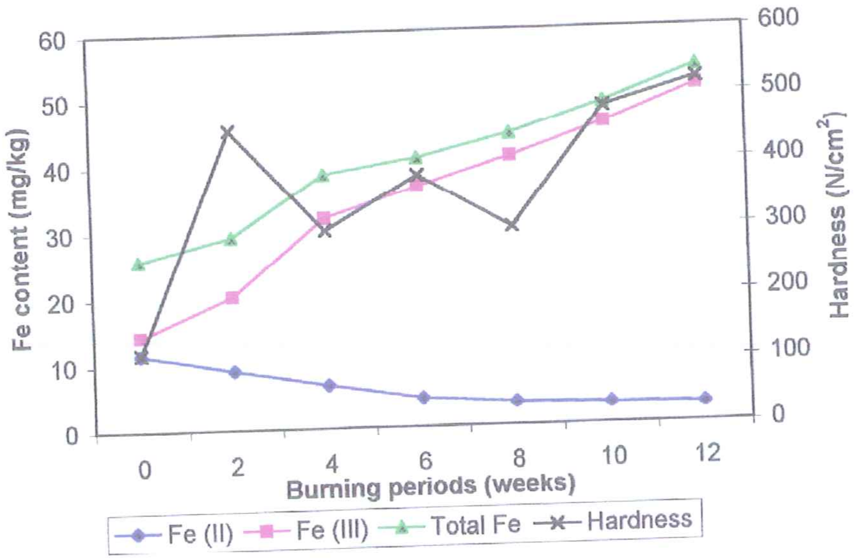


Fig.18 Influence of burning on hardness and iron contents of plinthite at Site CPU2

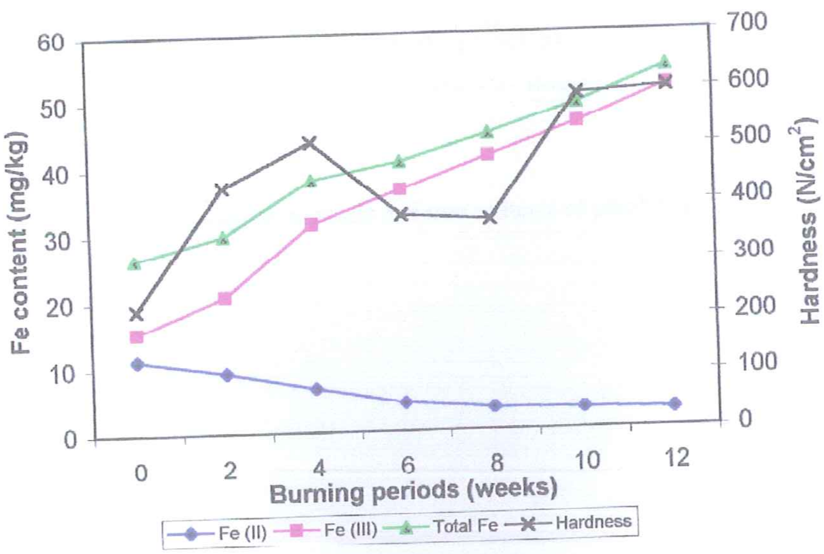


Fig. 19 Influence of burning on hardness and iron contents of plinthite at Site CPM2

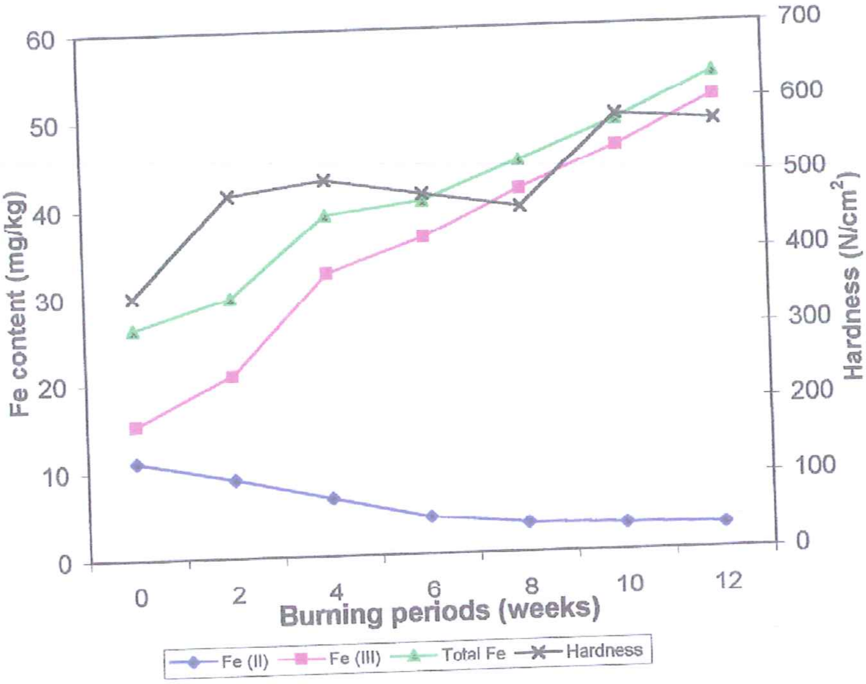


Fig. 20 Influence of burning on hardness and iron contents of plinthite at Site CPL2

4.9.3 ***Fe content of plinthite***

Burning had a significant effect on the dynamics of Fe in the plinthite from all the pits (Appendix 6). For all the three exposed plinthite layers in CPU2, CPM2 and CPL2, while there were significant increases in Fe(III) content over the period of observation, the Fe(II) content decreased.

The combustion of organic compounds produces a reducing condition and favours the production of Fe(II) which is subsequently oxidized into the Fe(III) form when air enters the soil upon cooling (Fine and Singer, 1989). High temperatures have also been found to favour the formation of Fe(III) compounds (McBride, 1994). Thus while there was a decrease in Fe(II) through oxidation, the Fe(III) content of plinthite was enhanced.

The Fe(II) content decreased from 11.0 to 2.7 mg/kg in CPU2 over the period of observation while Fe(III) content increased from an initial value of 15.3 to 51.6 mg/kg. This trend was similar in pits CPM2 and CPL2. Unlike the controlled experiment (Section 3.5) in which the initial total Fe content of the plinthite remained constant throughout the period of observation, the initial Fe in the burning studies increased presumably through enrichment from adjoining soil horizons as recorded in section 4.8.2.

It was also observed that although the threshold hardness of 500 N/cm^2 for irreversible hardening was attained at the end of the study, the Fe(III) content was below the threshold value of 79 mg/kg. Consequently, irreversible hardening could not be attained in the plinthic materials of the three soils subjected to burning.

CHAPTER FIVE

5.1 CONCLUSIÓN

The study has shown that plinthite and its hardened form, petroplinthite, are widely distributed in the agricultural soils of Ghana. Plinthite was found to occur in over 54% of the country's agricultural lands. These materials pose grave threat to sustainable agricultural production in future. Plinthite and petroplinthite formations were found to be on-going and active processes on several topographic sites from uplands to lowlands.

The material was found to occur in many soil types developed from varied parent materials. Contrary to the belief that plinthite forms only on flat lands which are imperfectly drained, this study identified its formation in well to moderately well drained upland soils with plinthite at all slope sites. Atmospheric precipitation was the source of moisture for the wetting cycles of plinthite in upland soils. In the lowlands, the wetting and drying cycles of plinthite were mainly due to fluctuations in groundwater levels.

Based on the source of water for the wetting cycles of plinthite, the study distinguished three types of plinthite: *Stagnic plinthite*, in which the source of the wetting cycles was due to atmospheric precipitation. This type was found in upland soils well above the reaches of the groundwater table. *Gleyic plinthite* occurred in soils of lowlands where the alternate wetting and drying cycles of the material were due to fluctuations in the groundwater levels. *Pseudo-plinthite* was found to occur at lower slope sites and valley bottoms, and it was noted to have a colouration resemblance of a plinthite but did not harden on exposure to the atmosphere since it occurred in undeveloped soils of colluvio-alluvial materials with low iron content.

Increasing dehydration and Fe(III) content of plinthite were the principal factors influencing its hardening. Whilst the hardness of plinthite was negatively correlated with its moisture content, it was positively correlated with its Fe(III) content.

Vegetative soil cover was found to maintain high moisture and low Fe(III) contents of the plinthite with a consequent reduction in the rate of its hardening. Within the 14 month period of study, irreversible hardening could not be attained for the soils under cover.

It should also be noted that plinthite became progressively dehydrated and progressively enriched with Fe(III) iron when exposed, especially, if the soil vegetative cover was removed, topsoils eroded and subjected to heating.

The findings of this study strongly suggest that the bulk of the soil resources of the country are capable of becoming permanently degraded by the formation of petroplinthite in them. Agricultural production, rural incomes, and food security are all at risk. There is therefore the urgent need for soil scientists and other environmental scientists to search for permanent solutions to prevent the formation of plinthite and its hardening and the subsequent degradation of the soil resources of the country.

5.2 RECOMMENDATIONS

The study has shown that for plinthite to harden irreversibly, it must be impregnated by Fe(III) to levels not less than 79 mg/kg and at a moisture content below 10% and hardness of more than 500 N/cm^2. These indicators and their threshold values need to be regularly monitored in agricultural soils. The determination of iron content in soils by the Phenanthroline method should form an integral part of the routine chemical analysis of agricultural soils.

Maintaining adequate vegetative soil cover all year round would be an important soil management option for preventing plinthite build-up and petroplinthite formation. Mulching, especially using life-mulch, zero tillage and agro-forestry practices, must be incorporated into farming systems rather than clean weeding of farmlands to keep the soils always covered and moist to prevent hardening of the subsoils.

Practices which expose and predispose soils to dehydration and formation of petroplinthite should be avoided. These include deforestation, overgrazing, bush burning, charcoal production, clean weeding of farmlands, surface mining, mechanical topsoil removal, improper tillage and soil erosion.

In order to facilitate the choice of appropriate management practices, the presence of plinthite in the soil to be managed should be known. This can be facilitated if plinthite is used as a diagnostic property in the Ghana soil classification system. In the light of the results of the study, it is proposed that the current definition of plinthite be reviewed to incorporate the findings of the study. The new definition would remove the notion that plinthite forms only in soils of flat terrain with shallow groundwater table and that the present occurrence of petroplinthite in upland soils was due to earth inversion.

CHAPTER SIX

6.0 LITERATURE CITED

Ahn, P.M. (1970). West African Soils. Oxford University Press.

Alexander, L.T (1951). Preliminary Report on African Laterite Soil Survey. Tech Asst. Prog. No. 47. Organisation for European Economic Cooperation, Paris.

Alexander, L.T. and Cady, J.G. (1962). Genesis and hardening of laterite in soils. Techn Bull. No. 1282, CSC, US Department of Agric. pp.90.

Aleva, G.J.J. (1994) Laterites concepts, geology, morphology and chemistry. ISRIC, Wageningen. pp.169

Asiamah, R.D. and Dadgari, F. (1985). A detail soil study of the 350 - hectare extension area to Kpong Farms, Akuse. Acres International Limited, Niagara Falls, Ontario, Canada.

Asiamah, R.D. and Dedzoe, C.D. (1999). Plinthization - A threat to agricultural production Journal of Agric. Science Vol. 32.

Ayetey, J.K. and Castel, A.K. (1970). Engineering-Geological study of some Ghana lateritic soils and their profiles. Project SM 12 BRRI, Kumasi.

Bain, A.G. (1952). On the geology of South Africa. Trans. Geol. Soc. 7: 175 - 182.

Bampoe-Addo, A., Raman, K.V. and Mortland, M.M. (1969). Clay mineral status of some major soil series in Ghana. Soil Sci. 107: 119 - 125.

Black, C.A. (1965). Methods of Soil Analysis, Part 1, 2; Agronomy No. 9; Am. Soc. Agron., Madison, WI.

Bonsu, M., Quansah, C. and Agyemang, A. (1996). Interventions for land and water conservation in Ghana. *In*: Ofori, F. and Safo, E.Y. (eds). Proceedings of the National Workshop on Soil Fertility Management Action Plan for Ghana. Ministry of Food and Agriculture, Accra, Ghana.

Bouyoucos, G.J. (1926). Hydrometer method improved for making particle size analysis of soils, Agron. Journ 54.

Brammer, H. (1962). Soils of Ghana. In Agriculture and Land use in Ghana (ed. J.B. Wills). Ministry of Food and Agriculture. Oxford University Press, London. pp 88-126.

Bremner, J.M. and Mulvaney, C.S. (1982). Total nitrogen. *In*: Page, A.L., Miller, R.H., and Keeney, D.R. (eds). Methods of Soil Analysis. Part 2. ASA; SSSA, Madison, WI, USA. pp. 595 -622.

Buchanan, F. (1807). A journey from Madras through the countries of Mysore, Canara and Malabar. Chap, XII: 116. East India Co. London.

Buol, S.W., Hole, F.D. and McCracken, R.S. (1973). Soil genesis and classification. The Iowa State University Press, Ames, Iowa.

Cassel, D.K. and Lal, R. (1992). Soil physical properties of the tropics: Common beliefs and management restraints. *In*: Lal, R. and Sanchez, P. (eds). Myths and Science of Soils in the Tropics SSSA Special Publ. No. 29:61-90, Soil Science Society of America. Madison, WI.

