DYNAMICS OF SOIL CARBON SEQUESTRATION UNDER OIL PALM PLANTATIONS OF DIFFERENT AGES

BY

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DEDICATION

To the greater glory and honour of God the Father Almighty

and

Mr. Kumi Prosper, Madam Esther Atukey and Mr. Aseweh Samuel

DECLARATION

I hereby declare that this thesis has been written by me and that this is the record of my own research work. It has neither in whole nor in part been presented for another degree elsewhere. Works of other researchers have been duly cited by references to the authors and all assistance received also acknowledged.

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ABSTRACT

It has been estimated that globally a lot of forest is lost in the tropics annually to agriculture. The removal of the forest cover has been cited as one of the main contributors of greenhouse gases. Tree plantations are advocated as carbon (C) sink, however, little is known about rates of C turnover and sequestration into soil organic matter under tropical tree plantations particularly oil palm. One of the commonest management practices adopted by farmers on oil palm plantations involves the prunning of the palm branches and heaping them in between the palm trees in the rows. The spaces or the alleys between the palm trees contained no heaped branch residues. So far very few studies have been conducted to assess the contributions of pruned branches heaped at the different locations under the palm plantations to the fertility status of the soil. The objective of this research was to assess the dynamics of soil C sequestration under oil palm (*Elaeis guineensis*) plantations at different ages in a semi deciduous forest zone of Ghana. A diagnostic field study was carried out to identify oil palm plantations at different ages occurring within the Kwaebibirem District, Ghana. The oil palm plantations were categorised into five age groups (0-5, 5-10, 10-15, 15-20 and 20-25 years). A forest reserve which had not been cultivated for more than 50 years served as a control. All the cultivated farms and the control plot were located at the valley bottom slope on Oda soil series (Aeric Endoaquent). Soil samples were collected under the heaped branches and from the spaces between the palm trees at a depth of 0-10 and 10-20 cm respectively. The control soil from uncultivated plot was also taken at the same depth. The soil samples were collected for bulk density (BD) and organic C determinations. Carbon stocks were calculated using measured C content and the corresponding soil bulk densities. The presence of the residue resulted in lower BD values under heaps than those under alleys with age irrespective of the depth. The OC in the soil decreased with cultivation but was drastic after 5 years of plantation establishment up to age 20 years in both layers under heaps with losses accounting for between 13-45% of the control. In the alleys the OC losses were greater with age in both depths with the lower layer having OC deficit of 57%. The conversion of the forest into the oil palm plantation led to a dramatic loss in soil C stocks of around 45% in the top 10cm irrespective of heap or alley location. In the 10-20cm layer loss was 50-60% with lower decline under residue heaps. Under heaps significant improvements in the C stocks in the top layer is discernible after 20 years but not in the alleys. The carbon saturation deficit followed a similar trend as the C stocks. The conclusion from this study is that oil palm plantations have the ability to sequester carbon over a period of time when palm fronds are added to the soil.

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CHAPTER ONE

1.0 INTRODUCTION

Farming system transformations with the introduction of cash crops have led to permanent cultivation of agricultural lands during the last decades, (Serpantié, 2003). Oil palm is one of the plantation crops grown in Ghana in addition to cocoa and rubber. This has been undertaken by companies such as the Benso Oil Palm Plantation (BOPP) in the Western Region, Ghana Oil Palm Development Company (GOPDC) at Kade in the Eastern Region, Twifo Oil Palm Plantation at Twifo, Central Region and also by other private companies as well as small holder farmers either in groups or as individuals. The production of oil palm has led to the conversion of natural vegetation into oil palm plantations. It is expected that the conversion of some rain forests and use of abandoned logged-off forests into oil palm plantations might have significantly contributed to losses in C from both soil and vegetation into the atmosphere.

Some studies (Ollagnier *et al.*, 1978; Olivin, 1980; Djegui *et al.*, 1992; Haron *et al.*, 1998) carried out under Ivorian conditions have measured changes in soil C content from destruction of the forest ecosystem to its replacement by an oil palm plantation. They observed that when such a replacement was made, there was a notable drop in soil carbon in the first 4 years as the young oil palms develop, then that rate seems to stabilize from 9 years old onwards.

If the effects of global warming are to be kept to a minimum, carbon already emitted to the atmosphere as a result of conversion of large tracts of natural rain forest vegetation into oil palm plantations must be sequestered into stable forms. According to Lal, (2009) C sequestration is enhanced when the input of C into the system exceeds the amount of C that is lost due to plant harvest, physiological respiration, mineralisation, erosion, and leaching. The rate of C sequestration is determined by the net balance between C inputs and C outputs. Carbon inputs and outputs are affected by management e.g. heaping of pruned branches and by two biotic processes- production of organic matter in the soil and decomposition of organic matter by soil organisms.

During cultivation of oil palm local farmers engage in prunning and the heaping of palm fronds in between the rows of plants. Most of these farmers do not add any external source of fertiliser to their farms. The heaping of palm fronds have been observed to be sources of organic material addition to the soil since organic resources have been found to play a vital role in the maintenance of soil organic matter (SOM) and nutrient cycling in most smallholder and large scale oil palm farming systems in the tropics (McNeil et al., 1997; Cadisch et al., 2002b). This management practice by farmers serves as a potential means of contributing C to the soil under oil palm. From an agro-ecological perspective, OM and its main constituent carbon play a crucial role in the functioning of these systems. They actually affect physical, chemical and biological properties of soils (Batjes, 2001; Feller et al., 2001).

From an environmental point of view, soil is an element of the global carbon cycle even if it seems that a dilemma still exists. The desire to increase SOM arises from the global climate issue whiles the desire to decrease it arises from agronomic needs as nutrient sinks for plants (Janzen, 2006). A change therefore in management practices such as heaping of pruned branches leading to an increase in C stocks (sinks) represents a means to reduce CO_2 concentration in the atmosphere which is responsible for the increase of the Earth’s surface temperature (GIECC, 1997). It is therefore imperative that SOM which is an important resource is well managed for agronomic and environmental challenges.

There is a need to assess the soil quality under smallholder oil palm plantations with particular reference to prunning and heaping of branches on farms. This has arisen because of poor management of oil palm prunnings in many of the smallholder farms leading to low soil fertility affecting yield. There is also a need to sequester C to overcome global climate change (Paustian et al., 1998a) and to improve soil quality, as we develop more sustainable and land management practices under oil palm (Carter, 2002).

So far there appears to be no information on soil carbon studies under pruned heaps on oil palm plantations in Ghana. There is also lack of information on C dynamics under this management system with age of the plantations. There is therefore the need to assess how management activities (prunning and heaping) undertaken by local farmers influence organic carbon stocks in the soil under oil palm plantations at the smallholder farms in Ghana.

The hypothesis of the study is that, management practice of prunning and heaping of fronds of oil palm trees in between the palms could serve as a means of building C in the soil and thereby minimising C emissions into the atmosphere.

The objectives of this research are: (1) to assess soil C content and stocks under pruned heaps in already established oil palm plantations of different maturity ages; (2) to examine the dynamics (changes) in soil C stocks over time under pruned heaps in these oil palm plantations.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This chapter critically aims at looking through available literature to find out works that have been done in relation to soil carbon sequestration under oil palm plantations under similar environmental (tropical) conditions. The review also aims at bringing to light all relevant information in relation to the topic and would look at past and current trends and possibly future events that are likely to occur. It also involves identifying the gaps that exist in the various researches that have been undertaken and how a suitable and appropriate approach can be taken to guide the undertaking of this research. The review would be in three main sections:

(i) the historical background, agronomy and economic benefits of the oil palm tree

(ii) the presence and role of carbon in the soil

(iii) the various factors and agents that directly or indirectly affect carbon present in soil

2.1 Oil palm

2.1.1 Historical Development of oil palm

The Oil Palm of commerce, *Elaeis guineensis*, is believed to be indigenous to West Africa (the specific name, *guineensis* shows that the first specimen described was collected in Guinea, West Africa) (USDA GRIN Taxonomy 2013). The closely related American oil palm *Elaeis oleifera* is also used to a lesser extent to produce palm oil, and a more distantly related palm *Attalea maripa* is another oil-producing palm (Zahara et al., 2009). Human use of oil palms may date as far back as 5,000 years in West Africa; in the late 1800s, archaeologists discovered palm oil in a tomb at

Abydos dating back to 3,000 BCE (Kiple and Corneeornelas, 2000). It is thought that Arab traders brought the oil palm to Egypt (Obahiagbon, 2012). Oil palms were introduced to Java by the Dutch in 1848, Lötschert and Beese (1983) and to Malaysia (then the British colony of Malaya) in 1910 by Scotsman William Sime and English banker Henry Darby. The species of palm tree *Elaeis guineensis* was taken to Malaysia from Eastern Nigeria in 1961. The southern coast of Nigeria was originally called the Palm oil coast by the first Europeans who arrived there and traded in the commodity. This area was later renamed the Bight of Biafra. There is a general consensus that commercially planted palms in Indonesia, Malaysia and other South–East Asian locations were derived from four West African Palm varieties including *E. guineensis* fo. *dura*, *E. guineensis* var. *pisifera, E. guineensis* fo. *tenera*.

2.1.2 Modern developments in oil palm

Planting materials currently used in commercial oil palm plantations consist of Tenera palms or D x P hybrids, which are obtained by crossing Dura (thick shelled) with Pisifera (shell-less) (Tweneboah, 2000). Instances were common when commercially germinated seed with thick-shell as the Dura mother palm was used, the resulting palm would produce thin-shelled Tenera fruit. To overcome this out-crossing phenomenon is to produce tissue-culture or "clonal" palms, which provide "true copies" of high yielding D x P palms (Foster and Prabowo, 1996a). However, constraints to mass production need to be dealt with.

It has been suggested that the right approach to oil palm development would be to introduce leguminous cover plants immediately after land clearing. These are meant to prevent soil erosion and surface run-off, improve soil structure and palm root development, increase the response to mineral fertilizer in later years, and reduce the danger of micronutrient deficiencies. Leguminous cover plants also help prevent outbreaks of *Oryctes* beetles, which breed in exposed decomposing vegetation (AsySyura and Tsan, 2009). There is a severe setback associated with young palms in areas where grasses are allowed to dominate the inter-row vegetation, more so on poor soils where the correction of nutrient deficiencies is difficult and costly (Foster and Goh, 1997).

According to Tweneboah (2000), oil palm does well under equatorial climate between latitude 10^o North and 10^o south of the Equator. It is within this region that the biggest area of semi-wild *Elaeis guineensis* groves in the lowland regions of Western Africa lie. This region is characterised by mean annual rainfall of 2000 mm with no severe dry season, minimum temperature not below 22^oC and maximum temperatures between $29\text{-}33^oC$. In addition sunshine should be at least five hours per day rising to about seven hours during special months in the year to support high oil palm production. Asamoah and Nuertey (1998a; 1998b) have outlined a description of some Ghanaian soils within Kusi, Twifo Praso and Adum which are suitable for large scale oil palm production. Further, Asamoah and Nuertey (2005) have shown that oil palm does well in areas considered as marginal and unsuitable within the forest zone of Ghana.