Cottenie, A. (1980). Soil and plant testing as a basis of fertilizer recommendations. FAO Soil Bulletin No. 38/2, FAO, Rome.

Daniels, R.B., Perkins, H.F., Hajek, B.F., and Gamble, E.E. (1978). Morphology of discontinuous phase plinthite and criteria for its field identification in the South Eastern United States. Soil Sci. Soc. Amer, J. 42: 944 - 949.

Donahue, R.L., Shicklima, J.C. and Lynn, S. (1983). An introduction to Soil and Plant growth. 3rd ed. Printice-Hall, Englewood Cliff, N.J.

Driessen, P.M. and Dudal, R. (1991). The major soils of the World. Lecture notes on their geography formation, properties and use. Agric. University of Wageningen and Katholieke Universiteit, Leuven, pp 310.

Eswaran, H. and Raghu Mohan, N.G. (1973). The microforbric of petroplinthite. Soil Sci. Soc. Amer. Proc. 37: 79-82.

Eswaran, H., De Coninck, F., and Varghese, T. (1990). Role of plinthite and related forms in Soil degradation. Adv. Soil Sci. 11: 109 - 127.

Fanning, D.S. and Fanning, M.C.B. (1989). Soil Morphology, Genesis and Classification. Wiley and Sons, Chichester.

FAO (1976). Soil Map of the World, Vol. VI, Africa. FAO, Rome.

FAO (1990a). Guidelines for Soil Description. 3rd Edition (Revised) FAO, Rome pp 70.

FAO (1990b). FAO/UNESCO Soil Map of the World. Revised Legend. FAO Rome. pp 119.

FAO (1991). World Soil Resources: World Soil Resources Report, 66, FAO, Rome. pp 58.

FAO (1996). The selection of soils for cocoa. Soil Bulletin No. 5. FAO, Rome.

FAO (1998). World Reference Base for Soil Resources. World Soil Resources Reports No. 84, FAO, Rome. pp. 88

Fine, P. and Singer, M.J. 91989). Pedogenic factors affecting magnetic susceptibility of Northern California soils. Soil Sci. Soc. Am. J. 53: 1119-1127.

Fitz Patrick, E.A. (1980). Soils, their formation, classification and distribution. Longman, London. pp 353.

Gidigasu, D.M. (1969). The formation and general charcteristics of laterite and Lateritic Soils. Project Report SM No.2 BRRI, Kumasi.

Gidigasu, M.D. (1971). A contribution to the study of the physico-chemical implications of tropical weathering and laterisation. J. Southeast Asian Soc. Soil Eng. Bangkok. 2: 131- 149

Gidigasu, M.D. (1972). Mode of formation and geotechnical characteristics of laterite materials of Ghana in relation to soil forming factors. Elsevier Publishing Company, Amsterdam pp. 150.

Gidigasu, M.D. (1974). Degree of weathering in the identification of laterite materials for engineering purposes. Eng. Geo. 8: 213 - 266.

GOG (1995). Ghana-Vision 2020 (The first step: 1996-2000). Presidential Report to Parliament. Government Printer, Accra.

Goodlan, R.J.A. and Irwin, H.S. (1975).. Amazon jungle: Green hell to red desert? Elsevier Amsterdam.

Grim, R.E. (1953). Clay mineralogy. McGraw Hill, New York pp. 384.

Hillel, D. (1998). Environmental Soil Physics. Academic Press, New York.

Hughes, J.C. (1981). Mineralogy. *In*: Greenland, D.J. (eds.). characterization of soils in relation to their classification and management for crop production: Examples from some areas of the Humid Tropics. Clarendon Press, Oxford. pp 30-79.

IAB. (1934). Soil, Vegetation and Climate. Tech. Comm. No. 29. IAB Harpenden, England.

Jackson, M.L. (1967). Soil Chemical Analysis. Printice Hall. Inc..Englewood Cliff, N.J.
Joffe, J.S. (1949). Pedology. Pedology publication, New Jersey.

Lee, T. (1996). Laterite facts. Electronic Communication: htt:/www.actwin.com/fish/ aquatic-plants/month.9602/msg00024.html.

Maignien, R. (1966). Review of research on laterites. Natural Resources Research Ser. IV. UNESCO, Paris. pp. 148

Matheis, G. (1982). Geochemical bedrock reflection in laterite covers-case histories from Nigeria, West Africa. Proceedings of the 11th Int. Seminar on Laterisation Processes, 4-12 July, 1982, University of Sao Paulo, Brazil. pp. 309-317.

McBridge, M.B. (1994). Environmental Chemistry of Soils. Oxford University Press, Oxford.

McFarlane, M.J. (1976). Laterite and landscape. Academic Press, London. pp. 151

McNeil M. (1964). Lateritic soils. Sci. Am. 211: 96 - 102.

Milne, G. (1935). A soil reconnaissance journey through parts of Tanganyika Territory. Journal of Ecology 35: 192 - 269.

MOFA, (1998). National Soil Fertility Management Action Plan. Ministry of Food and Agriculture, Accra.

Mohr, E.C.J., Van Baren, F.A. and Van Schuylenborgh (1972). Tropical soils. A comprehensive study of their genesis. Third, revised and enlarged edition. Mouton - Ichtiar Baru-van Hoeve, the Hague-Paris - Djakarta, pp 481.

Moormann, F.R. (1981). Representative toposequences of soils in Southern Nigeria, and their pedology. In: Greenland, D.J. (ed). Characterization of soils in relation to their classification and management for crop production. Examples from some areas of humid tropics. Clarendon Press, Oxford. pp. 10-29.

Munsell. (1994). Munsell Color Charts, (Rev. edition), Macbeth Division of Kollmorgan Instruments Corporation. 405 Little Britain Road, New Windsor, N.Y.

Obeng, H.B. (1960). Charistarization of some latosols and associated soils of the north western savanna zone of Ghana. 7th Intern. Congr. Soil Sci. Trans. 4 : 251 - 264.

Obeng, H.B. (1970). Characteristization and classification of some ironpan soils of Ghana. PhD Dissertation. Iowa State University, Ames, Iowa.

Ofori, F. (1998). Managing the soil resources base for accelerated agricultural growth in Ghana. Directorate of Crop Services, Ministry of Food and Agriculture, Accra. pp. 26.

Quansah, C. (1999). Integrated soil management for sustainable agriculture and food security in Ghana. A country paper for FAO Regional Office for Africa, Accra, Ghana.

Raychandhuri, S.P. (1981). The occurrence, distribution, clasification and management of laterite and lateritic soils. ORSTOM ser. Pedol., Vol. XVII pp. 249-252.

Sanchez, P.A. (1981). Soil management in the Oxisol Savannahs and utisol jungles of tropical south America. *In*: Greenland, D.J. (ed.). Characteriszation of soils in relation to their classification and management for crop production. Examples from some areas of the Humid Tropics, Clarendon Press, Oxford. pp. 214 - 253.

Sivarajasingham, S. Alexander, I.T., Cady, J.G. and Cline, M.G. (1962). Laterite. In Advances in Agronomy. Vol. 14 pp 1 - 60, Academic Press, New York.

Sombroek, W.G. and Camargo, M.N. (1982). Groundwater laterite and ironstone soils in Brazil with examples from the Amazon Region. Proceedings of the 11th Int. Seminar on Laterisation processes, 4-12 July, 1982. University of Sao Paulo, Brazil. pp 541-552.

SRI. (1998). FAO Soil Map of Ghana. Soil Research Institute, Accra Centre, Accra.

Sys, C. (1968). Suggestions for the classification of tropical Soils with lateritic materials in the American Classification. Pedologie XVIII (2): 189 - 198.

Tietz, G.F. (1982). Chemical and mineralogical alterations in the lateritic cover of Nigeria, West Africa. Proceedings of the 11th Int. Seminar on laterisation processes, 4-12 July, 1982. University of Sao Paulo, Brazil. pp 359-371.

USDA. (1975). Soil Taxonomy. A basic system of Soil classification for making and interpreting soil surveys. Agric. Handbook No. 436, SCS, U.S. Dept. Agric., US Govt. Printing Office, Washington, D.C., pp 754.

USDA. (1998). Keys to Soil Taxonomy, 6th Ed. SCS, US. Dept. Agric. U.S. Gov[illegible]t Printing Office, Washington, DC pp 306.

van Breeman, N. (1988). Long-term chemical, mineralogical, and morphological effects of iron-redox processes in periodically flooded soils. *In*: Stucki, J.W., Goodman, B.A. and Schwetmann, U. (eds.). Iron in soils and clay minerals. NATO A.S.I. Series. D Reidel Publishing Co. Dordrecht, Netherlands. Pp. 811-823.

van Reeuwijk, L.P. (ed) (1995). Procedures for Soil Analysis. 5th ed. Tech. Paper 9. International Soil Reference and Information Centre, Wageningen.

van Wambeke, A. (1991). Soils of the tropics. Properties and Appraisal. McGraw-Hill, New York.

Varghese, T. and Byju, G. (1993). Laterite Soils. Their distribution, characteristics, classification and management, State Committee Sci. Techn and Environ., Thiruvananthapuram, Kerala, pp 116.

Walkley, A. and Black, I.A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37: 29 - 38.

APPENDICES

APPENDIX 1

*Concentration of iron in effluent in the 4 tanks**

1. **Fe(III) (mg/L)**

	Tank A	**Tank B**	**Tank C**	**Tank D**
4/9/98	0.008	0.012	0.012	0.018
2/10/98	0.010	0.014	0.010	0.008
30/10/98	0.046	0.040	0.038	0.044
27/11/98	0.028	0.028	0.030	0.034
25/12/98		0.040	0.038	0.044
25/1/99			0.046	0.040
3/3/99				0.012

2. **Fe(II) (mg/L)**

	Tank A	**Tank B**	**Tank C**	**Tank D**
4/9/98	0.134	0.134	0.130	0.132
2/10/98	0.144	0.142	0.140	0.142
30/10/98	0.150	0.152	0.148	0.152
27/11/98	0.144	0.142	0.156	0.162
25/12/98		0.156	0.154	0.142
25/1/99			0.150	0.152
3/3/99				0.192

3. **Total Fe (mg/L)**

	Tank A	**Tank B**	**Tank C**	**Tank D**
4/9/98	0.142	0.146	0.142	0.150
2/10/98	0.154	0.156	0.150	0.150
30/10/98	0.196	0.192	0.186	0.196
27/11/98	0.172	0.180	0.186	0.196
25/12/98		0.196	0.192	0.186
25/1/99			0.196	0.092
3/3/99				0.204

* Each value represents the cumulative Fe released from the 3 blocks of plinthite in each tank.

APPENDIX 2

Changes in hardness and moisture contents of exposed plinthite in profile pits.

2.1 CPU2

	Mean hardness and moisture content (Standard error of the means in brackets)		
	Hardness (N/cm^2)	Moisture (%)	Monthly Total Rainfall (mm)
Mar-98	447 (±64.7)	16.6 (±1.5)	32.7
April-98	380 (±34.2)	16.5 (±0.8)	331.4
May-98	265 (±4.5)	18.4 (±0.5)	172.4
June-98	174 (±10.1)	21.6 (±0.1)	200.8
July-98	180 (±9.5)	21.0 (±0.5)	90.0
Aug-98	210 (±40.2)	20.6 (±1.1)	103.2
Sept-98	397 (±22.0)	16.4 (±0.5)	72.7
Oct-98	259 (±40.7)	17.6 (±0.3)	143.6
Nov-98	385 (±29.5)	16.9 (±0.7)	39.2
Dec-98	512 (±4.3)	15.5 (±0.8)	30.3
Jan-99	452 (±39.4)	9.9 (±1.1)	59.3
Feb-99*	629 (±31.9)	8.7 (±1.5)	12.4
Mar-99	713 (±59.3)	5.8 (±0.4)	149.2
April-99	710 (±5.1)	4.6 (±0.4)	267.3

* starting point of irreversible hardening

2.2 CPM2

	Mean hardness and moisture content (Standard error of the means in brackets)		
	Hardness (N/cm^2)	Moisture (%)	Monthly Total Rainfall (mm)
Mar-98	459 (±22.5)	15.0 (±0.5)	32.7
April-98	398 (±5.1)	17.4 (±0.1)	331.4
May-98	310 (±6.0)	18.3 (±0.4)	172.4
June-98	140 (±17.4)	22.3 (±0.4)	200.8
July-98	210 (±10.2)	22.5 (±0.2)	90.0
Aug-98	257 (±13.8)	19.6 (±0.3)	103.2
Sept-98	344 (±46.5)	17.6 (±0.1)	72.7
Oct-98	250 (±15.6)	20.5 (±1.1)	143.6
Nov-98	307 (±51.0)	19.0 (±1.6)	39.2
Dec-98	332 (±34.6)	16.3 (±1.2)	30.3
Jan-99	361 (±83.4)	14.9 (±1.2)	59.3
Feb-99	417 (±41.9)	10.9 (±1.3)	12.4
Mar-99*	507 (±54.6)	7.3 (±1.6)	149.2
April-99	513 (±57.0)	4.7 (±0.5)	267.3

* starting point of irreversible hardening

2.3 CPL2

	Means hardness and moisture content (Standard error of the means in brackets)		
	Hardness (N/cm^2)	Moisture(%)	Monthly Total Rainfall (mm)
Mar-98	457 (±56.2)	15.0 (±1.3)	32.7
April-98	350 (±10.1)	16.5 (±0.9)	331.4
May-98	254 (±9.0)	19.2 (±0.0)	172.4
June-98	100 (±12.9)	23.5 (±0.3)	200.8
July-98	120 (±11.1)	22.5 (±0.2)	90.0
Aug-98	215 (±15.7)	20.6 (±0.4)	103.2
Sept-98	288 (±32.2)	18.9 (±0.7)	72.7
Oct-98	265 (±7.9)	13.5 (±0.2)	143.6
Nov-98	321 (±53.8)	13.1 (±0.1)	39.2
Dec-98	420 (±43.6)	10.2 (±1.2)	30.3
Jan-99	532 (±56.1)	11.1 (±0.1)	59.3
Feb-99*	610 (±36.3)	9.4 (±1.0)	12.4
Mar-99	610 (±57.2)	6.5 (±1.5)	149.2
April-99	593 (±6.7)	4.7 (±0.3)	267.3

* starting point of irreversible hardening

2.4 APU

	Mean hardness and moisture content (Standard error of the means in brackets)		
	Hardness (N/cm²)	Moisture(%)	Monthly Total Rainfall (mm)
March-98	220 (±10.1)	19.5 (±0.2)	113.9
April-98	160 (±15.2)	17.3 (±0.1)	131.3
May-98	135 (±7.4)	17.6 (±0.2)	155.1
June-98	112 (±5.6)	23.0 (±0.1)	231.1
July-98	101 (±6.1)	23.0 (±0.2)	127.0
Aug-98	97 (±3.7)	23.3 (±0.1)	103.3
Sept-98	103 (±4.7)	23.2 (±0.1)	134.5
Oct-98	95 (±7.7)	21.1 (±0.2)	216.2
Nov-98	104 (±9.2)	19.9 (±0.4)	16.9
Dec-98	142 (±18.3)	20.1 (±0.4)	60.6
Jan-99	339 (±4.7)	18.1 (±0.2)	0.43
Feb-99	367 (±32.)	14.8 (±0.7)	37.3
Mar-99	393 (±24.0)	12.1 (±0.4)	63.9
April-99	400 (±23.1)	10.6 (±0.4)	174.9

2.5 APM

	Mean hardness and moisture content (Standard error of the means in brackets)		
	Hardness (N/cm²)	Moisture(%)	Monthly Total Rainfall (mm)
March-98	160 (±16.4)	22.5 (±0.2)	113.9
April-98	150 (±11.1)	18.7 (±0.2)	131.3
May-98	135 (±8.3)	18.5 (±0.2)	155.1
June-98	121 (±6.4)	22.8 (±0.2)	231.1
July-98	119 (±6.2)	22.3 (±0.2)	127.0
Aug-98	114 (±9.4)	22.8 (±0.1)	103.3
Sept-98	120 (±10.6)	22.8 (±0.2)	134.5
Oct-98	96 (±5.8)	23.3 (±0.8)	216.2
Nov-98	101 (±5.8)	23.3 (±0.2)	16.9
Dec-98	148 (±7.6)	21.8 (±1.4)	60.6
Jan-99	225 (±28.3)	21.5 (±0.3)	0.43
Feb-99	332 (±32.7)	19.3 (±0.2)	37.3
Mar-99	347 (±35.3)	18.1 (±0.9)	63.9
April-99	367 (±40.6)	16.1 (±0.5)	174.9

APPENDIX 3

Changes in iron contents of exposed plinthite in profile pits.

3.1 CPU2

	Means iron contents (Standard error of the mean in brackets)		
	Fe(III) (mg/kg)	Fe(II) (mg/kg)	Total Fe (mg/kg)
Mar-98	17.43 (±0.2)	16.33 (±2.7)	33.76 (±0.2)
April-98	19.25 (±0.1)	15.45 (±1.6)	34.70 (±0.2)
May-98	22.30 (±0.1)	12.24 (±2.5)	34.54 (±0.2)
June-98	23.80 (±0.1)	13.20 (±3.1)	37.00 (±0.1)
July-98	28.25 (±0.1)	11.40 (±1.0)	39.65 (±0.2)
Aug-98	35.23 (±0.0)	10.30 (±0.8)	45.53 (±0.2)
Sept-98	40.30 (±0.1)	6.60 (±0.1)	46.90 (±0.0)
Oct-98	44.63 (±0.0)	5.37 (±0.2)	50.00 (±0.2)
Nov-98	49.93 (±0.1)	4.40 (±0.1)	54.33 (±0.0)
Dec-98	52.63 (±0.1)	3.27 (±0.0)	55.90 (±0.1)
Jan-99	62.43 (±0.0)	2.70 (±0.3)	65.13 (±0.3)
Feb-99*	**79.40 (±0.0)**	**2.30 (±0.6)**	**81.70 (±0.6)**
Mar-99	86.77 (±0.0)	2.10 (±0.6)	88.87 (±0.6)
April-99	90.90 (±0.0)	1.87 (±0.3)	92.77 (±0.3)

* starting point of irreversible hardening

3.2 CPM2

	Means iron contents (Standard error of the mean in brackets)		
	Fe(III) (mg/kg)	Fe(II) (mg/kg)	Total Fe (mg/kg)
Mar-98	23.10 (±0.1)	10.27 (±0.1)	33.37 (±0.1)
April-98	24.35 (±0.1)	10.00 (±0.1)	34.35 (±0.1)
May-98	26.63 (±0.1)	9.23 (±0.1)	35.86 (±0.0)
June-98	27.97 (±0.0)	9.67 (±0.0)	37.64 (±0.1)
July-98	31.23 (±0.0)	8.00 (±0.1)	39.23 (±0.0)
Aug-98	33.23 (±0.1)	8.33 (±0.1)	41.56 (±0.2)
Sept-98	40.53 (±0.0)	6.60 (±0.0)	47.13 (±0.0)
Oct-98	45.57 (±0.0)	5.13 (±0.1)	50.70 (±0.1)
Nov-98	50.57 (±0.1)	4.50 (±0.2)	55.07 (±0.2)
Dec-98	53.53 (±0.1)	3.27 (±0.2)	56.80 (±0.1)
Jan-99	64.50 (±0.0)	2.73 (±0.2)	67.23 (±0.2)
Feb-99	70.23 (±0.0)	2.30 (±0.7)	72.53 (±0.7)
Mar-99*	78.77 (±0.0)	2.13 (±0.6)	80.90 (±0.6)
April-99	88.57 (±0.0)	1.98 (±0.6)	90.55 (±0.6)

* starting point of irreversible hardening

3.3 CPL2

	Means iron contents (Standard error of the mean in brackets)		
	Fe(III) (mg/kg)	Fe(II) (mg/kg)	Total Fe (mg/kg)
Mar-98	22.70 (±0.2)	16.67 (±0.1)	39.37 (±0.2)
April-98	24.30 (±0.1)	15.25 (±0.1)	39.55 (±0.1)
May-98	25.16 (±0.1)	14.60 (±0.2)	39.76 (0±.1)
June-98	26.17 (±0.0)	13.93 (±2.1)	40.10 (±0.3)
July-98	30.37 (±0.1)	12.55 (±0.3)	42.92 (±0.2)
Aug-98	34.00 (±0.1)	10.40 (±0.4)	44.40 (±0.4)
Sept-98	40.93 (±0.0)	6.57 (±0.1)	47.50 (±0.1)
Oct-98	45.60 (±0.1)	5.33 (±0.1)	50.93 (±0.0)
Nov-98	51.10 (±0.1)	4.10 (±0.0)	55.20 (±0.1)
Dec-98	53.83 (±0.1)	3.17 (±0.1)	57.00 (±0.0)
Jan-99	65.73 (±0.0)	2.67 (±0.2)	68.40 (±0.2)
Feb-99*	79.33 (±0.0)	2.17 (±0.2)	81.50 (±0.2)
Mar-99	86.47 (±0.0)	2.04 (±0.3)	88.51 (±0.3)
April-99	89.93 (±0.0)	1.85 (±0.3)	91.78 (±0.4)

* starting point of irreversible hardening

3.4 APU

	Means iron contents (Standard error of the mean in brackets)		
	Fe(III) (mg/kg)	Fe(II) (mg/kg)	Total Fe (mg/kg)
March-98	16.45 (±0.1)	12.68 (±1.0)	29.13 (±0.8)
April-98	18.23 (±0.1)	11.60 (±0.3)	29.83 (±0.5)
May-98	19.15 (±0.2)	11.20 (±0.3)	30.35 (±0.4)
June-98	23.30 (±0.1)	13.23 (±0.3)	36.53 (±0.4)
July-98	23.17 (±0.1)	10.10 (±0.1)	33.27 (±0.4)
Aug-98	25.20 (±0.0)	9.87 (±2.1)	35.07 (±0.2)
Sept-98	31.13 (±0.0)	6.53 (±0.3)	37.66 (±0.3)
Oct-98	37.93 (±0.0)	5.10 (±0.1)	43.03 (±0.1)
Nov-98	40.13 (±0.1)	4.10 (±0.2)	44.23 (±0.2)
Dec-98	41.93 (±0.1)	3.17 (±0.2)	45.10 (±0.1)
Jan-99	42.00 (±0.1)	3.61 (±0.4)	45.61 (±0.3)
Feb-99	42.90 (±0.0)	2.85 (±0.2)	45.75 (±0.2)
Mar-99	45.70 (±0.4)	2.70 (±0.2)	48.40 (±0.6)
April-99	47.67 (±0.4)	2.53 (±0.3)	50.20 (±0.3)

3.5 APM

	Means iron contents (Standard error of the mean in brackets)		
	Fe(III) (mg/kg)	Fe(II) (mg/kg)	Total Fe (mg/kg)
March-98	21.10 (±0.1)	10.00 (±0.1)	31.10 (±0.1)
April-98	22.45 (±0.0)	10.60 (±0.1)	33.05 (±0.1)
May-98	23.00 (±0.1)	10.67 (±0.1)	33.67 (±0.1)
June-98	23.20 (±0.0)	11.07 (±0.1)	34.27 (±0.2)
July-98	24.40 (±0.0)	10.05 (±0.3)	34.45 (±0.4)
Aug-98	28.57 (±0.0)	9.83 (±0.2)	38.40 (±0.1)
Sept-98	33.40 (±0.0)	6.50 (±0.3)	39.90 (±0.3)
Oct-98	38.33 (±0.0)	5.37 (±0.2)	43.70 (±0.2)
Nov-98	43.70 (±0.1)	4.20 (±0.2)	47.90 (±0.1)
Dec-98	46.80 (±0.0)	4.05 (±0.2)	50.85 (±0.2)
Jan-99	48.40 (±0.0)	3.87 (±0.1)	52.27 (±0.1)
Feb-99	49.77 (±0.0)	3.30 (±0.3)	53.07 (±0.3)
Mar-99	50.70 (±0.0)	3.20 (±0.2)	53.90 (±0.2)
April-99	51.12 (±0.0)	3.07 (±0.2)	54.19 (±0.2)

APPENDIX 4

Changes in iron contents of plinthite samples of Pits CPU2, CPM2 and CPL2 after variable wetting and drying cycles.

4.1 CPU2

	Fe(II) mg/kg				Fe(III) mg/kg				TOTAL mg/kg			
Week	A	B	C	D	A	B	C	D	A	B	C	D
0	5.7	5.2	5.0	2.6	39.1	41.4	42.6	43.1	44.8	46.6	47.6	47.7
2	4.5	4.0	3.7	3.3	40.4	42.7	43.1	44.4	44.9	46.7	46.8	47.7
4	3.7	3.2	2.6	2.4	41.2	43.4	44.0	45.3	44.9	46.6	46.6	47.7
6	3.0	2.8	2.3	1.8	41.9	43.4	43.7	45.9	44.9	46.2	46.0	47.7
8	2.8	2.6	2.2	1.8	42.2	43.7	44.1	46.0	45.0	46.3	46.3	47.8

4.2 CPM2

	Fe(II) mg/kg				Fe(III) mg/kg				TOTAL mg/kg			
Week	A	B	C	D	A	B	C	D	A	B	C	D
0	5.5	5.0	4.5	4.0	39.8	39.8	40.0	42.0	44.1	44.8	44.5	46.0
2	4.2	3.5	3.1	2.9	40.0	41.2	41.5	42.9	44.2	44.7	44.6	45.8
4	3.1	2.7	2.2	1.8	41.2	42.1	42.5	44.0	44.3	44.8	44.7	45.8
6	2.6	2.1	2.0	1.7	41.9	42.7	42.6	44.4	44.5	44.8	44.6	46.1
8	2.5	2.0	2.0	1.6	43.2	42.8	42.6	44.4	45.7	44.8	44.6	46.0

4.3 CPL2

	Fe(II) mg/kg				Fe(III) mg/kg				TOTAL mg/kg			
Week	A	B	C	D	A	B	C	D	A	B	C	D
0	5.7	4.5	3.5	3.2	38.7	39.8	40.8	41.1	44.4	443	44.3	44.3
2	4.4	3.2	2.7	2.1	40.2	40.8	41.6	42.5	44.6	44.0	44.3	44.6
4	3.3	2.5	2.0	1.6	41.1	41.9	42.1	42.8	44.4	44.4	44.1	44.4
6	2.9	2.0	1.9	1.5	41.5	42.5	42.2	43.0	44.4	44.5	44.1	44.5
8	2.7	1.8	1.8	1.4	41.6	42.7	42.4	43.1	45.3	44.5	44.2	44.5

APPENDIX 5

Changes in hardness and moisture contents of plinthite samples from exposed Pits CPU2, CPM2 and CPL2 after variable wetting and drying cycles in tanks A to D

5.1 Pit CPU2

	Moisture Content (%)				Hardness (N/cm^2)			
Week	A	B	C	D	A	B	C	D
0	9.0	10.0	10.4	10.5	80	83	90	100
2	3.0	3.0	2.8	2.7	260	270	290	295
4	2.5	2.9	2.6	2.4	275	290	310	320
6	2.1	2.6	2.4	2.1	285	310	345	360
8	1.8	2.1	2.0	1.8	320	330	360	400

5.2 Pit CPM2

	Moisture Content (%)				Hardness (N/cm^2)			
Week	A	B	C	D	A	B	C	D
0	9.7	10.2	10.6	10.8	73	80	85	80
2	3.5	3.3	3.1	2.9	240	265	275	280
4	2.9	2.6	2.4	2.3	265	280	300	300
6	2.2	2.3	1.9	1.8	280	295	340	330
8	1.7	2.0	1.5	1.6	300	310	360	380

5.3 Pit CPL2

	Moisture Content (%)				Hardness (N/cm^2)			
Week	A	B	C	D	A	B	C	D
0	10.4	10.6	10.7	10.9	60	75	80	85
2	2.5	3.2	3.1	3.1	200	250	270	280
4	2.1	2.9	2.7	2.8	250	260	290	310
6	1.8	2.5	2.2	2.1	265	275	340	350
8	1.5	2.2	2.1	2.0	295	300	350	390

APPENDIX 6

Influence of burning on hardness and iron contents of plinthite at sites CPU2, CPM2 and CPL2.