Successful oil palm development involves selecting a suitable soil even though oil palm does well on a wide variety of soils ranging from well drained deep loams to sandy loams and sandy clay loams having pH below 6. Oxisols and Ultisols both highly weathered deep soils occur in oil palm growing areas in Guinea-Bissau, Sierra Leone, Liberia, Southern Cote d' Ivoire, South eastern and western part of Ghana and South eastern Nigeria. However, Oxisols have been reported as being best for oil palm production (Tweneboah, 2000).

According to Tinker (1976) nutrient requirements of oil palm vary directly depending on yield target set, type of planting material used, spacing, age, soil type, ground cover conditions in addition to good climate and associated environmental factors. Nutrient demand can therefore be grouped according to:

1. That removed in the harvested crop (fruit bunch)
2. That immobilised in the palm biomass
3. That recycled to the soil in pruned fronds, male inflorescence and leaf wash.

After successful pollination, it takes about five to six months for fruits to mature. Matured fruits are reddish in colour about the size of a large plum and occur in a large bunch. Examination of a fruit reveals an oily fleshy outer layer (pericarp) with a single seed (palm kernel) with an inner portion rich in oil. A fully matured ripe bunch weighs between 40-50 kg (Fairhurst and McLaughlin, 2009).

2.1.3 Economic importance

Oil is extracted from both the pulp of the fruit (palm oil, an edible oil) and the kernel (palm kernel oil, used in foods and soap manufacture). For every 100 kg of fruit bunches, typically 22 kg of palm oil and 1.6 kg of palm kernel oil can be extracted (Fairhurst and McLaughlin, 2009). Also, high oil yield of oil palms (up to about 7,250 litres per hectare per year) has made it a common cooking ingredient in Southeast Asia and the tropical belt of Africa. Currently, its use in the commercial food industry in other parts of the world has increased as a result of its cheaper pricing (USDA, 2006). The high oxidative stability of refined oil palm product, (Che Man et al., 2009; Matthäus, 2007) and high levels of natural antioxidants (Sundram, 2003) make it a good source of raw material for the production of other items. Palm oil is known to contain more saturated fat than oils from sources such as canola, corn, linseed, soybeans, sunflower and safflower and is able to withstand extreme heat associated with deep frying and also resists oxidation (Goh and Hardter, 1995).

Malaysia was the world's largest producer in the year 1995, with a 51% of world market share, but since 2007, Indonesia has been the world's largest producer, supplying approximately 50% of world palm oil volume (USDA, 2012). Worldwide palm oil production for season 2011/2012 was 50.3 million metric tons, increasing to 52.3 million tons for 2012/13 (USDA, 2012). In 2010/2011, total production of palm kernels was 12.6 million tonnes (FAO, 2012).

2.1.4 Social and environmental impact of oil palm

Oil palm establishment and palm oil production has grown rapidly in Southeast Asia, with Indonesia and Malaysia currently accounting for more than 85% of global palm oil demand (Danielsen et al., 2009; Fargione et al., 2008). In 2006-07, production of palm oil in these two countries was 31.9×10^3 metric tonnes, rising to 41.1×10^3 metric tonnes in 2010-11. This increase has contributed to deforestation across the Southeast Asia region. Between 1990 and 2007, 5.1 Mha of total 15.5 Mha of peatland in peninsular Malaysia and the islands of Borneo and Sumatra was deforested, drained and burned while most of the remainder was logged intensively (Langner and Siegert, 2009; Miettinen and Liew, 2010). Over the same period, industrial oil palm and pulpwood (*Acacia*) plantations expanded dramatically from 0.3 Mha to 2.3 Mha (likely comprising 2.1 Mha of oil palm and 0.2 Mha of Acacia), an increase from 2-15% of the total peatland area (Miettinen and Liew, 2010).

Any discussion on the social and environmental impacts of oil palm cultivation is highly controversial. According to Malaysian Palm Oil Council (2013); Friends of the Earth, (2007) and

Fitzherbert et al., (2008) oil palm is a valuable economic crop and provides a major source of employment. It allows many small landholders to participate in the cash economy and often results in the upgrade of the infrastructure (schools, roads, and telecommunications) within that area. However, there are instances where native customary lands have been appropriated by oil palm plantations developers without any form of consultation or compensation leading to social conflict between the plantations developers and local residents (iDMC, 2007). In some cases, labour for oil palm plantation establishment are dependent on imported labour or illegal immigrants, with some concerns about the employment conditions and social impacts of these practices (Forest Peoples Programme, 2009).

Biodiversity loss (including the potential extinction of charismatic species) is one of the most serious negative effects of oil palm cultivation. Large areas of already threatened tropical rainforest are often cleared to make way for oil palm plantation development, especially in Southeast Asia, where enforcement of forest protection laws is lacking. In some countries where oil palm is established, lax enforcement of environmental legislation have led to encroachment of plantations into protected areas (UNEP, 2007), encroachment into riparian strips (New Straits Times, 2007) and release of palm mill pollutants such as palm oil mill effluent (POME) in the environment (New Straits Times, 2007). Some of these states have recognised the need for increased environmental protection, resulting in more environment-friendly practices (EIA, 2000; RSPO, 2007). Among those approaches is anaerobic treatment of POME, which can be a good source for biogas (methane) production and electricity generation. Anaerobic treatment of POME has been practised in Malaysia and Indonesia. Like most wastewater sludge, anaerobic treatment of POME results in dominance of *Methanosaetaconcilii*. It plays an important role in methane production from acetate, and the optimum condition for its growth should be considered to harvest biogas as renewable fuel (MohdRafein, 2009). In addition, the use of palm oil as biofuel has been described as perverse because it encourages the conversion of natural habitats such as forests and peatlands, releasing large quantities of greenhouse gases (Danielsen et al., 2009).

2.1.5 Oil palm and carbon balance

Oil palm production has been documented as a cause of substantial and often irreversible damage to the natural environment. Clay (2004) reported that the negative impacts of oil palm on the environment include deforestation and habitat loss of critically endangered species and a significant increase in greenhouse gas emissions (Bates et al., 2008). The pollution is exacerbated because many rainforests in Indonesia and Malaysia lie on top of peat bogs that store great quantities of carbon, which are released when the forests are cut down and the bogs are drained to make way for the plantations.

Environmental groups, such as Greenpeace, claim the deforestation caused by making way for oil palm plantations is far more damaging to the climate than the benefits gained by switching to biofuel. According to Andre (2007) and Fargione et al. (2008), fresh land clearances, especially in Borneo, are contentious for their environmental impact. The BBC (2007a, 2007b) broadcast reported that despite thousands of square kilometres of land standing unplanted in Indonesia, tropical hardwood forests are being cleared for palm oil plantations. Furthermore, as the remaining unprotected lowland forest dwindles, developers are looking to plant peat swamp land, using drainage that begins an oxidation process of the peat which can release 5,000 to 10,000 years worth of stored carbon. Drained peat is also at very high risk of forest fire. There is a clear record of fire being used to clear vegetation for oil palm development in Indonesia, where in recent years drought and man-made clearances have led to massive uncontrolled forest fires, covering parts of Southeast Asia in haze and leading to an international crisis with Malaysia. These fires have been blamed on a government with little ability to enforce its own laws, while impoverished small farmers and large plantation owners illegally burn and clear forests and peat lands to develop the land rather than reap the environmental benefits it could offer (AFP, 2007 and VOA news, 2007). Research conducted by the Tropical Peat Research Laboratory shows that oil palm plantations act as carbon sinks, converting carbon dioxide into oxygen (New Straits Times 2010) and according to the Malaysia's Second National Communication to the United Nations Framework Convention on Climate Change, the plantations contribute to Malaysia's status as a net carbon sink (Ministry of Natural Resources and Environment Malaysia, 2000). Efforts to promote sustainable cultivation of oil palm have been promoted by organizations including the Roundtable on Sustainable Palm Oil, (Morales, 2010) and through support for conservation and rehabilitation of tropical forest, including the Malaysian government, which is committed to preserve 50 percent of its total land area as forest (Adnan, 2013).

2.2 Carbon in soils

2.2.1 Forms of Carbon in soils

Soil C comprises soil organic carbon (SOC) and soil inorganic carbon (SIC). Soil organic carbon is a complex and dynamic group of compounds formed from C originally harvested from the atmosphere by plants. During photosynthesis, plants transform atmospheric C into the forms useful for energy and growth through reduction of oxidized C into organic forms (Schlesinger, 1997). Organic C then cycles from the plant to the soil, where it becomes an important source of energy for the ecosystem, driving many other nutrient cycles. Soil inorganic carbon is the result of mineral weathering and forms a small proportion of many productive soils. It could be in the form of carbonates and is less responsive to management than SOC (Izaurralde, 2005).

The Century Soil Organic Matter Model describes three main C pools: an active pool (1–5 years turnover time), a slow pool (20–40 years turnover time) and a passive pool (200–1500 years turnover time) (Parton et al., 1987). The active pool mainly represents soil microbes and microbial products, while slow and passive pools contain C compounds resistant to decomposition (Parton et al., 1987). However, experimental verification and validation of the modelled C pools are very important to improve the predictive capacity of the model for estimating long-term changes in SOC (Christensen, 1996).

Soil organic carbon makes up between 48-58% C approximately 50% of all soil organic matter (SOM) (Wilke, 2005; Nelson and Sommer, 1982). Soil organic matter content is correlated with productivity and defines soil fertility and stability (Herrick and Wander, 1998). Most SOC is present in the topsoil of soil profiles as a result of the presence and influence of biotic processes there, with approximately 64% of soil C located in the top 50cm (Conant et al., 2001). Jones (2007) reported a positive correlation between SOC accumulation and precipitation and a negative correlation between SOC accumulation and temperature. Soil C stocks are positively correlated with the presence of clay and iron, and negatively correlated with bulk density of soil. Soil organic carbon and SOM buffer soil temperature, water quality, pH and hydrology (Evrendilk et al., 2004; Pattanayak et al., 2005). Increase in SOC and SOM lead to greater pore spaces and surface area within the soil, which subsequently retains more water and nutrients (Tisdale et al., 2002; Greenhalgh and Sauer, 2003).

2.2.2 Fate of soil organic carbon

Decomposition of organic matter C can be assessed with the aid of simple models that make use of a single exponential decay functions to assess the changes in soil C stocks over time, eg

$$\frac{dC}{dt} = fA - kC \dots\dots\dots (2.1)$$

where A = amount of C added from residue, *f*= fraction of A that decomposes to become soil-C each year, k = the fraction of soil-C decomposed each year and C = organic soil C pool (Jenkinson, 1981). By this, the C-storage dynamics are strongly determined by the amount and quality of C added. It has been estimated that about 8 t C/ha is needed to be added in residues annually to compensate for CO_2-C respiration losses from SOM under humid tropical conditions (Sitompul et al., 1996). From the exponential model above, it can be seen that there exists equilibrium in SOC (C_e) under continuous soil management (Jenkinson, 1981):

$$\frac{dC}{dt} = 0 \longrightarrow Ce = \frac{fA}{k} \dots\dots\dots (2.2)$$

Carbon stocks measured under natural vegetation have often been used as a reference for the C storage potential of a soil under a given climate. As land use changes with management, soil C often declines in relation to levels in the natural vegetation where the difference between current and potential C storage is expressed as the C saturation deficit (van Noordwijk et al., 1997):

$$C_{SatDeficit} = \frac{C_{ref} - C_{org}}{C_{ref}} \dots\dots\dots (2.3)$$

where C_{ref} is a reference soil C level representative of a forest soil of the same texture and pH, and C_{org} is the current C stock. The saturation deficit not only depicts the potential amount of C that can be stored, but also influences the speed of C accumulation i.e. the closer a soil is to its maximum potential C storage, the slower the C accumulation, as proportionally less C becomes protected.