6.1 Site CPU2

	Time (weeks)						
	0	2	4	6	8	10	12
Fe(II) (mg/kg)	11	8.9	6.6	4.2	3.2	3	2.7
Fe(III) (mg/kg)	15.3	20.8	32.3	36.1	41.4	46.1	51.6
Total Fe (mg/kg)	26.3	29.7	38.9	40.3	44.6	49.1	54.3
Hardness (N/cm^2)	350	483	500	480	460	580	570

6.2 Site CPM2

	Time (weeks)						
	0	2	4	6	8	10	12
Fe(II) (mg/kg)	11.1	9.1	6.6	4.2	3.3	3	2.7
Fe(III) (mg/kg)	15.2	20.6	31.4	36.4	41.3	46.1	51.6
Total Fe (mg/kg)	26.3	29.7	38	40.6	44.6	49.1	54.3
Hardness (N/cm^2)	220	433	510	380	370	590	600

6.3 Site CPL2

	Time (weeks)						
	0	2	4	6	8	10	12
Fe(II) (mg/kg)	11.4	8.9	6.5	4.3	3.4	3.1	2.8
Fe(III) (mg/kg)	14.3	20.2	31.8	36.3	40.6	45.5	50.9
Total Fe (mg/kg)	25.3	29.1	38.3	40.6	44	48.6	53.7
Hardness (N/cm^2)	116	453	300	380	300	480	520

APPENDIX 7

Mean Temperature (°C) of Plinthite during burning*

Time elapse from start of burning (mins)	CPU2	Soil Pit CPM2 3 cm depth	CPL2	CPU2	Soil Pit CPM2 5 cm depth	CPL2
0	42	40	34	32	31	29
10	46	47	43	32	33	32
15	47	50	46	34	35	35
20	45	47	46	35	36	36
25	43	44	44	35	37	36
30	41	42	41	35	37	36
35	40	40	39	34	36	35

* Burning temperature was 250°C and average maximum atmospheric temperature was 33°C.

APPENDIX 8

Profile Pit Description and Laboratory Analysis Results

8.1 *Bekwai series*

1. **GENERAL INFORMATION**

Registration and Location

i.	Profile number:	CPU 1
ii.	Date of description:	19th December, 1997
iii.	Soil unit:	*Bekwai series*
iv.	Location:	Kwadaso, Central Agricultural Station near the Guest House

Soil Classification

i.	WRB (FAO, 1998):	Chromi-Endoplinthic Acrisol
ii.	FAO (1990b):	Plinthic Acrisol
iii.	ST (USDA, 1998):	Typic Plinthustult

Topo-site:	Upper slope
Landuse:	Cultivated annually to arable crops.
Parent material:	Sedentary materials derived from phyllite
Drainage class:	Well drained

II. **Brief description of the profile**

The profile consists of a well drained, very deep (>200cm) gravelly sedentary soil found on upper slope of a ridge and developed on Lower Birimian phyllite. It consists of moderately thick humus-stained topsoil with dark yellowish brown colour, loamy texture and granular structure containing few quartz gravels and ironstone gravels and concretions. The subsoil is thick (>150cm), yellowish red to dark red in colour, clayey, subangular blocky, firm with common quartz and ironstone gravels. The subsoil has illuvial clay with yellowish brown mottles which increase in abundance, sizes and contrast with depth.

III Profile Description

Horizon	Depth (cm)	Description
Ap	0 - 10	Dark yellowish brown (10YR 3/4) moist; clay loam; moderate fine granular; slightly sticky, slightly plastic, friable, soft; many very fine and fine pores; few fine fresh hard quartz gravels; few (2%) coarse, irregular, hard ironstone gravels and concretions; common fine and common very fine roots; clear, smooth boundary; pH 5.5.
AB	10 - 20/25	Yellowish red (5YR 4/6) moist, clay loam; moderate fine and medium granular; slightly sticky, slightly plastic, friable, soft; many fine and medium pores; common coarse angular fresh quartz gravels; few (3%) fine and medium hard irregular ironstone concretions, common fine roots; diffuse, wavy boundary; pH 5.2.
Bcs	20/25 - 37	Yellowish red (5YR 4/6) moist, clay loam; weak fine sub-angular blocky; slightly sticky, slightly plastic, friable; many fine, many medium and coarse pores; many medium coarse fresh angular quartz gravels; common (6%) medium hard irregular ironstone concretions; common, fine and coarse roots; clear, smooth boundary; pH 5.0.
Btcs	37 - 53/66	Dark red (2.5YR 4/6) moist; clay; weak medium subangular blocky; slightly sticky, slightly plastic, firm; many faint clay cutans on ped faces; many fine and medium pores; many medium and coarse fresh angular quartz gravels; many (16%) medium hard irregular ironstone concretions; few coarse roots; abrupt wavy boundary; pH 4.8.

Btcsv1	53/66 - 80	Dark red (2.5YR 4/8) moist; silty clay; few, fine faint diffuse yellowish brown mottles (plinthite materials), strong medium and coarse subangular blocky; sticky, slightly plastic, firm; common faint clay cutans on ped faces; common fine and medium pores; few medium angular fresh quartz gravels; common (15%) medium hard irregular ironstone concretions; very few, fine very few coarse roots; clear, smooth boundary; pH 4.7.
Btcsv2	80 - 105	Dark red (2.5YR 4/8) moist; clay; common fine distinct clear; yellowish red and many fine and medium distinct clear yellowish brown mottles (plinthite material), strong medium and coarse; subangular blocky, sticky, slightly plastic; firm; common distinct clay cutans on ped faces; and in voids, common fine and medium pores; few medium angular fresh quartz gravels; common (15%) medium hard irregular ironstone gravels and concretions; common fine and medium roots; diffuse, smooth boundary; pH 4.7.
Btcsv3	105 - 136	Dark red (2.5YR 4/6) moist; clay; common fine and medium distinct clear; yellowish red and common distinct clear; yellow brown mottles (plinthite material), strong medium and coarse subangular blocky; sticky, slightly plastic; firm; many distinct clay cutans on ped faces; and in voids, common fine and medium pores; very few medium angular fresh quartz gravels; common (15%) medium hard irregular ironstone gravels and concretions; very few fine roots, diffuse; smooth boundary; pH 4.5.
2Bcsv	136 - 179	Dark red (2.5YR 4/6) moist; silty clay loam; many medium prominent, clear yellowish red mottles (plinthite material), moderate, medium and coarse subangular blocky; sticky and slightly plastic; firm;

		common fine pores; very few medium angular fresh quartz gravels; few (5%) medium hard ironstone gravels and concretions; very few fine roots; clear, smooth boundary; pH 4.3.
3BC	179 - 200	Dark red (2.5YR 4/6) moist; common fine distinct clear yellowish red mottles; silty clay; weak fine and medium subangular blocky; sticky, slightly plastic, friable; common fine pores; very few (1%) hard irregular ironstone concretions; very few fine roots; weathered phyllite; pH 4.0.

LABORATORY INVESTIGATION RESULTS

Profile No: CPU1 Soil Name: *Bekwai series*

Horizon	Depth (cm)	pH H_2O 1:1	EC mS/cm	Org. C (%)	Total N %	Org. Matter %	Exchangeable Cations cmol (+)/kg Ca	Mg	K	Na	TEB	(Al+H)	CEC cmol (+)/kg	Base Sat. %
Ap	0 - 10	5.5	0.08	2.16	0.19	3.72	6.40	13.92	0.32	0.10	20.74	0.50	21.24	98
AB	10 - 20/25	5.2	0.08	0.98	0.08	1.69	5.92	2.08	0.43	0.64	9.07	0.20	9.27	98
Bcs	20/25 - 37	5.0	0.11	0.82	0.07	1.41	4.64	1.76	0.13	0.11	6.64	0.20	6.84	97
Btcs	37 - 53/66	4.8	0.08	0.80	0.06	1.38	2.24	0.64	0.07	0.05	3.00	2.10	5.10	59
Btcsv1	53/66 - 80	4.7	0.05	0.58	0.06	1.00	2.08	0.64	0.06	0.05	2.83	2.60	5.43	52
Btcsv2	80 - 105	4.7	0.04	0.55	0.04	0.95	2.40	0.48	0.05	0.05	2.98	2.60	5.58	53
Btcsv3	105 - 136	4.5	0.03	0.46	0.03	0.79	1.60	0.48	0.04	0.04	2.16	3.00	5.16	42
2Bcsv	136 - 179	4.3	0.04	0.40	0.03	0.69	0.80	0.48	0.06	0.07	1.41	2.90	4.31	33
3BC	179 - 200	4.0	0.03	0.35	0.03	0.60	0.96	0.48	0.03	0.04	1.51	2.90	4.41	34

Horizon	Mechanical Analysis % Sand	% Silt	% Clay	Texture
Ap	44.10	26.72	29.18	Clay loam
AB	42.98	25.56	31.46	Clay loam
Bcs	42.24	26.72	31.04	Clay loam
Btcs	21.15	17.31	61.54	Clay
Btcsv1	23.08	22.47	54.45	Clay
Btcsv2	21.41	21.88	56.71	Clay
Btcsv3	15.56	24.05	60.39	Clay
2Bcsv	15.65	56.88	27.47	Silty clay loam
BC	18.22	51.71	30.07	Silty clay loam

8.2 *Kumasi series*

1. GENERAL INFORMATION

Registration and Location

i.	Profile number:	CPU 2
ii.	Date of description:	19th December, 1997
iii	Soil unit:	*Kumasi series*
v.	Location:	Soil Fertility Trial plot CAS, Kwadaso

Soil Classification

i.	WRB (FAO, 1998):	Chromi-Endoplinthic Acrisol
ii.	FAO (1990b):	Plinthic Acrisol
iii.	ST (USDA, 1998):	Typic Plinthustult

Topo-site:	Upper slope
Landuse:	Research plots for arable crops
Parent material:	Granite (Cape Coast)
Drainage class:	Well drained

II. Brief description of the profile

The profile is sited on a soil developed on residual weathered products of Cape Coast Granite complex on the upper slope. The profile is very deep (200cm) and well drained. The topsoil (17cm) consists of very dark greyish brown, sandy loam with weak fine granular structure and contains few ironstone and quartz gravels. The subsoil is thick (>180cm), yellowish red to red in colour and has sandy clay loam to clay textures with medium to coarse subangular blocky structure and common quartz and ironstone gravels. The subsoil is firm and contains mottles that increase in abundance, size and contrast with depth.