2.3 Effect of organic matter on soil properties

Pierzynski et al. (2000), Baddock and Nelson (2000) have come out with three properties of soil (biological, chemical and physical) and how they are affected by OM.

2.3.1 Soil Biological properties

Mineralization-Immobilisation in soils is affected by OM. The decomposition of OM in soils yields NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-}, micronutrients and CO_2. This provides nutrients for plant growth and is also essential for the global cycling of elements such as C and N in soils. Organic matter plays a key role in the stimulation and inhibition of enzyme activities and of plant and microbial growth. Soil enzyme activity and the growth of plants and microorganisms can be stimulated or inhibited by the presence of humic materials which control the size, growth and activity of plant and microbial communities in soil. The biological diversity (biodiversity) in soil is affected by OM. Organic matter supports life processes for a wide range of species of microbes and fauna and this contributes to the functional integrity/ resilience of ecosystems. Organic matter present in soils act as a reservoir of metabolic energy for microorganisms and store of atmospheric C. It does this by providing metabolic energy for soil microorganisms and fauna which in turn drive biological processes (ammonification, nitrification, denitrification, mineralisation, and immobilisation).

2.3.2 Soil chemical properties

Cation exchange which involves total exchange capacities of isolated OM fractions range from 300 to 1400 cmol/kg and this functions to enhance retention of cations in soils. Organic matter present in soils plays a role in the chelation of metals which involves formation of stable complexes with Cu^{2+}, Mn^{2+}, Zn^{2+} and other polyvalent cations. This enhances dissolution of soil minerals, reduces loss of micronutrients; enhances the availability of micro- and macronutrients to higher plants; reduces the potential toxicity of metals. Another feature of OM is its low solubility in water. The insolubility is due to association of OM with clay and the hydrophobic nature of its constituents; also, salts of divalent and trivalent cations with OM are insoluble in soil water. This reduces the loss of OM through leaching in soils. Buffer action of soils is affected to an extent by the presence of OM when it acts as a buffer in slightly acid and alkaline soils. This helps to maintain many biochemical properties in acceptable range. In addition OM combines with xenobiotics to affect bioactivity, persistence and biodegradability of pesticides in soils by modifying application rates of pesticides for effective control.

2.3.3 Soil physical properties

Organic matter affects the physical properties of soils through combination with clay minerals during which it cements soil particles into aggregates. This stabilises structure, thereby reducing erosion and improving tilth; increase permeability of soil to gases and water. Water retention in soils is enhanced by OM which can hold up to 20 times its weight in water and indirectly contributes to water retention through its effects on soil structure. This improves moisture-retaining properties of coarse-textured soils; helps prevent drying and shrinking. The colour of some soil can be used to predict the type of minerals or constituents present in them. The typical dark colour of many soils is caused by OM and this facilitates warming to promote most soil activities.

2.4 Effect of temperature on soil organic carbon

Respiration activities in soils is affected in a complex way by temperature, moisture, soil properties, quality and quantity of decomposing organic substrates (Kirschbaum, 2000; Raich and Tufekcioglu, 2000), and predictions of future changes rely on detailed knowledge on the effects of each of these factors but also on their interaction. Soil respiration is strongly dependent on temperature. At the global scale CO_2 efflux strongly correlates with annual mean temperature (Raich and Schlesinger, 1992), though it has been debated that it depicts in large a relationship between soil respiration and ecosystem net primary production (NPP) or gross primary productivity (GPP) (Kirschbaum, 2000; Janssens et al., 2001). However, at the ecosystem scale, e.g. in forests with no moisture stress, temperature exerts the dominant control over seasonal variability of soil respiration (Janssens et al., 2001). Temperature may explain up to 72–96% of the variation in soil respiration in temperate forests (Keith et al., 1997; Boone et al., 1998; Rey et al., 2002; Subke et al., 2003). Variations in temperature are a fundamental entity of the soil environment in the temperate zone. These variations show fast (diurnal) and slow (seasonal) dynamics and represent the natural environmental background of ecosystem processes. The range of diurnal fluctuations in litter and topsoil depends on a number of factors and can reach 25–30 ^{o}C (Byzova, 1977). However, work by Fujii et al. (1998) showed that soil temperature in surface (15–50 cm depth) and subsurface (150–200 cm depth) zones varied from 12 to 33 ^{o}C and 13 to 27 ^{o}C, respectively.

The size of the soil carbon pool depends on the productivity of vegetation and the decomposition of organic material in soil, which are both climate-dependent processes. Decomposition is considered to increase or decrease with increasing temperature than does net primary productivity of C in plant tissues (Schimel et al., 1994; Kirschbaum, 2000). For example, Thomson et al., (2006) have suggested that at higher temperature and precipitation, the soil carbon sequestration rate and the soil carbon content will increase. This further affects the organic material decomposition and the losses from soil are also likely to increase (Ågren and Hyvo¨nen, 2003). In contrast, predictions of reduced carbon input to soil at higher temperature have been made by Alvarez and Alvarez (2001). In addition, higher temperature and precipitation result in the decline of (SOC) (Grace et al., 2006), but the cumulative dissolved organic carbon (DOC) in the humus layer will increase (Andersson and Nilsson, 2001). The temperature sensitivity of soil organic carbon mineralization has recently attracted considerable interest because of its potential importance in the global carbon cycle. The response of SOC decomposition to environmental change especially to changes in temperature is of great concern, because the increase in atmospheric greenhouse gas concentrations and the subsequent temperature increase may stimulate SOC decomposition, resulting in strong positive feedback to global warming (e.g. Solomon et al., 2007).

The temperature sensitivity of soil respiration has been a topic of very intense debate over recent years, as summarised by Davidson and Janssens (2006). There is evidence to suggest that under higher temperatures soil carbon decomposition will increase, thus resulting in increased CO_2 emissions from heterotrophic respiration (Knorr et al., 2005). However there is a contrasting opinion that soil carbon decomposition will be rather insensitive to temperature (Giardina and Ryan, 2000), being mostly determined by the supply rate of substrate. Much of the debate centres on the temperature sensitivity of the labile versus recalcitrant fractions of the soil carbon. It has been suggested that the “fresh” (i.e. younger) soil carbon is more sensitive to temperature changes, whilst the older fraction is not sensitive, as it includes hard-to-decompose materials and organic matter that is protected in the interior of soil particles (Giardina and Ryan, 2000; Thornley and Cannell, 2001; Davidson and Janssens, 2006). Fang et al., (2005) have, however, shown that the recalcitrant and labile pools present in soils do not show any significant differences in temperature sensitivity, implying that both of these pools in the soil organic matter will respond similarly to global warming (Fang et al., 2005). As a large component of SOM is made up of such recalcitrant material, the temperature sensitivity and potential availability as a substrate for microbial respiration of this pool are of acute importance with respect to climate change (Biasi et al., 2005). Berg et al. (1993), showed that a standard pine litter produced more recalcitrant products of decomposition per unit of accumulated mass loss when it decomposed rapidly (under warm and wet conditions) than when it decomposed more slowly (in cooler and dryer environments). These authors also proposed that late decomposition would be slower in systems with high initial mass loss rates.

Marschner and Bredow (2002) conducted a study which showed a close interaction between the processes of degradation and production in the control of DOC in the soil solution. In the studied soil, DOC was found to be the most important substrate for microorganisms and was, therefore, depleted during incubation. But the effects on DOC properties cannot be solely attributed to the selective mineralization of certain fractions or size classes as it reflected in the relative accumulation of UV-active compounds at higher incubation temperatures. At the same time, microbially produced compounds that have high metal complexing abilities and are easily degradable are released into the soil solution with increasing temperature and microbial respiration. The nature and exact origin of these compounds is still unknown. They could be metabolites from degradation processes, actively released substances such as siderophores or biomass constituents liberated after starvation and lysis of organisms. These easily degradable compounds apparently can persist in the soil solution when microbial activity is reduced by nutrient deficiency or during adverse environmental conditions (low temperature and drought) and will thus enhance the availability and transport of metal micronutrients or contaminants.

Soil temperature has been recognised as the primary factor regulating soil respiration, (R_S) while soil moisture is secondary, its control over R_S being mostly effective under extreme moisture values (Conant et al., 2004; Luo and Zhou, 2006; Li et al., 2008; Litton and Giardina, 2008; Wang et al., 2011b). Besides these two major environmental factors, the size of the soil organic C (SOC) pool, the quality of organic matter, the abundance of roots, and the distance from the nearest tree stem also affect R_S and its components (i.e. heterotrophic respiration, R_H and autotrophic respiration, R_A) (Saiz et al., 2006; Wang et al., 2010b; Luan et al., 2011). Since all these variables are affected by the nature of the vegetation present e.g. forest cover (De Deyn et al., 2008), it is expected that R_S, R_H and R_A should differ with forest composition.

Temperature sensitivity of respiration is often expressed by Q_{10}, the factor by which respiration rate increases with every 10 ^{o}C increment of temperature. The Q_{10}-based formulation has been used commonly to calculate soil or ecosystem respiration from local to global scales (Cox et al., 2000; Fang and Moncrieff, 2001; Falge et al., 2002).

However, the response of respiration to temperature has been questioned recently (Luo et al., 2001; Tjoelker et al., 2001). This has brought out suggestions to the point that the terrestrial ecosystem respiration rate has been overestimated in global carbon cycles (Cox et al., 2000). For now, it still remains unclear regarding how Q_{10} is affected by factors other than temperature (Tjoelker et al., 2001; Fang and Moncrieff, 2001). It has been documented that in order to successfully assess the impacts of changing climate on ecosystem carbon fluxes it would be very necessary to understand the effects of temperature and moisture on Q_{10} which are of critical importance in any such assessment (Betts, 2000; Cox et al., 2000). Recently conducted studies have shown that seasonal values of Q_{10} are negatively correlated with temperature, but positively related to soil water content over a limited range of soil water content (Xu and Qi, 2001; Reichstein et al., 2002; Qi et al., 2002; Janssens and Pilegaard, 2003). Currently, when temperature and moisture effects on soil or ecosystem respiration are described simultaneously, e.g., using models of global climate change, assumptions are made to the effect that individual factors may be multiplicative (Fang and Moncrieff, 1999). This hypothesis has not been well tested and may lead to errors associated with an overestimation of the respiration response of ecosystem to warming under dry soil conditions (Cox et al., 2000; Reichstein et al., 2002). Unfortunately, applying different sensitivity values of soil or ecosystem respiration to temperature and moisture has not been explicitly looked at in the ecosystem models that are commonly used in the studies of global climate change. This has the potential of resulting in a significant missing link in the current ecosystem models (Qi et al., 2002). Simulating soil or ecosystem respiration without a sufficient understanding of variation in temperature sensitivity will certainly limit a model's utility (Fang and Moncrieff, 2001; Qi et al., 2002).

2.5 Moisture and soil organic matter turnover

Temperature variation and that of precipitation act as the dominant factors controlling SOC cycling over global to regional scales (Jenny, 1980; Post et al., 1982). The overriding climatic control of SOC cycling in arid and semiarid ecosystems has to do with the timing and frequency of precipitation. Water-limited ecosystems are typically characterised by a pulse-dynamic whereby sporadic precipitation events drive pulses of biological processes (Noy-Meir, 1973; Huxman et al., 2004; Schwinning and Sala, 2004). Therefore, the spatial pattern and close association of soil–litter interfaces are critical to controlling microbial access to nutrient resources during brief periods of soil moisture (Whitford et al., 1986). Given the projected major impact of climate change on water balance as a result of fluctuations in the distribution of precipitation and global warming (IPCC 2007), it is very necessary to understand how the interaction of temperature and moisture may influence SOM decomposition and C release from different soils. For example, it has been suggested that aerobic soil respiration is a non-linear function of temperature as long as soil water content does not limit the ecophysiological performance of microbes, but becomes a function of water content when soil dries out (Smith et al. 2003).

Similarly, the effect of increased temperature on water tables has also been linked to dissolved organic carbon (DOC) rise (Freeman et al. 2001a; Evans et al. 2002; Pastor et al. 2003). Compared with areas receiving constant water, drier soils are expected to have higher turnover rates of SOM due to the favourable aerobic conditions for the heterotrophic and enzymatic activities. For example, lowering the water table increases peat aeration and consequently, removes the oxygen constraints on the activity of the phenol-oxidase enzyme, capable of degrading phenolic compounds (Freeman et al. 2001b). These substances are strong inhibitors of microbial and hydrolytic activities responsible for peat decomposition (Wetzel 1992) and therefore, their removal also eliminates the restrictions on the release of CO_2 to the atmosphere and the subsequent movement of DOC to the rivers (Freeman et al. 2001a,b, 2004). Periods of little or no precipitation also influence soil water chemistry by promoting oxidation reactions which result in pH reductions and increasing ionic strength (Adamson et al. 2001), both of which suppress DOC mobility. However, the lack of corresponding trends between hydrological changes and DOC increases indicates that finding the satisfactory mechanism remains a challenge.

In addition, decreasing soil moisture at the top layers can induce the vertical migration of soil microorganisms such as enchytraeid worms (dominant mesofauna in peatlands) and consequently, accelerate C turnover in the deeper layers (e.g. Briones et al. 1998a, 2010). However, if water becomes severely restricted their populations become significantly reduced because most species lack an adaptive drought tolerant stage (Maraldo et al. 2008). Therefore, any alterations in these two abiotic factors and their influence on soil biota will be of key importance in determining the responses of SOM decomposition to climate change.

2.6 Soil type and soil organic matter turnover

Different soil types have been found to affect the growth as well as other processes and materials added to the soil. West Africa soils are fragile, predominantly of kaolinitic clay, with low effective cation exchange capacity (ECEC) and plant nutrients (Juo and Wilding, 1996). In addition tropical climate is characterised by high rainfall and insolation, the attendant problems of nutrient leaching and low level of soil organic matter which in some cases has made nitrogen (N) the most limiting nutrient to crop production in Nigeria (Carsky and Iwuafor, 1995). Young et al. (1998) emphasised the importance of the soil’s structure in maintaining biological diversity through the provision of habitat and by influencing patterns of resource storage and transport. Modern tools in analytical chemistry are forcing researchers to re-examine long held theories of soil organic matter formation. Hassink et al. (1997) have shown that the amount of organic matter that a soil can store is largely regulated by its silt and clay content although management can also influence storage, particularly of larger macro-organic matter fractions (Balesdent et al., 2000; Denef et al., 2001). Spatial variation of soil organic matter content particularly at national and regional scales are also strongly influenced by climate and land use (Joos et al., 2001; Paustian et al., 1998b).

2.7 Effect of microorganisms on soil organic carbon

Microbial populations in soil are of great importance due to their role in serving as an important reservoir of plant nutrients (Wardle, 1992), in addition to their ability to alter ecological processes (Smithwick et al., 2005). In order to understand the role that microbial communities play in different environments, it is very important to understand microbial functional diversity and its response to soil perturbations and climate warming (Lagomarsino et al., 2007; Rinnan et al., 2009). Both microbial biomass and community composition are sensitive to belowground profile which often correlates with the soil organic matter content (Aanderud et al., 2008; Fierer et al., 2003, Rajaniemi and Allison 2009). Research has shown that sites with lower fertility have lower soil microbial biomass compared to those with higher fertility (Mendham et al., 2003). However, microbial communities are also affected by different environmental variables such as soil salinity, or other factors which change during ecosystem development (Aanderud et al., 2008; Rajaniemi and Allison 2009 and, Zornoza et al., 2009).

The impact that earthworm invasion has on the stability of SOC is of great significance in biogeochemical studies with their overall effect on C dynamics being dependent on time scales (Martin, 1991), soil disturbances (Bohlen et al., 2004a and, Villenave et al., 1999), and SOC levels (Bohlen et al., 2004b). Several studies have shown that earthworm activity has the potential of contributing to the stabilization of SOC through enhanced long-term protection by soil aggregates (Fonte et al., 2007; Pulleman et al., 2005; Scheu, and. Wolters, 1991, Tiunov, and. Scheu, 2000) and to a loss of unprotected C through increased short-term mineralization rates (Alban and Berry, 1994; Bohlen et al., 2004a, Coq et al. 2007, Martin, 1991). Therefore the relative significance of short-term mineralization and longer-term C protection may affect carbon cycling and the optimal management practices for tropical plantations. Coq et al. (2007) in a study noted that short-term (150 days) C mineralization enhancement was greater than long-term (420 days) C protection with *P. corethrurus* present. Bossuyt et al. (2004) in looking at earthworms also noted that their presence increased levels of macro- and micro-aggregates, thus enhancing long-term C incorporation in soils during a laboratory study, while other researchers found no changes in the size distribution of aggregates (Fonte et al., 2007 and Villenave et al., 1999).

Soil microbial biomass carbon (MBC) has been found to be an effective measurement used as an index to evaluate soil quality because it is sensitive and measurable, and it is related to global carbon cycle (Wardle, 1992), soil quality (Rice et al., 1996), soil C/N ratio (Smolander and Kitunen, 2002) and linkage of plants and soil (Hofman et al., 2004). Microbial biomass carbon is very much linked with soil organic carbon and soil carbon cycling (Follett, 1997). It has been found out that soil microbes utilise only labile organic carbon when SOC input is limited. After all labile organic carbon is fully utilized, soil microbial biomass then falls (Follett, 1997). The addition to the soil in the form of falling litter increase the amount of soil organic matter during forest ecosystem recovery, which may lead to increasing food resource for microbes and further increase microbe population as well. Therefore, soil MBC can indicate soil quality in the red soil region (Yu et al., 1999), and thus can be used to indicate the role of different vegetations on the reconstruction of the red soil ecosystems.

Soil microbial entropy is another important indicator defined as the ratio of soil MBC to total organic carbon (TOC). It can be used to reflect the percentage of the soil active organic carbon in the soil, demonstrate the difference of soil fertility, monitor the efficiency of soil carbon, and reflect the change of soil environment (Anderson, 2003). It is also an important tool used to assess the soil carbon accumulation or loss in soil ecosystems. Higher index results in more accumulation of the soil carbon, or otherwise soil carbon loss (Singh et al., 1989). Thus, the variations in soil microbial entropy reflect organic matter inputs to soils, the efficiency of conversion to microbial C, losses of C from the soil, and stabilisation of organic C by soil mineral fractions. Also affecting this index is clay content, mineralogy, vegetation and management history of the soil (Sparling, 1992). It has also been proven that stores of carbon at depth are often more resistant to decomposition by soil microbes due to their inherent physical properties and chemical constituents (Fierer et al., 2003), and also due to the fact that recalcitrant soil fractions enriched with resistant alkyl carbon structures increase with soil depth and age (Lorenz et al., 2007).

2.8 Soil carbon sequestration under forests and plantations

Carbon sequestration in forest soils has a potential to decrease the rate of enrichment of atmospheric concentration of CO_2. Increase in C stock of forest soils can be achieved through forest management including site preparation, fire management, afforestation, species management/selection, use of fertilisers and soil amendments (Lal, 2005). The SOC concentration in forest soils may range from 0% in very young soils to as much as 50% (w/w) in some organic or wetland soils (Trettin and Jurgensen, 2003), with most soils containing between 0.3 and 11.5% C in the surface 20 cm of mineral soil (Perry, 1994). According to Jones (1989) SOC concentration in mineral soils is lower in tropical forests and higher in montane and boreal forests. Knoepp and Swank (1997) studied the SOC dynamics in five watersheds in the southern Appalachian region and reported that the SOC and N concentrations generally declined during the first years following the whole tree harvest, but SOC remained stable 14 years after cutting. In California, Black and Harden (1995) also observed that timber harvest resulted in an initial loss of SOC (15%) within 1–7 years due to oxidation and erosion. For 17 years of forest re-growth, there was a continued loss of SOC (another 15%) despite the slight accumulation of new litter and roots. After 80 years of re-growth, rates of C accumulation exceeded rates of loss. Over the 80-year period, the SOC stock did not recover to the pre-harvest level. In Oregon, Law et al. (2001) observed that SOC stock was consistently lower at all soil depths compared to pre-disturbance conditions.

Other studies have, however, shown that the observed post-harvesting decline in SOC is generally due to mixing and movement of the organic material or litter layer into the mineral soil (Yanai et al., 2003). Harvesting operations often cause drastic soil disturbance (Nyland, 2001) mixing the forest floor into the mineral soils. The exposure of the soil also exacerbates losses due to soil erosion (Elliot, 2003), and leaching of dissolved organic carbon (Kalbitz et al., 2000). Numerous studies have shown that decomposition rates of surface litter generally decrease after clear cutting because of the reduction in biotic activity and decrease in soil moisture content.

Afforestation/reforestation and the manager’s choice of species are also important to enhancing soil C stock. Reforestation of abandoned/marginal agricultural lands can increase SOC stock (Akala and Lal, 2001). In northern Belgium, Schauvlieghe and Lust (1999) assessed C budgets under different land use systems. The total C stock was 128 Mg/ha under pasture, 173 Mg/ha under 29-year-old forest and 232 Mg/ha under 69-year-old stand. The total C stock was 117 Mg/ha under 27-year-old pin oak stand and 227 Mg/ha under 69-year-old oak beech stand. It was observed that the older the stand, the larger the importance of soil C became, especially the stable soil C. In east-central Minnesota, Johnston et al. (1996) reported an average increase in SOC stock at the rate of 0.8 Mg C ha^{-1}year^{-1} in the mineral soil over a 40-year period due to afforestation of degraded agricultural soils. Afforestation of reclaimed mine soil, an important economic activity affecting deforestation, has a strong impact on SOC sequestration (Akala and Lal, 2000).