II. Profile Description

Horizon	Depth(cm)	Description
Ap	0 - 17	Very dark greyish brown (10YR 3/2) moist; sandy clay loam; weak fine granular; friable, non sticky, non plastic; many fine interstitial pores; few (2%) fine and medium, irregular, ironstone concretions; many (16%) fine and medium angular fresh quartz stones; many very fine, common fine and few medium roots; abrupt, smooth boundary; pH 5.1.
Bsc	17 - 29	Yellowish red (5YR 4/6) moist; sandy clay loam; moderate fine, subangular blocky; friable; slightly sticky, slightly plastic; common fine interstitial pores; few (5%) medium angular fresh quartz stones and gravels; common (10%) fine and medium irregular hard ironstone gravels and concretions; few fine and medium roots; abrupt, smooth boundary; pH 5.0
Btsc1	29 - 44	Yellowish red (5YR 5/6) moist; clay; moderate fine sub angular blocky, firm; slightly sticky, slightly plastic; common faint clay cutans on ped faces; common fine and few medium interstitial pores; few (5%) angular fresh quartz stones and gravels; common (10%) fine and medium irregular ironstone gravels and concretions; few very fine and fine roots; gradual; smooth boundary; pH 4.6.
Btsc2	44 - 75	Reddish yellow (5YR 7/6) moist; clay; moderate, fine, subangular blocky; firm; sticky, plastic, common distinct clay cutans within pores; and on ped faces, common fine interstitial pores; very few (1%) angular fresh quartz stones and gravels; common (11%) fine, irregular soft and hard, ironstone gravels;

		and concretions, few very fine and fine roots; clear, smooth boundary; pH 4.2.
Btcsv1	75 - 134	Red (2.5YR 5/6) moist; clay; few fine faint clear reddish brown mottles (plinthite material), moderate fine subangular blocky; firm; sticky, plastic, few distinct clay cutans within pores; and on ped faces, few fine and common medium interstitial pores; very few (2%) fine irregular soft and hard, ironstone gravels and concretions; very few (1%) fine angular fresh quartz gravels; very few, very fine and fine roots; diffuse, smooth boundary; pH 4.0.
Btcsv2	134 - 173	Red (2.5YR .5/8) moist; clay; common fine distinct clear; reddish brown and yellowish brown mottles (plinthite material), moderate fine subangular blocky; firm; sticky, plastic, common distinct clay cutans within pores; and on ped faces; few fine interstitial pores; common (6%) feldspar and mica flakes; few (4%) fine and medium angular fresh quartz stones and gravels; very few (2%) fine, hard irregular, ironstone gravels and concretions; very few, very fine and fine roots; diffuse, smooth boundary; pH 4.0.
Btcsv3	173 - 200	Red (10R 5/8) moist; clay; many medium distinct clear reddish and yellowish brown mottles; (plinthite material), strong coarse subangular blocky; sticky, plastic, firm; common distinct clay cutans on ped faces; few fine and medium interstitial pores; few (4%) mica flakes, few (3%) fine angular fresh quartz stones; very few (1%) soft and hard ironstone concretions; pH 3.8.

LABORATORY INVESTIGATION RESULTS

Profile No.: CPU2 Soil Name: *Kumasi series*

Horizon	Depth (cm)	pH H_20 1:1	EC MS/cm	Org. C %	Total N %	Org. Matter %	Exchangeable Cations cmol (+)/kg Ca	Mg	K	Na	TEB	(Al+H)	CEC Cmol (+)/kg	Base Sat. %
Ap	0 - 17	5.1	0.08	2.25	0.18	3.88	5.44	5.28	0.23	0.11	11.06	0.40	11.46	97
Bcs	17 - 29	5.0	0.08	1.92	0.16	3.31	3.84	0.96	0.09	0.06	4.95	0.30	5.25	94
Btcs1	29 - 44	4.6	0.12	0.94	0.08	1.62	3.20	0.80	0.09	0.07	4.16	0.20	4.36	95
Btcs2	44 - 75	4.2	0.09	0.80	0.06	1.38	3.20	0.80	0.06	0.06	4.12	0.75	4.87	85
Btcsv1	75 - 134	4.0	0.04	0.56	0.06	0.97	1.28	0.32	0.04	0.05	1.69	1.70	3.39	50
Btcsv2	134 - 173	4.0	0.03	0.55	0.05	0.94	1.12	0.48	0.04	0.05	1.69	1.90	3.59	47
Btcsv3	173 - 200	3.8	0.03	0.50	0.05	0.86	1.28	0.32	0.04	0.05	1.69	2.50	4.19	40

Horizon	Mechanical Analysis % Sand	% Silt	% Clay	Texture
Ap	53.49	23.26	23.25	Sandy clay loam
Bcs	50.94	20.60	28.46	Sandy clay loam
Btcs1	40.21	14.40	45.39	Clay
Btcs2	36.34	8.57	55.09	Clay
Btcsv1	26.75	15.48	57.77	Clay
Btcsv2	18.49	22.45	59.06	Clay
Btcsv3	18.00	25.80	56.20	Clay

8.3 *Nzima Series*

1. GENERAL INFORMATION

Registration and Location

i. Profile number: CPM1

ii. Date of description: 16th December, 1997

iii. Soil unit: *Nzima series*

v. Location: Close to the Meteorological Station, CAS, Kwadaso

Soil Classification

i. WRB (FAO, 1998): Epiferric-Bathiplinthic Acrisol

ii. FAO (1990b): Plinthic Acrisol

iii. ST (USDA, 1998): Typic Plinthustult

Topo-site: Middle slope

Landuse: Annual field cropping

Parent material: Phyllite

Drainage class: Moderately well drained

II. Brief Description of the Profile

The profile is moderately well drained, it has many fine and medium quartz gravels and stones and few manganese dioxide concretions. Apart from the top layer which has clear and smooth boundary, the rest have diffuse and wavy boundary. Roots are distributed throughout the profile.

III. Profile Description

Horizon	Depth (cm)	Description
Ap	0 - 12	Dark yellowish brown (10YR 3/4) moist; silty loam; moderate to strong fine and medium granular; non sticky non plastic; very firm; very hard; common fine pores; many fine and few medium roots; clear smooth boundary; pH 4.5.

BA	12 - 30	Dark yellowish brown (10YR 4/4) moist; silty clay loam; strong and medium granular; slightly sticky slightly plastic; very firm; very hard, common fine pores; many fine and few medium roots; krotovina; diffuse, smooth boundary; pH 4.4.
Bt	30 - 42/58	Dark yellowish brown (10YR 4/6) moist; silty clay loam; strong, medium subangular blocky; slightly sticky slightly plastic; firm; hard, fine faint clay skins on ped surfaces; few fine, very few medium pores; fine roots; krotovinas; abrupt, wavy boundary; pH 4.5.
Btcs1	42/58 - 75	Strong brown (7.5YR 4/6) moist; silty clay loam; moderate fine and medium sub angular blocky, slightly sticky, slightly plastic; firm; hard; few faint clay skins on ped surfaces; many (15%) fine rounded hard iron and manganese dioxide; concretions, krotovinas; few fine and few very fine roots; diffuse, smooth boundary; pH 4.8.
Btcs2	75 - 100/110	Strong brown (7.5YR 4/6) moist; silty clay loam; slightly sticky, slightly plastic; firm; hard, moderately fine and medium subangular blocky; common (10%) fine and medium angular fresh quartz gravels; and few (2%) angular fresh quartz stones; many (16%) fine, rounded hard iron and manganese dioxide; concretions; very few fragments of strongly weathered phyllite; few fine clay skins on ped surfaces; krotovinas; few very fine pores; abrupt, wavy boundary; pH 4.8.
Btcsv4	100/110 - 135	Brown (7.5YR 4/4) moist; silty clay loam; many medium distinct clear; yellow (10YR 7/6) and many fine medium

		distinct clear red (2.5YR 5/6) mottles; slightly sticky, slightly plastic; firm; hard; moderate fine and medium sub angular blocky; very few (2%)medium hard rounded iron and manganese dioxide; concretions; common (15%) fragments of strongly weathered phyllite; krotovinas; few very fine roots; diffuse, smooth boundary; pH 4.6.
Btcsv5	135 - 155	Brown (7.5YR 4/4) moist; many, medium, distinct, clear; yellow (10YR 7/6) and fine, medium, distinct clear red; (2.5YR 5/6) mottles; silty clay loam; slightly sticky slightly plastic; firm; hard; moderate fine and medium subangular blocky; common (10%) fine and hard rounded iron and manganese dioxide; concretions; many (30%) fragments of strongly weathered phyllite; few fine pores; few very fine roots; diffuse, smooth boundary; pH 4.4.
Btcsv6	155 - 192	Brown (7.5YR 4/4) moist; silty clay loam; many medium, distinct; clear yellow (10YR 7/6) and fine, medium, distinct clear red (2.5YR 4/6) mottles; slightly sticky, slightly plastic; firm; hard; weak fine and medium subangular blocky; common (15%) fine and medium hard rounded iron and manganese concretions; few faint clay skins on the ped surfaces; few fine pores; few very fine roots; pH 4.1.

LABORATORY INVESTIGATION RESULTS

Profile No.: CPM1 Soil Name: *Nzima series*

Horizon	Depth cm	pH H_2O 1:1	EC MS/cm	Org. C %	Total N %	Org. Matter %	Exchangeable Cations cmol (+)/kg Ca	Mg	K	Na	TEB	(Al+H)	CEC cmol (+)/kg	Base Sat.%
Ap	0 - 12	4.5	0.05	2.35	0.21	4.05	4.96	1.92	0.06	0.02	6.96	1.10	8.06	86
BA	12 - 30	4.4	0.04	1.38	0.12	2.38	2.08	1.28	0.04	0.03	3.43	1.50	4.93	70
Bt1	30 - 42/58	4.5	0.04	1.99	0.08	1.71	2.08	1.28	0.03	0.03	3.42	1.80	5.22	65
Btcs2	42/58 - 75	4.8	0.04	0.74	0.05	1.28	2.24	1.28	0.04	0.03	3.59	2.60	6.19	58
Btcs3	75 - 100/110	4.8	0.03	0.58	0.04	1.00	2.08	1.28	0.03	0.03	3.42	2.90	6.32	53
Btcsv1	100/110 - 135	4.6	0.05	0.47	0.04	0.81	2.08	1.12	0.03	0.03	3.26	3.10	6.36	51
Btcsv2	135 - 155	4.4	0.03	0.44	0.03	0.76	1.60	0.96	0.03	0.03	2.62	3.10	5.72	46
Btcsv3	155 - 192	4.1	0.04	0.37	0.03	0.64	1.60	0.48	0.03	0.03	2.14	3.00	5.14	41

Horizon	Mechanical Analysis Sand	Silt	Clay	Texture
Ap	41.73	31.82	26.45	Loam
BA	35.99	35.00	29.01	Clay loam
Bt1	34.20	25.31	40.49	Clay
Btcs2	28.08	29.42	42.50	Clay
Btcs3	27.44	26.49	46.07	Clay
Btcsv1	25.13	27.76	47.11	Clay
Btcsv2	25.30	29.74	44.96	Clay
Btcsv3	30.14	30.21	39.65	Clay

8.4 *Nzima series*

1. **GENERAL INFORMATION**

Registration and Location

i.	Profile number:	CPM2
ii.	Date of description:	15th December, 1997
iii.	Soil Unit:	*Nzima series*
v.	Location:	Behind the Aboretum at Central Agric Station, Kwadaso.

Soil Classification

i.	WRB (FAO, 1998):	Epiferri-Endoplinthic Lixisols
ii.	FAO (1990b):	Plinthic Lixisol
iii.	ST (USDA, 1998):	Typic Plinthustalf

Topo-site:	Middle slope
Land use:	Cultivated annually to arable crops
Parent material:	Sedentary derived from phyllite
Drainage Class:	Well drained.

II. **Brief description of the profile**

The profile is developed on sedentary materials derived from Lower Birimian phyllite on middle slope. It is very deep (>200cm) well drained, concretionary and gravelly with illuvial clay in the subsoil. The humus-stained topsoil (10cm) is dark greyish brown with loamy texture, moderate granular structure and contains few quartz and ironstone gravels. The subsoil is thick (200cm), yellowish red in colour and has sandy clay loam to clay textures and medium to coarse subangular blocky structure. It has common yellowish brown to reddish brown mottles in the subsoil.

III. Profile Description

Horizon	Depth (cm)	Description
Ap	0 - 10	Dark greyish brown (10YR 4/2) moist; loam; moderate fine and medium granular; slightly sticky, slightly plastic; very friable; many medium and common fine pores; few (3%) medium and coarse angular fresh quartz gravels; few (2%) fine irregular hard ironstone concretions; very few coarse, few medium and common very fine roots; clear, smooth boundary; pH 5.4.
Bcs	10 - 29	Dark yellowish brown (10YR 4/6) moist; sandy clay loam; weak fine subangular blocky; sticky, slightly plastic; firm; hard; few medium, common fine interstitial pores; few (3%) medium coarse angular fresh quartz stones; common (6%) very fine, irregular hard black ironstone concretions; few medium, few fine roots; clear, smooth boundary; pH 4.5.
Btcs	29 - 55	Yellowish red (5YR 4/6) moist; clay; strong fine and medium subangular blocky; sticky, slightly plastic; firm; hard; common distinct clay cutans on ped faces; common, fine very few, medium, interstitial pores; few (3%) medium angular fresh quartz gravels and stones; many (15%) very fine few medium, irregular, hard, black ironstone concretions; very few pieces of charcoal; very few, very fine roots; gradual, smooth boundary; pH 4.4.
Btcsv1	55 - 86	Yellowish red (5YR 4/6) moist; clay; few, fine and medium distinct clear yellowish brown and few, fine distinct clear reddish brown mottles (plinthite material); strong medium subangular blocky; sticky, slightly plastic, firm; hard, many distinct clay cutans on ped faces; few fine interstitial pores; few (5%), medium, angular, fresh quartz

		gravels and stones; common (14%), fine irregular, hard, black ironstone gravels and concretions; very few, very fine roots; diffuse, smooth boundary; pH 3.9.
Btcsv2	86 - 115	Yellowish red (5YR 4/6) moist; clay; many fine and medium, distinct, clear, yellowish brown and common fine distinct, clear; reddish brown mottles (plinthite material), strong medium and coarse subangular blocky; sticky, plastic, firm; hard; many distinct clay cutans on ped faces; very few coarse few, fine interstitial pores; very few (2%) medium angular fresh quartz gravels; few (4%), fine irregular hard black ironstone concretions; very few, fine roots; diffuse, smooth boundary; pH 4.0.
BC1	115 - 153	Yellowish red (5YR 4/6) moist; clay loam; moderate, fine and medium subangular blocky; sticky, slightly plastic; firm; hard; very few, fine interstitial pores; very few (2%), medium, angular, fresh quartz gravels; very few (2%), fine irregular, hard; black ironstone concretions; few very fine roots; many fragments of weathered phyllite; diffuse, smooth boundary; pH 4.0.
2BC2	153 - 210	Yellowish red (5YR 4/6) moist; clay; weak fine and medium, subangular blocky; sticky, slightly plastic; firm; hard; very few (1%), medium, angular, fresh quartz gravels; very few (2%), fine, irregular, hard black ironstone concretions; very few, very fine roots; common fragments of weathered phyllite; pH 4.0.