Past and current studies of soil C sequestration during forest re-growth on previously cultivated agricultural soils have provided varying results. Post and Kwon (2000) reviewed 46 studies, and reported that soil C increased at an average rate of 0.34 Mg C ha^{-1} year^{-1}, with a broad variation range between -0.5 and +0.7 Mg C ha^{-1} year^{-1}. The study locations ranged from cool temperate to tropical and the forest ages ranged from 8 to >250 years old. Paul et al. (2002) also reviewed these estimates and computed an average rate of soil C sequestration of 0.14 Mg C ha^{-1} year^{-1}. The highest rates of soil C accumulation were observed under deciduous or N-fixing species, established on previously cultivated land in tropical or subtropical regions. Estimated rates of soil C sequestration under intensively managed plantations ranged from 0 Mg C ha^{-1} year^{-1} under eucalyptus (*Eucalyptus saligna* Sm.) (Bashkin and Binkley, 1998) and hybrid poplar (Grigal and Berguson, 1998) to 1.6 Mg C ha^{-1} year^{-1} under other hybrid poplar plantations (Hansen, 1993).

Hansen (1993) observed that fast-growing species (i.e., poplar) can significantly increase the soil C pool, after an initial C loss caused by site preparation. Twelve- to eighteen-year old poplar plantations had greater average soil C pool than adjacent soils cultivated to row crop or grassland on 11 sites across North Dakota, Minnesota, Iowa, and Wisconsin. In a similar study under 6- to 15-year-old poplar plantations, Grigal and Berguson (1998) estimated an input of 1.2 Mg C ha^{-1} year^{-1} as root biomass into the soil, without detecting any overall significant increase in the soil C pool. Similarly in Hawaii, Bashkin and Binkley (1998) observed no overall increase in the soil C pool under 10- and 13-year old eucalyptus plantations (114 Mg C ha^{-1}) compared to adjacent abandoned sugarcane fields (113 Mg C ha^{-1}) in the 0- to 55-cm depth. Smitha et al., 2002 studied C stocks after conversion of forests into tree plantations and observed that there was no significant effect for stand type in surface soils when the C was determined under the tree plantations. Similarly, carbon stocks in the forest floor was not significant for stand type even though the C content in both cases were high.

2.9 Carbon sequestration under a Chronosequence

Sartori et al., (2007) in a Chronosequence experiment involving poplar observed that during 10 years of plantation management and re-growth on eolian soils, the soil C pool tended to increase primarily because of management-induced C inputs in the 0-10-cm depth. Their study supports other similar research findings, indicating that it is not possible to observe measurable changes in the mineral soil C pool under poplar plantation compared to adjacent agricultural lands over a decadal time scale (Grigal and Berguson, 1998; Coleman *et al.*, 2004). Also, Coleman et al. (2004) compared poplar stands of varying ages (from 1 to 12 years old) to adjacent agricultural lands and woodlots in 27 locations across Minnesota, Wisconsin, Iowa, and North Dakota and observed significant increases in soil C concentration compared to adjacent agricultural lands only in presence of soils with low-inherent C concentration. In general, there were no differences in soil C concentration between agricultural lands and poplar plantations.

Richards et al., 2007 studied carbon sequestration in native subtropical tree plantations by estimating rates of C input and loss after land use conversion to a hoop pine plantation Chronosequence (25–63 years) or pasture. They used the Century C model to split the slow turnover pool into an intermediate and a stable C pool, where it was observed that hoop pine C inputs to the more stable section were much lower than rainforest or pasture C inputs. Total C stocks only reached 16 t C ha^{-1} under the 63-year-old hoop-pine, compared to rainforest (37 t C ha^{-1}) and pasture (31 t C ha^{-1}). Interestingly, there was no difference in total light fraction (LF) C between older hoop pine plantations and rainforest, indicating that hoop pine plant biomass enters the LF soil C pool initially, but that the majority of these inputs are not further stabilized within the soil matrix. This may result from disruption or modification of the mechanisms responsible for SOC protection, such as aggregation and organo-mineral interactions (Baldock and Skjemstad, 2000).

2.10 Carbon studies under oil palm in Africa

In Africa, with special reference to West Africa some works have been done in Benin and Ivory Coast. Dufrêne and Saugier (1993) in Ivory Coast looked at photosynthetic measurements in oil palm which had results quite lower than that carried out by Lamade and Setiyo (1996) in North Sumatra. Jourdan (1995) also studied and modelled root growth under oil palm in Ivory Coast to assess the contribution of roots to CO_2 emissions and C storage in soil. Similarly, soil respiration studies have been conducted by Lamade *et al.*, (1996) at Ouidah (Benin), taking a look at ambient temperature of 27°C, which they claim led to an estimation of carbon loss through root respiration of 76 kg C yr^{-1} palm^{-1} in a 20-year-old plantation. On the other hand some studies (Ollagnier *et al.*, 1978; Olivin, 1980; Djegui *et al.*, 1992; Haron *et al.*, 1998) under Ivorian conditions have also measured changes in soil carbon content from destruction of the forest ecosystem to its replacement by an oil palm plantation. They observed that when such a replacement was made, there was a notable drop in soil carbon (in the upper horizons, 0-30 cm) in the first 4 years as the young oil palms develop, then that rate seems to stabilize from 9 years old onwards at between 55% and 65% of the previous forest soil content.

2.11 Summary

From the literature review, it is clear that even though the oil palm tree originated from Africa, there is not much information regarding its contribution to CO_2 emissions into the atmosphere. There also appears not to be adequate information on C storage and dynamics under oil palm plantation in Ghana and other oil palm producing countries in West Africa. Much of the information currently available and used in scientific discussions has come from studies that have been undertaken elsewhere. It is important for oil palm growing countries in Africa to undertake research into the various contributions of oil palm to the environment and possibly come out with innovations that would be beneficial to maximising yield and at the same time protecting the environment. This has become necessary as companies involved in oil palm business appear to be shifting their focus from well known production areas such as Kalimantan, North Sumatra, Borneo, Indonesia and surrounding regions as a result of pressure from environmental pressure groups to Africa for possible expansion. This expansion would certainly affect current vegetation which would also have an overall effect on prevailing and future climate in Africa and the world. There is the need to come out with clear cut guidelines regarding the future of oil palm production in Ghana so that the country does not lose out in its bid to expand agriculture, increase revenue and improve livelihood of its nationals. This can only be done through government and private sector support for appropriate research into this sector.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Site selection and description

The sites chosen for the study were private oil palm plantations in and around Kade, Kusi, and Anwaem located within the Kwaebibirim District of the Eastern Region of Ghana. The reference soil, (uncultivated forest soil) was taken from the Forest and Horticultural Crops Research Centre, Okumaning within the same district (Fig3.1). The private oil palm plantations are owned by local farmers; some residents in these communities or in nearby towns. These farmers owned oil palm farms at different maturity ages from very young ones of about three months old to farms as old as twenty-six years. The farms were located on different points along the toposequence with some farms spreading right from the top to the bottom slope. The current palm trees standing on the land at the time of sampling are between two and a half years and twenty six years.

3.1.1 Site selection

Sampling of farms begun with creating five clusters according to age of oil palm plantation into which various farmers were grouped. During farm visits some questions were asked and farms that had any form of cover cropping were struck out of the list (Appendix C). Multi-stage sampling was employed to further group farms depending on position of farms along the toposequence into three distinct groups; Top slope, Middle slope and Bottom slope. Using modal instance sampling the research targeted farms located at the valley bottoms. Farms included in this list were chosen based on having similar land use history and cultural practices involved in oil palm plantation establishment. Eight farms were targeted under each age group so further sampling could be carried out to select five. Having exhausted the original list of farmers and not getting the targeted number snow balling was carried out to get more farms for each of the age groups. In the end it was difficult to get even four farms for one of the age groups whiles some had about five and others six or seven. In the end three farms were selected for each age group. Random sampling was carried out in groups with more than three farms taken into consideration sampling costs and location. Fifteen farms in total were selected for sampling. In addition, a reference soil was chosen from the forest reserve (plot 16) having similar characteristics as soils from each of these farms (Appendix A).

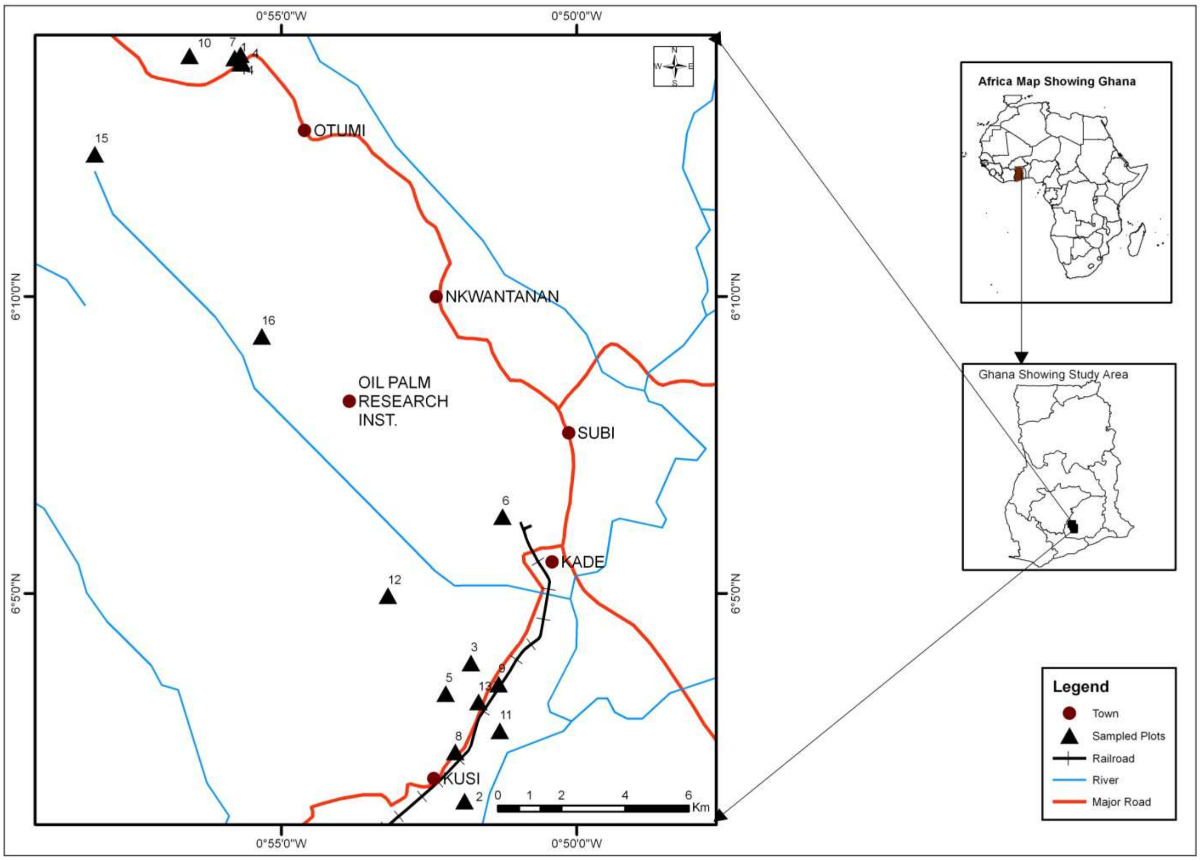

Fig. 3. 1 Location of farms territory and sampled plots.

3.1.2 Site description

The vegetation of the district is largely semi-deciduous with perennial tree species such as cocoa, teak, mahogany, neem, bamboo, mango, orange and coconut interspersed. There are also grass species like *Panicuum maximum*, giant star grass, spear grass among others.

3.1.3 Prevailing climate of Kwaebibirim district

Present climatic conditions within the district are not different from those found within oil palm belts in Ghana and parts of West Africa. These include high rainfall and temperature, long sunshine duration, etc which play a key role in the growth and optimum yield of oil palm (Tweneboah, 2000).