LABORATORY INVESTIGATION RESULTS

Profile No.: CPM2 Soil Name: *Nzima Series*

Horizon	Depth (cm)	pH H_2O 1:1	EC mS/cm	Org. C %	Total N %	Org. Matter %	Exchangeable Cations cmol (+)/kg Ca	Mg	K	Na	TEB	(Al+H)	CEC cmol (+)/kg	Base Sat. %
Ap	0 - 10	5.4	0.08	2.45	0.21	4.22	9.60	1.12	0.14	0.03	10.89	1.20	12.09	90
Bcs	10 - 29	4.5	0.04	1.65	0.14	2.84	3.84	1.28	0.08	0.06	5.27	1.50	6.77	77
Btcs	29 - 55	4.4	0.04	0.98	0.08	1.69	3.36	1.28	0.05	0.02	4.68	1.80	6.48	72
Btcsv1	55 - 86	3.9	0.04	0.59	0.07	1.02	2.72	0.96	0.02	0.02	3.72	2.20	5.92	63
Btcsv2	86 - 115	4.0	0.03	0.58	0.05	1.00	1.60	0.80	0.02	0.02	2.44	2.20	4.54	53
2BC1	115 - 153	4.0	0.03	0.58	0.05	1.00	1.28	0.64	0.02	0.02	1.96	2.20	4.16	47
2BC2	153 - 210	4.0	0.03	0.52	0.04	0.90	1.12	0.32	0.02	0.02	1.48	2.70	4.18	35

Horizon	Mechanical Analysis %Sand	%Silt	% Clay	Texture
Ap	44.91	36.03	19.06	Loam
Bcs	45.39	26.55	28.06	Sandy clay loam
Btcs	30.21	21.15	48.64	Clay
Btcsv1	27.60	23.92	48.48	Clay
Btcsv2	23.18	23.32	53.50	Clay
2BC1	25.54	36.17	38.29	Clay loam
2BC2	26.57	30.41	43.02	Clay

8.5 *Kokofu series*

I. GENERAL INFORMATION

Registration and Location

i.	Profile Number:	CPL1
ii.	Date of description:	15th December, 1997
iii.	Soil Unit:	*Kokofu series*
iv.	Location:	SRI Experimental farm adjacent to aboretum, Kwadaso.
v.	Elevation:	

Soil Classification

i.	WRB (FAO, 1998):	Hapli-Endoplinthic Lixisols
ii.	FAO (1990b):	Plinthic Lixisol
iii.	ST (USDA, 1998):	Typic Plinthustalf

Position:	Lower slope
Land use:	Research plots for annual crops
Parent material:	Colluvium materials derived from phyllite.
Drainage class:	Imperfect

II. Brief description of the profile

The profile, sited on *Kokofu series* is very deep (>190cm) and free of gravels and concretions. The soil is developed on colluvial deposits derived from Lower Birimian phyllite on lower slope site. It is imperfectly drained with varying colours that range from dark greyish brown, strong brown to light grey. It has a humus-stained thick topsoil (20cm) with dark greyish brown colour, sandy loam texture and granular structure. The thick subsoil (>150cm) has mostly sandy loam to clay loam textures and subangular structure with clay cutans on pedfaces. The subsoil colours range from strong brown to light grey.

III. **Profile Description**

Horizon	Depth (cm)	Description
Ap1	0 - 10	Dark greyish brown (10YR 4/2) moist; sandy loam; weak fine and medium granular; non-sticky, non-plastic, friable, soft; common very fine and fine, few coarse pores; common very fine and fine, few medium roots; clear, smooth boundary; pH 5.4.
Ap2	10 - 15/20	Dark greyish brown (10YR 4/2) moist; sandy loam; moderate medium granular; non-sticky, non-plastic, friable, soft; common very fine and fine and common medium pores; common very fine and medium roots; gradual, wavy boundary; pH 4.9.
AB	15/20-30	Brown (10YR 6/4) moist; sandy loam; moderate fine subangular blocky; slightly sticky, slightly plastic; friable; slightly hard; common very fine and fine pores; few, very fine and fine and few medium roots; gradual, smooth boundary; pH 4.6.
Bt1	30-40/49	Brownish yellow (10YR 6/6) moist; sandy loam; moderate fine and medium subangular blocky; slightly sticky, slightly plastic; friable; hard; few distinct clay cutans on ped faces; few, very fine and fine few medium pores; few fine and few medium roots; clear, wavy boundary; pH 4.3.
.Bt2	40/49-84	Strong brown(7.5YR 4/6) moist; sandy clay; strong medium subangular blocky; slightly sticky, slightly plastic; friable; common distinct clay cutans on ped faces; few, very fine and

		fine and few medium pores; few fine and medium roots; diffuse, smooth boundary; pH 4.2.
2Btv	84-100/110cm	Strong brown (7.5YR 5/6) moist; clay loam; common medium distinct clear yellowish brown mottles (plinthite material); strong medium subangular blocky; friable; slightly sticky, plastic; common distinct clay cutans on ped faces; few very fine and fine pores; few, very fine and fine and few medium roots; clear, wavy boundary; pH 4.2.
3Bv1	100/110 - 140	Light grey (10YR 7/1) moist; sandy loam; common medium distinct sharp yellowish brown mottles (plinthite material), moderate medium subangular blocky; friable; slightly sticky, slightly plastic; very fine and fine pores; very few fine roots; clear, smooth boundary; pH 4.2.
3Bv2	140 190	Light grey (2.5YR 7/1) moist; clay loam; abundant coarse prominent sharp yellowish brown and reddish brown mottles (plinthite material); strong medium subangular blocky; sticky, plastic, few very fine and fine pores; few fine roots; pH 4.0.

LABORATORY INVESTIGATION RESULTS

Profile No.: CPL1 Soil Name: *Kokofu series*

Horizon	Depth (cm)	pH H_2O 1:1	EC mS/cm	Org. C %	Total N %	Org. Matter %	Exchangeable Cations cmol (+)/kg Ca	Mg	K	Na	TEB	(Al+H)	CEC cmol (+)/kg	Base Sat. %
Ap1	0 - 10	5.4	0.07	3.17	0.27	5.47	5.44	1.28	0.10	0.07	6.89	0.50	7.39	93
Ap2	10 - 15/20	4.9	0.03	2.09	0.19	3.60	2.40	0.48	0.05	0.05	2.98	0.50	3.48	86
AB	15/20 - 30	4.6	0.02	1.15	0.10	1.98	2.08	0.48	0.05	0.05	2.66	0.50	3.16	84
Bt1	30 - 40/49	4.3	0.03	0.58	0.04	1.00	2.24	0.32	0.04	0.04	2.64	0.60	3.24	81
Bt2	40/49 - 84	4.2	0.02	0.53	0.04	0.91	2.24	0.48	0.05	0.05	2.82	0.80	3.62	78
2Btv	84 - 100/110	4.2	0.02	0.44	0.03	0.76	1.92	0.64	0.04	0.04	2.64	0.85	3.54	75
3Bv1	110/111 - 140	4.2	0.02	0.33	0.03	0.57	1.76	0.32	0.04	0.04	2.16	1.10	3.26	66
3Bv2	140 - 190	4.0	0.03	0.24	0.02	0.41	1.76	0.32	0.04	0.04	2.16	1.45	3.61	60

Horizon	Mechanical Analysis % Sand	% Silt	% Clay	Texture
Ap1	55.66	35.00	9.34	Sandy loam
Ap2	65.30	27.99	6.71	Sandy loam
AB	58.34	28.40	13.26	Sandy loam
Bt1	54.50	27.43	18.07	Sandy loam
Bt2	46.78	17.08	36.14	Sandy clay
2Btv	39.48	25.27	35.25	Clay loam
3Bv1	50.92	22.11	26.97	Sandy clay loam
3Bv2	44.97	27.63	27.40	Clay loam

8.6 *Kokofu series*

1 GENERAL INFORMATION

a. Registration and Location

i.	Profile number:	CPL2
ii.	Date of description:	10th December, 1997
iii.	Soil unit	*Kokofu series*
iv.	Location:	SRI Management Farm near the fish pond.

b. Soil classification

i.	WRB (1998):	Endogleyi-Plinthic Acrisol
	FAO (1980):	Plinthic Acrisol
ii.	ST (USDA, 1998):	Typic Plinthustult

Topo-site:	Lower slope
Landuse:	Annual cultivation to arable crops
Parent material:	Colluvial sediment derived from phyllite
Drainage class:	Moderately well drained

II General Description

The profile is a deep, yellowish brown silty clay loam. It lies on the lower slope. The topsoil is silty loam, dark brown to brown; it is friable; non sticky and non plastic. The subsoil is however sticky and plastic and is clay loam to clay.

III Profile Description

Horizon	Depth (cm)	Description
Ap1	0 - 6	Dark brown (10YR 3/3) moist; fine sandy loam; weak, very fine to fine granular; loose, non sticky, non plastic; common very fine and fine, interstitial pores; common, very fine and fine, few medium and very few coarse roots; clear, smooth boundary; pH 4.0.
Ap2	6 - 22	Brown (10YR 5/3) moist; fine sandy loam; weak fine and medium granular; friable, slightly sticky, non plastic; slightly hard; common very fine, few medium interstitial pores; very few (2%) fine rounded hard brown iron concretions; very few, very fine and fine, few medium and very few coarse roots; clear, smooth boundary; pH 3.6.
BA	22 - 32/43	Yellowish brown (10YR 5/4) moist; silty loam; moderate fine and medium subangular blocky; friable; slightly sticky, non plastic; slightly hard; common very fine, few fine interstitial pores; few medium termite channels; few (4%) fine and medium hard and soft subrounded brown iron concretions; very few, very fine and fine roots; diffuse, wavy boundary; pH 3.6.
Btcs	32/43 - 66	Yellowish brown (10YR 5/6) moist; silty clay loam; moderate fine, medium subangular blocky; firm; slightly sticky, non plastic; hard; common faint clay films on ped faces; common very fine, few fine and medium interstitial pores; few (2%) fine, medium

		subrounded fresh quartz stones; common (5%) fine, medium, irregular hard and soft brown iron concretions very few, very fine roots; gradual, smooth boundary; pH 3.5.
Btcsv1	66 - 111	Yellowish brown (10YR 5/8) moist; silty clay loam; yellowish red (5 YR 5/6) few fine distinct mottles; moderate to strong, medium subangular blocky; slightly plastic and slightly sticky; common faint clay films on ped faces; common very fine and fine interstitial pores; few (2%) fine, medium irregular and subangular fresh quartz gravels; few (4%) irregular hard and soft red iron and manganese dioxide concretions; very few, very fine roots; clear smooth boundary; pH 3.6.
Btcsv2	111 - 143	Yellowish brown (10YR 5/8) moist; silty loam; yellowish red (5YR 4/6) common fine distinct mottles; moderate to strong, fine, medium subangular blocky; slightly sticky, slightly plastic, few faint clay films on ped faces; common, very fine, few fine, very few medium interstitial pores; very few, fine and medium termite tunnels; very few (1%) fine soft rounded and subrounded brown iron concretions; very few, fine and very fine roots; clear, smooth boundary; pH 3.6.
Bycsv3	143 - 194	Yellowish brown (10YR 5/8) moist; silty clay loam; grey (5Y 6/1) common fine distinct, dark red (2.5YR 3/6) common medium distinct and very pale brown (10YR 7/3) few fine distinct mottles; moderate fine,

		medium subangular blocky; friable to firm; slightly sticky, slightly plastic; few faint clay films on ped faces; common very fine and fine, medium interstitial pores; very few termite channels; few (2%) fine and medium subrounded fresh quartz gravels; common (5%) fine, hard and soft rounded and subrounded red iron concretions; very few, very fine roots; clear, smooth boundary; pH 3.6.
Btcsv4	194 - 216	Yellowish brown (10YR 5/8) moist; silty clay loam; red (2.5YR 5/8) common fine distinct and light olive grey (5Y 6/2); common medium distinct mottles; weak fine and medium subangular blocky; friable slightly sticky, slightly plastic; common (5%) soft irregular red iron concretions; pH 3.6.