3.1.3.1 Rainfall

The study site is marked with high rainfall usually between 1200 and 2200 mm with an average of about 2000 mm distributed fairly throughout the year. There are periods of slight dry season occurring between December and February due to the harmattan but no severe dry periods are recorded. Annually high intense rainfall usually occurs between May and early parts of September which are often in excess of plant evapotranspiration needs providing enough moisture needed for optimum yield production. Adequate rainfall is recorded for the remaining period of the year but in low amounts. The high precipitation accounts for erosion which is very common on exposed land surfaces. Tweneboah (2000) reported that an area suitable for oil palm production should have a long wet season with rainfall exceeding 180 mm and a short dry season usually not more than a month with rainfall of at least 100 mm.

3.1.3.2 Sunshine duration

The photoperiod in the district varies depending on the time of the year. Usually the sun appears earlier than in other places since it is to the east of Ghana. During high rainfall months such as July and parts of August, sunshine hours is usually between five to six hours. However, towards the end of the year to early February longer sunshine hours of about eight to ten hours are experienced. These sunshine periods are characterised by high temperatures which support the establishment and productivity of oil palm in areas where they are grown such as Brazil, South-East Asia, Malaysia and Indonesia as published by Tweneboah (2000).

3.1.3.3 Temperature

The long sunshine duration allows for high temperatures of about 28-34^{o}C and low temperatures of about 22-24^{o}C with an average of about 25-29^{o}C. These temperatures are within the requirements for good oil palm production as has been reported by Tweneboah (2000).

3.1.4 Soil description

The sites selected were oil palm farms established at the valley bottom along a typical catena. The dominant soil at this location is Oda Soil Series which has been classified as Aeric Endoaquent (Owusu-Bennoah, 1997, USDA, 1998) and as Eutric Gleysol (FAO; 1998; WRB, 1998).

3.1.5 Sample collection and preparation

The soils were sampled from a depth of 0-10 and 10-20 cm with the aid of an earth chisel after the land surface had been cleared using a cutlass. The 0-20 cm layer from the literature reviewed is the depth considered for many C studies due to root activity present in it.

Sampling was preceded by marking out an area 25m by 25m. These sampling plots contained both alleys between rows of palm trees and pruned and heaped palm fronds within the palm rows. A total of thirty six spots were marked in the alleys using short pegs for sampling. Heaps of prunnings of the palm fronds which fell within the marked area had samples taken under them. In all a total of 72 soil samples were taken from the alleys from 0-10 and 10-20 cm layers respectively. Core samplers were driven into the ground to take undisturbed soil samples within the alleys for bulk density analysis. Soil samples under the heaped fronds were carefully collected within the marked area using two methods. These methods depended on the age of the plantation. The first method involves taking soil samples from younger heaps (< 10 yrs) which had been pushed over whiles the second method involves taking soil samples after cutting through the huge prunnings (> 10 yrs) with a cutlass to get to the top soil. The soil samples under the heaped fronds were taking using the same procedure as that under alleys for both layers. Sampling under the prunnings was done carefully especially under old heaps since there was the need to distinguish the top layer from the decomposed material sitting just above it.

Total number of heaps from which soil samples were taken were three per sampling site. Random soil samples were taken from the natural forest reserve.

Soils sampled were packed into polythene bags, labelled and put into another polythene bag to prevent contamination. Soils from the sampled spots from each farm were put together to obtain a composite sample and a sub sample taken. Soils were air dried, crushed and sieved through a 2 mm sieve to get rid of stones, roots, twigs and other unwanted materials. Processed soil samples were put in well labelled polythene bags before being packed into well labelled boxes for transportation to the laboratory for analyses. Soil samples were stored at room temperature and this was followed by analyses at the Department of Soil Science laboratory, University of Ghana.

3.2 Soil physical properties

3.2.1 Bulk density (ρb) determination

Bulk density was determined using the core method. A cylindrical metal core of known diameter and height was driven into the soil with the help of a mallet. The soil sample was taken out together with the ends of the metal core trimmed. The sample was taken to the laboratory for oven drying for 24 hrs at 105°C after which the dry weight was determined. The weight of the empty metal core was also taken.

Bulk density was calculated using the formula (Blake and Hartge, 1986)

$$\rho b = M/V \quad \text{……………………………………………………………………………(3.1)}$$

Where M= Mass of oven dried soil

V= Volume of soil in core sampler

3.2.2 Particle size analysis

Particle size analysis of the soil was done by the Bouyoucos hydrometer method modified by Day (1965). Forty grams of ground, air-dried soil screened through a 2 mm sieve was weighed into a polyethylene bottle and 100 mL of sodium hexametaphosphate (calgon) solution added to it and covered. The suspension was put into a mechanical shaker and shaken for 2 hrs after which the suspension was transferred into a sedimentation cylinder with distilled water and topped up to the 1000 mL mark. A plunger was lowered into the cylinder and moved up and down to mix the suspension thoroughly. This was left for about 5 mins after which the hydrometer was lowered into the suspension and the scale read at the top of the meniscus as the hydrometer reading for clay and silt.

The suspension was allowed to stand undisturbed and the hydrometer reading for clay alone was taken after 4 hrs 55 mins. After the second reading, the suspension was poured out directly into a 50 mm sieve from the sedimentation cylinder with the affluent collected into a waste container. The residue on the sieve was agitated by running ordinary tap water into it to obtain the sand particle. This was transferred into a moisture can using a wash bottle and oven dried for about 24 hrs at 105°C. The weight of sand was recorded. The percent sand, silt and clay were then determined by:

$$\% \text{ X}= \frac{X \times 100}{Weight\ of\ soil} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Where X= Weight of sand/ Readings for silt and clay

3.3 Soil chemical properties

3.3.1 Determination of pH water (1:1)

Twenty grams of soil were weighed into a beaker and 20 mL of distilled water was added, to give a soil to water ratio of 1:1. The mixture was stirred several times for about 30 mins and left to stand for about 1 hr to allow most of the suspended clay particles to settle and also to attain the surrounding temperature of the instrument room.

The glass electrode pH metre- CG818, Schott Great was standardised using two solutions of pH 4 and 7. The electrode was then rinsed with distilled water and then immersed into the partly settled suspension with the reading on the pH meter recorded. This was done thrice and the mean value taken.

3.3.2 Determination of pH $CaCl_2$ (1:2)

Ten grams of soil were weighed into a beaker and 20 mL of $CaCl_2$ solution was added, to give a soil to salt ratio of 1:2. The mixture was stirred several times for about 30 mins and left to stand for about 1 hr to allow most of the suspended clay to settle and also to attain the surrounding temperature of the instrument room.

The glass electrode pH metre- CG818, Schott Great was standardised using two solutions of pH 4 and 7. The electrode was then rinsed with distilled water and then immersed into the partly settled suspension with the reading on the pH meter recorded. This was done thrice and the mean value taken.

3.3.3 Determination of organic carbon in the soil

Organic carbon was determined using the wet oxidation method of Walkley and Black (1934). This method involves the reduction of $Cr_2O_7^{2-}$ ion by the organic matter and the unreduced $Cr_2O_7^{2-}$ measured by titration with Ammonium Ferrous Sulphate. The quantity of organic matter oxidised is calculated from the amount of $Cr_2O_7^{2-}$ reduced.

One half of a gram of finely ground soils sieved through a (0.5mm) was weighed in triplicate into 500 mL Erlenmeyer flasks. Ten millilitres of 1.0 M ($K_2Cr_2O_7$) followed by 20 mL of concentrated H_2SO_4 were added to the soil. The flask was swirled making sure the solution was in contact with all particles of the soil and allowed to stand on asbestos sheets for about 30 minutes.

Then, 200 mL of distilled water was added and this was titrated against 0.5 M acidified Ammonium Ferrous sulphate. In the titration, 5 mL of 85% orthophosphoric (H_3PO_4) acid and 2 mL of Barium diphenyl-4 sulphonate indicator was added before titrating against the Ammonium

Ferrous sulphate from an orange colour to a green end point. Organic matter content was calculated by multiplying percent organic carbon by the conventional factor of 1.33 using the formula

$$\%\ \mathrm{OC} = \frac{\text{Volume of } Cr_2O_7^{2-} \text{ used} - (\text{Titre value} \times \text{Molarity of blank}) \times \text{Meq C } (0.3) \times 1.33 \times 100}{\text{Weight of soil (g)}} \ldots (3.3)$$

3.3.4 Determination of total nitrogen in the soil

Total Nitrogen was determined by a modified Kjeldahl digestion method (Bremner, 1960). The nitrogen in the sample was converted to ammonia by digestion with concentrated H_2SO_4 using a nitrogen catalyst (Selenium tablet). The ammonium formed was determined by distillation of the digest with an alkali and titrating with a standard acid.

Air-dried soil of 2 g was weighed in triplicate into a Kjeldahl flask and a 2-3 mL of distilled water added to moisten the soil. The nitrogen catalyst was added followed by 20 mL of concentrated H_2SO_4. The mixture was digested for at least 30 mins till it became clear. The digest was allowed to cool, transferred with distilled water into a 100 mL volumetric flask, and made up to the volume. Five millilitres aliquot was pipetted into a Markham distillation apparatus and 5 mL of 40% NaOH added and rinsed to about 100 mL. Five millilitres of 20% Boric acid and a few drops of a mixed indicator (0.13 g of methyl red plus 0.666 g of methylene blue dissolved in 100 mL of 95% ethanol) were put into a conical flask. The distillation process was set up to titrate to trap NH_3 gas which appeared light green at endpoint. This was back titrated against 0.01 M HCl from green to purple endpoint. From the results, the percent Nitrogen in the soil was calculated by

$$\%\ \mathrm{N} = \frac{\text{Titre value} \times \text{Molarity of acid} \times \text{Volume of extract} \times \text{N factor} \times 100}{\text{Volume of aliquot} \times \text{Weight of soil (g)}} \ldots \ldots \ldots \ldots \ldots \ldots (3.4)$$

3.3.5 Determination of exchangeable bases

3.3.5.1 Extraction of exchangeable bases

Ten (10) grams of soil was weighed into an extraction bottle and 100 mL of 1M ammonium acetate solution (NH_4OAc) buffered at pH 7.0 added. The bottle and its contents were placed on a mechanical shaker and shaken for an hour after which it was centrifuged for 20 mins. The supernatant solution was then filtered through a No. 42 Whatman filter paper. The filtered solutions (aliquot) were used for the determination of Ca, Mg, K and Na.