LABORATORY INVESTIGATION RESULTS

Profile No.: CPL2 Soil Name: *Kokofu series*

Horizon	Depth (cm)	pH H_2O 1:1	EC MS/cm	Org. C %	Total N %	Org. Matter %	Exchangeable Cations cmol (+)/kg Ca	Mg	K	Na	TEB	(Al+H)	CEC cmol (+)/kg	Base Sat. %
Ap1	0 - 6	4.0	0.14	2.00	0.17	3.45	1.60	0.80	0.11	0.08	2.59	0.70	3.29	79
A2	6 - 22	3.6	0.07	1.28	0.10	2.21	0.96	0.48	0.05	0.06	1.55	1.90	3.34	45
BA	22 - 32/43	3.6	0.05	0.83	0.08	1.43	0.64	0.48	0.04	0.05	1.21	3.30	4.51	27
Btcs	32/43 - 66	3.5	0.04	0.62	0.05	1.07	0.80	0.64	0.05	0.06	1.55	2.70	4.25	37
Btcsv1	66 - 111	3.6	0.04	0.45	0.03	0.78	0.64	0.48	0.05	0.07	1.24	3.00	4.24	29
Btcsv2	111 - 143	3.6	0.03	0.37	0.03	0.64	0.64	0.48	0.04	0.06	1.22	2.80	4.02	30
Btcsv3	143 - 194	3.6	0.02	0.35	0.03	0.60	1.44	0.48	0.04	0.05	2.01	2.50	4.51	45
Btcsv4	194 - 216	3.6	0.02	0.34	0.02	0.59	1.60	1.12	0.05	0.01	2.84	2.30	5.14	55

Horizon	Mechanical Analysis Sand	Silt	Clay	Texture
Ap1	71.86	19.87	8.27	Sandy loam
A2	57.43	25.42	17.14	Sandy loam
BA	52.76	36.62	10.62	Sandy loam
Btcs	43.48	28.39	28.13	Sandy clay loam
Btcsv1	38.10	22.69	39.21	Clay loam
Btcsv2	34.95	27.19	37.86	Clay loam
Btcsv3	35.36	23.82	40.82	Clay
Btcsv4	36.48	22.85	40.67	Silty clay

8.7 *Akumadan series*

I. GENERAL INFORMATION

Registration and Location

i. Profile number: APU

ii. Date of description: 5th December, 1997

iii. Soil Unit: *Akumadan series*

iv. Location: One kilometer east of Abesewa town on Kumasi-Sunyani road.

Soil Classification

i. WRB (FAO, 1998): Epichromi-Endoplinthic Lixisols

ii. FAO (1990b): Plinthic Lixisol

iii. ST (USDA, 1998): Typic Plinthustalf

Topo-site: Upper slope

Landuse: The site is under close cocoa plantation.

Parent material: Peneplain drift materials derived from phyllite

Drainage class: Well drained

II. Brief Description of the Profile

The profile of *Akumadan series* is very deep (>200cm) well drained and reddish in colour. It is sited on upper slope of a ridge under cocoa plantation. The soil is developed from weathered products of Lower Birimian phyllite. It consists of humus-stained moderately thick (>9cm) dark brown topsoil with clay loam texture, weak granular structure, few quartz and ironstone gravels. The thick subsoil (>200cm) is dusky red to red in colour, and medium to strong subangular blocky structure with few quartz gravels and ironstone concretions. Clay cutans are common on pedfaces.

III. **Profile Description**

Horizon	Depth (cm)	Description
Ap	0 - 9	Dark brown (7.5YR 3/4) moist; clay loam; weak fine and medium granular; slightly sticky, slightly plastic; friable; many very fine, many fine and few medium interstitial pores; very few (1%) medium and coarse angular fresh quartz gravels; few (2%) medium and common very fine and fine irregular hard brown and black ironstone concretions; common fine and many medium roots; clear, smooth boundary; pH 6.1.
AB	9 - 20/40	Yellowish red (5YR 4/6) moist; clay; weak fine and medium subangular blocky; sticky, plastic, friable; common very fine and common fine interstitial pores; few (2%) medium and very few coarse angular fresh quartz gravels; common (5%) fine and common medium irregular, hard and black ironstone gravels; common fine and few medium roots; clear, wavy boundary; pH 5.2.
Btcs1	20/40 - 48/52	Dusky red (2.5YR 4/4) moist; clay; moderate medium subangular blocky; sticky, plastic, firm; common distinct clay cutans on ped faces; common fine and very fine interstitial pores; common fine and few (3%) medium angular fresh quartz gravels; common (5%) very fine, few medium irregular hard black ironstone gravels; few fine roots; clear, wavy boundary; pH 4.6.
Btcs2	48/52 - 83	Dark red (2.5YR 4/6) moist; clay; moderate medium subangular blocky; sticky, plastic, firm; common distinct clay cutans on ped faces; common fine and many very fine interstitial pores; few (3%) fine irregular soft black ironstone gravels; very few medium roots; gradual, smooth boundary; pH 4.7.

Btcsv1	83 - 118	Dark red (2.5YR 4/6) moist; clay; few fine faint diffuse strong brown mottles (plinthite material); weak medium subangular blocky; sticky, plastic, friable; few faint clay cutans on ped faces; common fine and many very fine interstitial pores; very few (2%) fine and medium irregular soft black ironstone gravels; few fine and very few medium roots; diffuse, smooth boundary; pH 4.8.
Btcsv2	118 - 192	Dark red (2.5YR 4/8) moist; clay; few fine distinct clear strong brown mottles (plinthite material), weak medium subangular blocky; sticky, plastic, friable; few faint clay cutans on ped faces; common very fine and common fine interstitial pores; very few (2%) fine irregular soft black ironstone gravels; very few fine roots; clear, smooth boundary; pH 4.9.
Bv	192 - 223	Red (10R 4/6) moist; clay; common fine distinct clear reddish yellow mottles (plinthite material); strong medium subangular blocky; sticky, plastic, friable; common very fine and common fine interstitial pores; few fine and very few medium roots; pH 4.7.

LABORATORY INVESTIGATION RESULTS

Profile No.: APU . Soil Name: *Akumadan series*

Horizon	Depth (cm)	pH H_2O 1:1	EC MS/cm	Org. C %	Total N %	Org. Matter %	Exchangeable Cations cmol (+)/kg Ca	Mg	K	Na	TEB	(Al+H)	CEC cmol (+)/kg	Base Sat. %
Ap	0 - 9	6.1	0.23	3.15	0.26	5.43	14.28	8.00	0.48	0.15	22.87	0.85	23.72	96
AB	9 - 20/40	5.2	0.07	2.45	0.20	4.22	6.72	2.88	0.18	0.06	9.84	0.80	10.64	92
Btcs1	20/40 - 48/52	4.6	0.03	1.07	0.09	1.84	2.08	1.12	0.07	0.04	3.31	0.60	3.91	85
Btcs2	48/52 - 83	4.7	0.03	0.66	0.06	1.14	2.24	0.96	0.05	0.03	3.28	0.65	3.93	83
Btcsv1	83 - 118	4.8	0.03	0.54	0.04	0.93	2.40	0.80	0.05	0.03	3.28	0.70	3.98	82
Btcsv2	118 - 192	4.9	0.03	0.46	0.03	0.79	2.24	0.64	0.05	0.03	2.96	0.70	3.66	81
Bv	192 - 223	4.7	0.02	0.40	0.03	0.69	2.08	0.64	0.05	0.03	2.80	0.80	3.60	78

Horizon	Mechanical Analysis % Sand	% Silt	% Clay	Texture
Ap	37.89	26.52	35.59	Clay Loam
AB	35.86	17.01	47.13	Clay
Btcs1	19.03	12.02	68.95	Clay
Btcs2	16.88	15.43	67.69	Clay
Btcsv1	17.05	16.00	66.95	Clay
Btcsv2	20.88	23.67	55.45	Clay
Bv	28.79	25.85	45.36	Clay

8.8 *Afrancho series*

I. GENERAL INFORMATION

Registration and Location

i. Profile number: APM

ii. Date of description: 5th December, 1997

iii. Soil Unit: *Afrancho series*

iv. Location: One and half kilometers on the right side of Abesewa town on Kumasi-Sunyani road.

Soil Classification

i. WRB (FAO, 1998): Epichromi-Bathiplinthic Lixisols

ii. FAO (1990b): Plinthic Lixisol

iii. ST (USDA, 1998): Typic Plinthustalf

Topo-site: Middle slope

Landuse: The site is under close cocoa plantation

Parent material: Sedentary materials derived from phyllite

Drainage class: Moderately well drained

II. Brief Description of the profile

The profile is very deep (>200cm), moderately well drained, reddish in colour with quartz gravels and ironstone concretions. The soil is developed on peneplain drift materials of Lower Birimian phyllite on middle slope site. It consists of dark brown, sandy clay loam, humus-stained topsoil (>7cm) with moderate granular structure overlying thick (>200cm) yellowish red to dark red subsoil with medium subangular blocky structure and quartz and ironstone gravels. Clay cutans are located on ped faces.

III. Profile Description

Horizon	Depth (cm)	Description
Ap	0 - 7	Dark brown (7.5YR 3/4) moist; sandy clay loam; moderate fine and medium granular, slightly sticky, slightly plastic, friable; many fine interstitial pores; many fine and very few medium roots; clear, smooth boundary; pH 6.2.
BA	7 - 16	Reddish brown (5YR 4/4) moist; clay; moderate fine and medium subangular blocky; sticky, plastic, friable; common very fine and few medium interstitial pores; few fine and very few medium roots; gradual, smooth boundary; pH 5.7.
Bt	16 - 38	Yellowish red (5YR 4/6) moist; clay; moderate fine subangular blocky; sticky, plastic, firm; common distinct clay cutans on ped faces and inside voids; common fine pores; few fine and very few medium roots; diffuse, smooth boundary, pH 4.8.
Btcs1	38 - 93	Dark red (2.5YR 4/6) moist; clay; moderate medium subangular blocky; sticky, plastic, firm; common distinct clay cutans on ped faces and inside voids; common fine pores; very few (1%) fine quartz gravels; and very few (1%) hard fine and medium irregular ironstone concretions; few fine and few medium roots; very few termite burrows; clear, smooth boundary; pH 4.5.
Btcs2	93 - 117	Dark red (2.5YR 4/6) moist; clay; moderate medium subangular blocky; slightly sticky, plastic, firm; common distinct clay cutans on ped faces and inside voids; common fine pores; few (3%) fine and medium quartz gravels; few (2%) fine and medium hard irregular

		black ironstone gravels and concretions; very few fine and few medium roots; very few termite burrows; clear, smooth boundary; pH 4.4.
Btcsv1	117 - 140	Dark red (2.5YR 4/8) moist; clay; few fine distinct clear yellowish brown and few fine distinct reddish brown mottles (plinthite material), moderate medium subangular blocky; sticky, plastic, firm; common distinct clay cutans on ped faces; many few fine interstitial pores; common (6%) fine and medium quartz gravels; common (10%) fine and common medium black irregular ironstone gravels; very few fine and common medium roots; gradual, smooth boundary; pH 4.5.
Btcsv2	140 - 177	Dark red (2.5YR 4/8) moist; clay; common medium distinct clear yellowish brown and common medium distinct clear reddish brown mottles (plinthite material); moderate medium subangular blocky; sticky, plastic, firm; common distinct clay cutans on ped faces; many fine interstitial pores; many (16%) medium irregular black ironstone gravels; common medium roots; diffuse, smooth boundary; pH 4.4.
Btcsv3	177 - 215	Dark red (2.5YR 4/8) moist; clay; abundant coarse prominent sharp yellowish brown and common coarse prominent clear reddish brown mottles (plinthite material), strong medium subangular blocky; sticky, plastic, friable; common distinct clay cutans on ped faces; many very fine interstitial pores; few (3%) medium irregular black ironstone gravels; very few fine and medium roots; pH 4.2.

LABORATORY INVESTIGATION RESULTS

Profile No.: APM Soil Name: *Afrancho series*

Horizon	Depth (cm)	pH H_20 1:1	EC MS/cm	Org. C %	Total N. %	Org. Matter %	Exchangeable Cations cmol (+)/kg Ca	Mg	K	Na	TEB	(Al+H)	CEC cmol (+)/kg	Base Sat. %
Ap	0 - 7	6.2	0.33	3.26	0.29	5.62	9.12	8.16	0.44	0.11	17.67	0.70	18.37	96
BA	7 - 16	5.7	0.09	2.87	0.25	4.95	5.12	1.44	0.16	0.04	6.76	0.75	7.51	90
Bt	16 - 38	4.8	0.06	1.20	0.10	2.07	3.36	1.28	0.08	0.04	4.76	0.80	5.56	86
Btcs1	38 - 93	4.5	0.03	0.78	0.07	1.34	2.88	0.64	0.06	0.04	3.62	0.80	4.42	82
Btcs2	93 - 117	4.4	0.03	0.60	0.05	1.03	2.24	1.12	0.05	0.03	3.44	0.85	4.29	80
Btcsv1	117 - 140	4.5	0.03	0.48	0.04	0.83	2.24	0.96	0.05	0.04	3.29	0.90	4.19	79
Btcsv2	140 - 177	4.4	0.03	0.46	0.03	0.79	2.56	0.48	0.05	0.04	3.13	1.10	4.23	74
Btcsv3	177 - 215	4.2	0.03	0.37	0.03	0.64	1.76	0.64	0.05	0.04	2.49	1.15	3.64	68

Horizon	Mechanical Analysis %Sand	% Silt	% Clay	Texture
Ap	50.50	17.44	32.06	Sandy clay loam
BA	43.03	15.37	41.60	Clay
Bt	31.05	18.67	50.28	Clay
Btcs1	24.97	10.83	64.20	Clay
Btcs2	19.37	13.93	66.70	Clay
Btcsv1	19.30	21.54	59.16	Clay
Btcsv2	20.23	18.78	60.99	Clay
Tcsv3	20.63	29.36	50.01	Clay

8.9 *Oda series*

I. GENERAL INFORMATION

Registration and Location

i.	Profile number:	APL
ii.	Date of description:	5th December, 1997
iv.	Soil unit:	*Oda series*
v.	Location:	Two kilometers east of Abesewa town on Kumasi-Sunyani road

Soil Classification

i.	WRB (FAO, 1998):	Endogleyic Cambisol
ii.	F.A.O. (1990b):	Eutri-Gleyic Cambisol
iii.	ST (USDA, 1998):	Oxyaquic Haplustept

Topo-site:	Lower slope
Landuse:	Site is under cocoa plantation adjacent to swamp thicket
Parent Material:	Colluvio-alluvial materials derived from phyllite on old alluvial terrace
Drainage class:	Poorly drained

II. Brief description of the profile

The profile was sited on the lower terrace of a stream on very deep (>200cm), poorly drained soil developed on colluvial-alluvial deposits of Lower Birimian phyllite. It has moderately thick (>10cm) humus-stained topsoil with dark greyish brown colour, sandy clay loam texture and medium granular structure. The subsoil which is very thick (>250cm) has sandy clay loam to clay textures and weakly developed subangular blocky structure with yellowish brown colour while the deeper layers of the subsoil are structureless.