3.3.5.2 Determination of exchangeable calcium

To a 10mL aliquot of the sample solution, 10mL of 10% KOH and 1mL triethanolamine (TEA) were added. Three drops of 1M KCN solution and a few crystals of cal-red indicator were then added after which the mixture was titrated against 0.02N EDTA solution from red to blue end point. The titre value was used in the calculation of calcium as shown below.

$$\text{Ca (Cmol/Kg)} = \frac{\text{Titre value} \times \text{Molarity of EDTA} \times \text{vol. of extract} \times 100}{\text{Volume of aliquot} \times \text{Weight of soil (g)}} \dots\dots\dots.\dots\dots.\dots \quad (3.5)$$

3.3.5.3 Determination of exchangeable magnesium

To a 10mL aliquot of the sample solution, 5mL of ammonium chloride – ammonium hydroxide buffer solution was added followed by 1mL of triethanolamine. Three drops of 1M KCN solution and a few drops of Eriochrome black T solution was then added after which the mixture was titrated with 0.02N EDTA solution from red to blue end point. This end point titre value determines the amount of calcium and magnesium in the solution. The titre value of magnesium was then determined by subtracting the value obtained for calcium above. This titre value of magnesium was then used for the calculation of the concentration of magnesium (Mg) as shown below.

$$\text{Mg (cmol}_c\text{/ Kg)} = \frac{\text{Titre value} \times \text{Molarity of EDTA} \times \text{Vol. of extract} \times 100}{\text{Volume of aliquot} \times \text{Weight of soil (g)}} \ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

3.3.5.4 Determination of exchangeable potassium

The flame photometer was standardized such that 10 mg/Kg of K gave 100 full scale deflections. The flame photometer after standardization was used to determine the concentration of potassium in the aliquot. The result was used in the calculation of the amount of potassium present in the soil as shown in the formula below.

$$\text{K (cmol}_c\text{/Kg)} = \frac{\text{R} \times \text{Vol.of extract} \times 100}{\text{Weight of soil (g)} \times 39.1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

Where, R is the flame photometer reading (ppm)

3.3.5.5 Determination of exchangeable sodium

The flame photometer was standardized in a way that 10 mg/Kg of Na gave 100 full scale deflections. After the standardization of the photometer, the concentration of sodium in 10 mL aliquot was determined. The result was then used in the calculation of the amount of sodium (Na) present in the soil as shown by the formula below.

$$\text{Na (cmol}_c\text{/Kg)} = \frac{\text{R} \times \text{Vol. of extract} \times 100}{\text{Weight of soil (g)} \times 23} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

Where, R is the flame photometer reading (ppm)

3.3.6 Determination of cation exchange capacity (CEC)

Ten (10) grammes of soil sample was weighed into an extraction bottle and 100 mL of 1 M ammonium acetate solution added. The bottle with its content was shaken for 30 mins on a mechanical shaker. The content was filtered through a No. 42 Whatman filter paper and the sample leached four times with 25 mL of methanol to wash off excess ammonium. Thereafter another 25 mL of 1 M acidified potassium chloride was used to leach the soil four times. A 5 mL aliquot of the leachate was taken into a Markham distillation apparatus and 5 mL of 40% NaOH solution added to distil. The distillate was collected into 5 mL of 2% boric acid to which three drops of methyl red and methylene blue indicator was added. The distillate was back titrated against 0.01 M HCl to purplish end point. The cation exchange capacity in cmol_c/Kg soil was then calculated from the number of moles of HCl consumed in the back titration.

3.4 Calculation for C stocks

Carbon stocks for each layer i.e. 0-10 and 10-20 cm were determined on the fine earth fraction after bulk density and C content had been determined on the soils using the formula below:

$$\text{C stocks (Mgha}^{-1}\text{)} = \rho b \left(\frac{\text{Mg}}{\text{m}^3}\right) \times \text{C content} \left(\frac{\text{kg}}{\text{kg}}\right) \times \text{a}\ (\text{m}^2) \times \text{d}\ (\text{m}) \ldots .\ (3.9)$$

Where ρb- Bulk density

a- Area of a hectare

d- Sampling depth

3.5 Calculation for carbon saturation deficit

Carbon saturation deficit was calculated from stocks for each of the layers using:

$$\text{Csatdef} = \frac{(\text{Cref}-\text{Corg})}{\text{Cref}} \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.3.10$$

Where Cref- Carbon stock in reference soil

Corg -Current carbon stock in sampled soil under oil palm

3.5 Calculation for carbon changes (dynamics)

This was done by subtracting the current C stock of an age group from that of the previous age group and the difference recorded as what has been added to the soil under both prunnings and alleys.

3.6 Calculation for average C increment per year

This was done by subtracting the value under dynamics for a particular age group from that of the preceding year and dividing the resultant by 5 since the age groupings were done using intervals of 5 years.

3.7 Data analysis

Genstats (12th edition) and Minitab (16th edition) were used for computer analysis and separation of means was done using the Least Significant Difference (LSD) method with particular reference to the Tukey family test method of means separation in Minitab. All tests were conducted at a significance level of 5%.

Fig. 3. 2 shows prunnings stacked in between the rows under an oil palm plantation.

CHAPTER FOUR

RESULTS

4.0 Introduction

This section presents results of the study under three broad headings:

(a) physico-chemical properties of the uncultivated (reference) and cultivated soils

(b) soil characteristics under pruning and heaping with different maturity ages

(c) characteristics of soils within alleys of oil palm plantation

4.1 Physical and chemical properties of the uncultivated (reference) and cultivated soils

The physico-chemical properties of the soils under the uncultivated rainforest and cultivated soils with oil palm trees less than 5 years old are given in Table 4.1. The uncultivated rainforest refers to the reference forest which had not been cultivated for the past century.

Particle size analysis showed that sand and silt content decreased with depth whiles the clay content increased in the uncultivated forest soil. For the cultivated soil, sand and clay increased with depth whereas silt decreased. The texture of all the soils was sandy loam. Bulk density values were generally higher in the uncultivated than cultivated soils. The results also show that the bulk density of the upper soil (0-10 cm) was lower than the soil for the 10-20 cm layer.

The soil pH determined in 0.01M $CaCl_2$ solution was lower than that in water in all instances. The pH values of the uncultivated soils were generally higher than the cultivated soils. For the 0-10 cm layer the pH was slightly higher than the 10-20 cm layer.

Table 4. 1 Physico-chemical properties of soils under cultivated and uncultivated sites

Properties	*uncultivated	**cultivated (0-5yrs)	uncultivated	cultivated (0-5yrs)
	------------------0-10 cm----------------		------------------ 10-20 cm----------------	
Sand (%)	64a	58a	61a	64a
Silt (%)	23a	31a	22a	24a
Clay (%)	13a	11a	17a	12a
Texture	Sandy loam		Sandy loam	
Bulk density (Mg/m^3)	1.36a	1.24c	1.64b	1.48d
pH (water)	5.0a	4.4a	4.8a	4.7a
pH ($CaCl_2$)	4.8a	4.0a	4.6a	4.1a
K^+ (cmol$_c$/kg)	0.18a	0.13c	0.05b	0.08d
Na^+ (cmol$_c$/kg)	0.35a	0.24c	0.22b	0.32d
Ca^{2+} (cmol$_c$/kg)	3.0a	2.1a	2.4a	1.3b
Mg^{2+} (cmol$_c$/kg)	1.8a	1.3a	1.6a	0.7b
CEC (cmol$_c$/kg)	18.5a	15.6a	16.5a	11.1a
BS (%)	28.8a	24.0a	25.8a	21.3a
Organic C (g/kg)	25.5a	22.3c	15.2b	11.0d
Total N (g/kg)	1.44a	1.87c	0.53b	0.73d
C:N ratio	17.71a	11.93c	28.68b	15.07ac
C Stock	34.7a	27.7c	24.9b	16.3d

*Uncultivated represents the forest reserve soil used as the reference
**Cultivated soil following forest removal for oil palm establishment of less than 5 years old
Means without the same letter are significantly different

The cultivation of the forest for oil palm caused a decline in the level of exchangeable bases in the soil in the 0-10 cm layer. With the exception of exchangeable K^+ and Ca^{++}, the exchangeable Na+ and Mg^{++} also declined significantly with cultivation for the 10-20 cm layer. The CEC values decreased with cultivation in both layers. Table 4.1 also shows that CEC values were higher in the 0-10 cm than the 10-20 cm layer. Similar trends were observed for the % BS. The differences observed between the two were not statistically significant (p =0.05).

The cultivation of the forest soil caused a reduction in the level of OC in the soil. The OC content decreased significantly from the 0-10 cm horizon to the 10-20 cm horizon.

Total N content was higher in the cultivated soil than uncultivated in all cases. On the other hand, the C:N ratio was higher in the uncultivated than in the cultivated with the values increasing with depth in both soils.

4.2 Effect of oil palm prunnings and heapings on the physico-chemical properties of the soils

The physico-chemical characteristics of the soils sampled under heaps of oil palm prunnings are presented in Table 4.2.

Relatively high values of sand ranging between 59±4.05 and 61±5.32 % were obtained for both 0-10 cm and 10-20 cm layers respectively across the different age groups. These values were not statistically significantly different at p=0.05. The sand content increased after 5-10 years period. It decreased during the 20-25 years period in the 0-10 cm layer. Similar trend was observed for the 10-20 cm layer. The average values of silt across the maturity periods ranged from 23±4.11 to 26±3.73 % for both layers. For each soil layer, the silt content decreased up to 15-20 years period, but increased during the 20-25 years. Clay content in the soils increased in the two soil layers with age, but decreased at 20-25 years period. Comparison of the clay content of the soils under prunning (Table 4.2) to the uncultivated forest soil (Table 4.1) indicated that the latter was lower than the former. Similar trend was observed with sand and to some extent silt.

Table 4. 2 Physico-chemical properties of soils under oil palm heaps

No.	sand	silt	clay	texture	pH		sand	silt	clay	texture	pH	
	-----------%-----------				H_2O (1:1)	$CaCl_2$ (1:2)	-----------%-----------				H_2O (1:1)	$CaCl_2$ (1:2)
	------0-10 cm------						------10-20 cm------					
1*	55a	31a	14a	SL	3.8a	3.6a	57b	28b	15b	SL	3.7b	3.4b
2*	61a	25a	14a	SL	5.0a	4.7a	64b	21b	15b	SL	5.3b	4.9b
3*	61a	22a	17a	SL	4.4a	4.0a	62b	19b	19b	SL	4.4b	4.0b
4*	58a	27a	15a	SL	4.8a	4.5a	60b	25b	15b	SL	4.6b	4.4b
Mean	**59±4.05**	**26±3.73**	**15±2.7**		**4.5±0.51**	**4.2±0.54**	**61±5.32**	**23±4.11**	**16±2.39**		**4.5±0.6**	**4.2±0.6**

No.	K^+	Na^+	Ca^{2+}	Mg^{2+}	CEC	BS	K^+	Na^+	Ca^{2+}	Mg^{2+}	CEC	BS
	----------cmol$_c$/kg----------					%	----------cmol$_c$/kg----------					%
1*	0.11a	0.31a	1.4ac	0.9a	15.9a	17.1a	0.07b	0.24b	1.3c	0.9b	12.2b	20.2b
2*	0.10a	0.39a	2.4a	1.5a	17.5a	25.2a	0.06b	0.36b	1.8b	0.9b	14.5b	21.6b
3*	0.08a	0.29a	2.1a	1.4a	18.8a	21.0a	0.05b	0.27b	1.7b	0.7b	14.0b	21.2b
4*	0.10a	0.32a	2.6a	1.3a	17.3a	24.6a	0.06b	0.29b	1.9b	0.9b	13.3b	23.1b
Mean	**0.10±0.03**	**0.33±0.07**	**2.1±0.6**	**1.3±0.39**	**17.4±1.45**	**22.0±4.68**	**0.06±0.03**	**0.29±0.07**	**1.7±0.14**	**0.9±0.29**	**13.5±2.7**	**21.5±5.25**

*1= 5-10 years; 2= 10-15 years; 3= 15-20 years and 4= 20-25 years

*SL= Sandy loam

Means without the same letter are significantly different

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The average pH in water for the 0-10 cm and 10-20 cm layers was 4.5±0.51 and 4.5±0.6 respectively. No significant difference was observed among the pH values. The pH increased and decreased with depth for some age groups. However, there were no significant differences in pH values in water for both the 0-10 cm and 10-20 cm layers for the different age groups.