III. **Profile Description**

Horizon	Depth (cm)	Description
Ap	0 - 10	Dark greyish brown (10YR 4/2) moist; sandy clay loam; weak fine and medium granular; slightly sticky, slightly plastic; friable; many fine interstitial pores; common fine, few medium and very few coarse roots; clear, smooth boundary; pH 5.5.
BA	10 - 22	Brown (10YR 4/3) moist; sandy clay loam; moderate, fine and medium granular; slightly sticky, slightly plastic, firm; many very fine, common fine and few medium pores; few fine and common medium roots; gradual, smooth boundary; pH 5.2.
Bw	22 - 49	Dark yellowish brown (10YR 4/4) moist; sandy clay loam; very weak fine subangular blocky; sticky, plastic, firm; common fine and medium pores; few fine and common medium roots; gradual, smooth boundary; pH 4.6.
Bwcs	49 - 70	Yellowish brown (10YR 5/4) moist; sandy clay loam; weak medium subangular blocky, sticky, plastic, firm; few medium pores; very few (1%) fine subrounded soft black ironstone gravels; very few fine and few medium roots; clear, smooth boundary; pH 4.5.
Bwcsg1	70 - 100	Yellowish brown (10YR 5/4) moist; clay; few fine distinct clear light yellowish brown mottles; weak medium subangular blocky; sticky, plastic, firm; few fine interstitial pores; common (6%) fine and medium rounded and irregular hard and soft ironstone gravels; very few fine and very few medium roots; clear, smooth boundary; pH 4.7.

Bwcsg2	100 - 142	Yellowish brown (10YR 5/8) moist; clay; common medium distinct clear light olive grey mottles; moderate fine and medium subangular blocky; sticky, plastic, firm; many very fine and few medium interstitial pores; very few (1%) rounded quartz gravels; common (6%) fine and medium rounded and irregular hard and soft black ironstone gravels; few very fine and common medium roots; clear, smooth boundary; pH 4.9.
BC	142 - 185	Pale olive grey (5Y 6/4) moist; clay; common medium distinct clear yellowish brown mottles; very weak medium subangular blocky; sticky, plastic, firm; many very fine and few fine pores; few (3%) fine and medium angular quartz gravels; very few fine roots; gradual, smooth boundary; pH 6.9.
2Cg1	185 - 223	Pale olive grey (5Y 6/4) moist; sandy clay loam; common medium distinct clear yellowish brown mottles; structureless, sticky, plastic, firm; many very fine and common fine pores; very few (3%) fine and medium quartz gravels; very few fine roots; gradual, smooth boundary; pH 6.7.
2Cg2	185 - 259	Pale olive grey (5Y 6/4) moist; sandy clay; common medium, distinct, clear yellowish brown mottles; structureless; sticky, plastic, firm; few fine pores; very few (1%) fine and medium quartz gravels; very few fine roots; pH 6.3.

LABORATORY INVESTIGATION RESULTS

Profile No.: APL — Soil Name: *Oda series*

Horizon	Depth (cm)	pH H_20 1:1	EC MS/cm	Org. C %	Total N %	Org. Matter %	Exchangeable Cations cmol (+)/kg						CEC cmol (+)/kg	Base Sat. %
							Ca	Mg	K	Na	TEB	(Al+H)		
Ap	0 – 10	5.2	0.28	3.32	0.30	5.72	8.64	5.60	0.24	0.11	14.59	0.50	15.09	97
BA	10 – 22	5.2	0.10	2.96	0.24	5.10	4.64	3.04	0.12	0.09	7.89	0.50	8.39	94
Bw	22 – 49	4.6	2.13	0.81	0.07	1.40	4.64	2.40	0.13	0.10	7.27	0.50	7.77	94
Bwcs	49 - 70	4.5	2.90	0.66	0.03	1.14	4.64	4.16	0.16	0.12	9.08	0.55	9.63	94
Bwcsg1	70 – 100	4.7	2.15	0.49	0.04	0.84	4.80	3.52	0.17	0.17	8.66	0.60	9.26	94
Bwcsg2	100 – 142	4.9	2.30	0.36	0.03	0.62	5.60	3.68	0.20	0.24	9.72	0.60	10.32	94
2BC	142 – 185	6.9	2.14	0.32	0.02	0.55	17.76	12.00	0.74	0.78	31.28	0.40	31.73	99
2Cg1	185 - 223	6.7	2.77	0.30	0.02	0.52	12.48	4.00	0.54	0.74	17.76	0.40	18.16	98
Cg2	223 - 259	6.3	0.10	0.24	0.02	0.41	11.04	4.00	0.36	0.63	16.03	0.40	16.93	98

Horizon	Mechanical Analysis			Texture
	% Sand	% Silt	Clay	
Ap	60.41	16.04	23.55	Sandy clay loam
BA	58.28	20.33	21.39	Sandy clay loam
Bw	48.20	29.87	21.93	Sandy clay loam
Bwcs	45.57	19.84	34.59	Sandy clay loam
Bwcsg1	39.13	11.10	49.77	Clay
Bwcsg2	36.79	15.13	48.08	Clay
BC	31.69	21.68	46.63	Clay
Cg1	50.60	16.60	32.77	Sandy clay loam
Cg2	52.33	9.62	38.05	Sandy clay

8.10 *Bomso series*

1. **GENERAL INFORMATION**

Registration and Location

i.	Profile number:	UPU1
ii.	Date of description:	25th November, 1997
iii.	Soil unit:	*Bomso series*
iv.	Location:	KNUST Trial plot, Kumasi

Soil Classification

i.	WRB (FAO, 1998):	Epichromi-Endoplinthic Acrisols
ii.	FAO (1990b):	Plinthic Acrisol
iii.	ST (USDA, 1998):	Typic Plinthustult

Topo-site:	Upper Slope
Landuse:	Annual field cropping to arable crops
Parent material:	Sedentary materials derived from granite
Drainage class:	Well drained

II. **Brief Description of Profile**

The profile is very deep (>220cm), reddish, gravelly, well drained and developed on sedentary granitic materials. The soil has a thick (>28cm) humus-stained, very dark greyish brown topsoil with sandy loam texture and weak fine and medium granular structure. The subsoil is very thick (>120cm), yellowish red to dark red and has sandy clay to clay textures with moderate to strong subangular blocky structure. Also found in the subsoil are quartz and ironstone gravels, white mica flakes and clay cutans on pedfaces.

III. Profile Description

Horizon	Depth (cm)	Description
Ap1	0 - 11	Very dark greyish brown (10YR 3/2) moist; sandy loam; weak fine and medium granular; friable; non-sticky, non-plastic; common very fine and fine interstitial pores; few (2%) fine and medium mica flakes; few (2%) fine angular and irregular fresh quartz gravels; many very fine and common fine roots; clear, smooth boundary; pH 5.3.
Ap2	11 - 28	Brown (10YR 4/3) moist; sandy clay loam; weak fine and medium granular; firm; slightly plastic, slightly sticky; common very fine and fine interstitial pores; few (2%) medium mica flakes; few (2%) fine and medium angular fresh quartz gravels; common very fine and very few medium roots; clear, smooth boundary, pH 5.3.
BA	28 - 44	Yellowish red (5YR 4/6) moist; sandy clay; weak fine and medium subangular blocky; firm; slightly sticky, slightly plastic; few very fine and fine interstitial pores; very few (1%) fine and medium mica flakes; very few (1%) angular fresh quartz gravels; very few (1%) fine irregular hard and soft black ironstone gravels; few very fine and very few fine roots; gradual, smooth boundary; pH 5.5.
Bt	44 - 79	Yellowish red (5YR 4/6) moist; sandy clay; moderate fine and medium subangular blocky; firm; slightly sticky, slightly plastic; few faint clay cutans on ped faces; few fine interstitial pores; few (5%) angular fresh quartz stones; common (6%) fine and medium angular fresh quartz gravels; few (3%) fine

		irregular hard black ironstone gravels; few very fine and very few fine roots; clear, smooth boundary; pH 5.3.
Btcsv1	79 - 100	Yellowish red (5YR 4/6) moist; clay; common fine faint diffuse reddish brown mottles (plinthite material); moderate, medium and coarse subangular blocky; firm; slightly sticky, slightly plastic; common distinct clay cutans on ped faces; few very fine and fine interstitial pores; very few (1%) fine angular fresh quartz gravels; common (6%) fine hard and soft irregular black ironstone gravels; very few very fine and fine roots; diffuse, smooth boundary, pH 5.1.
Btcsv2	100 - 130	Dark red (2.5YR 4/6) moist; clay; common medium distinct clear reddish brown mottles (plinthite material); moderate fine and medium subangular blocky; firm, sticky, plastic; common distinct clay cutans on ped faces; few very fine and fine interstitial pores; few (3%) fine and medium fresh quartz gravels; common (10%) fine hard and soft irregular black ironstone gravels; very few very fine and fine roots; gradual, smooth boundary, pH 5.0.
Btcsv3	130 - 154	Dark red (2.5YR 4/6) moist; clay; many coarse prominent sharp yellowish and reddish brown mottles (plinthite material); strong medium subangular blocky, firm; sticky, plastic; many distinct clay cutans on ped faces; few very fine and fine interstitial pores; few (2%) fine mica flakes; few

		(5%) fine and medium angular fresh quartz gravels; common (10%) fine hard and soft irregular black ironstone gravels and concretions; few very fine roots; diffuse, smooth boundary, pH 4.9.
C	154 - 223	Brownish yellow (10YR 6/8) moist; clay loam; structureless, firm, slightly sticky, slightly plastic; few very fine and fine interstitial pores; very few (1%) fine mica flakes; very few (2%) fine and medium fresh quartz gravels; common (10%) fine and medium soft and hard irregular black ironstone gravels and concretions; very few fine roots; pH 4.8.

LABORATORY INVESTIGATION RESULTS

Profile No.: UPU1 Soil Name: *Bomso series*

Horizon	Depth (cm)	pH H_20 1:1	EC mS/cm	Org C %	Total N %	Org. Matter %	Exchangeable Cations cmol (+)/kg						CEC cmol (+)/kg	Base Sat. %
							Ca	Mg	K	Na	TEB	(Al+H)		
Ap1	0 - 11	5.3	0.09	1.43	0.15	2.47	5.60	1.76	0.14	0.07	7.57	0.90	8.47	89
Ap2	11 - 28	5.3	0.04	0.89	0.08	1.53	4.00	1.12	0.06	0.04	5.22	1.80	7.02	74
BA	28 - 44	5.5	0.03.	0.70	0.06	1.21	2.88	1.12	0.06	0.04	4.10	1.20	5.30	77
Bt	44 - 79	5.3	0.03	0.57	0.05	0.98	2.40	0.32	0.05	0.04	2.81	1.50	4.31	65
Btcsv1	79 - 100	5.1	0.03	0.41	0.04	0.71	1.92	0.32	0.03	0.04	2.31	3.20	5.51	42
Btcsv2	100 - 130	5.0	0.04	0.35	0.03	0.60	1.44	0.16	0.03	0.04	1.67	4.20	5.87	29
Btcsv3	130 - 154	4.9	0.04	0.33	0.02	0.57	1.28	0.16	0.03	0.04	1.51	4.90	6.41	24
C	154 - 223	4.8	0.04	0.21	0.02	0.36	1.12	0.16	0.03	0.04	1.35	5.10	6.45	21

Horizon	Mechanical Analysis			Texture
	% Sand	% Silt	% Clay	
Ap1	73.71	10.24	16.05	Sandy Loam
Ap2	58.65	9.82	31.53	Sandy clay loam
BA	55.50	6.80	37.70	Sandy clay
Bt	45.61	8.43	45.96	Sandy clay
Btcsv1	37.16	13.24	49.60	Clay
Btcsv2	33.38	16.16	50.46	Clay
Btcsv3	29.76	16.69	53.55	Clay
C	41.39	20.46	38.15	Clay loam