Similarly, the average pH in $CaCl_2$ was 4.2±0.54 for the upper layer and 4.2±0.6 for the lower layer with differences between the layers not significant. The trend was similar to that in water except that pH values in salt were lower than that in water.

Exchangeable potassium in the 0-10 cm layer was higher (Table 4.2) than those in the 10-20 cm layer. There were no significant differences among mean values of the exchangeable K for all age groups in both layers.

The results further show a decrease in exchangeable sodium with depth. The differences observed were not consistent in all cases either for age groups under the same layer or between ages across layers. Average values obtained ranged from 0.29±0.07 to 0.33±0.07 $cmol_c$/kg which were fairly higher than those for potassium. On the whole the exchangeable K^+ and Na^+ values were observed to be higher in the uncultivated soil than the soil under prunnings (Tables 4.1, 4.2).

Low values were obtained for exchangeable Ca^{++} and ranged from 1.7±0.14 to 2.1±0.6 $cmol_c$/kg for the two layers. In general the exchangeable values were higher in the top soil (0-10 cm) than the layer below. Also, the exchangeable values observed indicated a fluctuation with age of the oil palm plantations as shown in Table 4.2. Statistical analyses showed no significant differences between means of different layers except for within the 10-20 cm layer.

Exchangeable Mg^{++} ranged from 0.9±0.29 to 1.3±0.39 $cmol_c/kg$. The exchangeable Mg^{++} content of the top layer was 50% higher than the sub-layer. The results also showed that the exchangeable Mg^{++} content tended to increase after the first period of prunning and heaping (5-10 years) and subsequently increased with. As noted previously in Table 4.1, the values of both exchangeable Ca^{++} and Mg^{++} were higher in the reference soil (uncultivated soil) than in the soils under prunnings.

Cation exchange capacity (CEC) of the soils was generally below19 $cmol_c/kg$ (Table 4.2) and decreased with depth. There was a general increase in the CEC in both layers after 5-10 years of the prunning and heaping of the palm fronds to the soil. Subsequently, the CEC remained fairly stable in the soil with age of the palms. The per cent base saturation values followed the same trend as the CEC. From Table 4.1, CEC values were generally higher in the uncultivated soil than under prunnings except for the 15-20 years which was slightly higher. Per cent base saturation of the uncultivated soil on the other hand was higher than all soils under prunnings.

4.3 Physico-chemical properties of soils sampled from oil palm alleys

The physico-chemical characteristics of the alleys within the oil palm trees are presented in Table 4.3.

Sand, silt and clay values obtained after analyses did not show any significant differences when compared within and between age groups for both layers. Generally, increases in sand and clay content were observed with depth whiles silt decreased fairly with depth. Changes in sand, silt and clay contents with age were inconsistent.

Table 4. 3 Physico-chemical properties of soils within the oil palm alleys

No.	sand	silt	clay	texture	pH		sand	silt	clay	texture	pH	
	--------------%---------------				$H_2O_{(1:1)}$	$CaCl_{2\,(1:2)}$	--------------%--------------				$H_2O_{(1:1)}$	$CaCl_{2\,(1:2)}$
------------0-10 cm------------							------------10-20 cm------------					
1*	55a	30a	15a	SL	3.8a	3.6a	57b	26b	17b	SL	3.8b	3.5b
2*	65a	22a	13a	SL	4.8a	4.5a	65b	21b	14b	SL	5.2b	4.6b
3*	57a	25a	18a	SL	4.2a	3.9a	59b	22b	19b	SL	4.0b	3.5b
4*	61a	25a	14a	SL	4.1a	3.7a	63b	22b	15ab	SL	4.1b	3.6b
Mean	**60±6.07**	**26±5.15**	**15±3.54**		**4.2±0.45**	**3.9±0.48**	**61±7.31**	**23±5.02**	**16±3.23**		**4.3±0.66**	**3.8±0.62**

No.	K^+	Na^+	Ca^{2+}	Mg^{2+}	CEC	BS	K^+	Na^+	Ca^{2+}	Mg^{2+}	CEC	BS
	-------------------------cmol$_c$/kg--------------------------					%	---------------------------cmol$_c$/kg-------------------------					%
1*	0.08a	0.23a	1.3a	0.7a	17.5a	13.3a	0.05b	0.27b	1.3b	0.6b	13.6b	16.9b
2*	0.11a	0.35a	2.1a	1.1a	15.8a	22.8a	0.06b	0.36b	1.6b	1.1b	10.7b	28.8b
3*	0.10a	0.32a	1.8a	0.9a	18.9a	16.6a	0.06b	0.32b	1.4b	1.1b	14.9b	19.7b
4*	0.13a	0.38a	1.7a	0.9a	16.8a	18.9a	0.06b	0.30b	1.4b	0.7b	10.9b	21.8b
Mean	**0.11±0.03**	**0.32±0.08**	**1.7±0.44**	**0.9±0.29**	**17.3±1.49**	**17.9±3.89**	**0.06±0.02**	**0.31±0.07**	**1.4±0.51**	**0.9±0.45**	**12.5±2.16**	**21.8±6.46**

*1= 5-10 years; 2= 10-15 years; 3= 15-20 years and 4= 20-25 years.

Means without the same letter are significantly different

Analysis of the soil under alleys showed a mean sand content of 60±6.07% which was fairly higher than when the soil was initially cultivated (Table 4.1). On the other hand contrary result for silt content was obtained for soils under alleys with clay content in the cultivated soil also being lower than those of the other age groups.

The average pH values in water and $CaCl_2$salt for 0-10 and 10-20 cm layers followed a similar trend as those under prunnings. Differences observed were not statistically significant at p=0.05. When compared with soils from the cultivated site in Table 4.1, the pH of soils from within the palms (alleys) were lower than that of cultivated soil as cultivation continued with time.

Exchangeable K^+ followed a similar trend as that observed for under prunning. The exchangeable K^+ decreased with depth. Differences observed were also not significant. The results also show an increase in exchangeable Na^+ with depth for some age groups whiles others decreased with depth. The exchangeable Na^+ content at both layers showed average values between 0.31±0.07 to 0.32±0.08 $cmol_c$/kg but differences observed were not significant. On the whole the exchangeable K^+ values were observed to be higher in the cultivated soil than the soils under alleys (Tables 4.1, 4.2). However, exchangeable Na^+ was observed to be lower in 0-10 cm layer for the cultivated soil but was slightly higher than those in the lower layer of soils under alleys.

Low values were observed for exchangeable Ca^{++} ranging from 1.4±0.51 to 1.7±0.44 $cmol_c$/kg for both layers. Higher values were obtained for the 0-10 cm layer compared to the 10-20 cm layer. Exchangeable Mg^{++} ranged from 0.9±0.29 to 0.9±0.45 $cmol_c$/kg. There was an initial increase in exchangeable Mg++ with age but a decreased followed with a further stabilisation of the value. From Table 4.1, exchangeable Ca^{++} in the top layer of the newly cultivated soil was significantly different from the rest ($p< 0.05$) in the 0-10 cm layer but in the 10-20 cm layer no significant differences were observed. Exchangeable Mg^{++} on the other hand was lower in the top layer of the cultivated soil than the alley but higher in the 10-20 cm layer.

The CEC decreased with depth with no significant differences among means for both layers. Per cent base saturation (PBS) was higher in the lower layer than in the upper layer for all age groups but was not significant at $p= 0.05$. The base saturation fluctuated with age under both layers and was low just as was observed for the exchangeable bases and CEC. From previous results the CEC was higher in both layers for soils under alleys than the cultivated soils (Tables 4.1, 4.3). Per cent base saturation was lower in soils from the alleys in the 0-10 cm layer and higher than those of the cultivated soil in the 10-20 cm layer.

4.4 Bulk density, Total N, C content and stocks in soils under prunnings

The bulk density, total nitrogen content, C content and C stocks are presented in Table 4.4. Also included in this Table are results for C:N ratio and Carbon saturation deficit calculated for each age group.

Table 4.5 also shows the C dynamics and average incremental C additions to the soil under prunnings per year.

The average bulk density across all the age groups in the 0-10 cm layer was 1.22±0.01 Mg/m^3 and 1.38±0.02 Mg/m^3 in the 10-20 cm layer. The bulk density was 13 % higher in the lower layer than in the upper layer for all the age groups and this was significant at $p<0.05$. The bulk density also decreased with the age groups and was significant ($p<0.001$). Comparison of the bulk density of the soils under pruning to the reference soil (uncultivated soil) (Table 4.1) showed that the bulk density values were higher for the reference than the soil under prunning.

Table 4. 4 Bulk density, Total Nitrogen, C content and stocks for 0-10 and 10-20 cm layers under oil palm heaps.

No.	BD Mgm^{-3}	OC ---------------gkg^{-1}-----------	TN	C:N	C Stocks Mgha^{-1}	Csatdef (%)	BD Mgm^{-3}	OC -----gkg^{-1}-----	TN	C:N	C Stocks Mgha^{-1}	Csatdef (%)	∑stocks Mgha^{-1}
	---------------------------------0-10 cm-----------------------------------						--10-20 cm---------------------------------						
1*	1.34a	14.6ae	1.19a	12.3a	19.6a	43.7a	1.43b	8.42b	0.70b	12.0a	12.1b	51.5b	30.8
2*	1.18c	15.6a	1.23a	12.9a	18.4a	47.0ab	1.40be	8.68b	0.72b	12.1a	12.2b	51.1 b	30.6
3*	1.21c	16.6a	1.32a	12.6a	20.1a	42.2a	1.36be	10.8d	0.96bd	11.3a	14.7c	41.0 ac	34.8
4*	1.15c	22.0c	1.87c	11.8a	25.2d	27.5d	1.34de	13.1e	1.27d	10.3a	17.6e	29.4 de	42.8
Mean	**1.22±0.01**	**17.2±1.29**	**1.40±0.07**	**12.4±0.92**	**20.8±1.3**	**40.1±3.75**	**1.38±0.02**	**10.3±0.64**	**0.91±0.15**	**11.4±1.99**	**13.9±0.9**	**43.3±3.61**	**34.8**

*1= 5-10 years; 2= 10-15 years; 3= 15-20 years and 4= 20-25 years

C_{satdef}. = Carbon saturation deficit

∑stock= C stocks in 0-10 cm layer + C stocks in 10-20 cm layer

Means without the same letter are significantly different

Table 4. 5 Changes in C stocks under oil palm heaps with age of plantation

Property	1	2 current	3	4	1	2 changes wit time	3	4
	--------------------------0-20 cm-----------------------				--------------------------0-20 cm-----------------------			
C stocks (Mgha^{-1})	30.8	30.6	34.8	42.8	**	-0.2	4.2	8.0
Average increments/yr						-0.04	0.84	1.6

*1= 5-10 years; 2= 10-15 years; 3= 15-20 years and 4= 20-25 years ** Represents initial year from which additions took place later.

The organic carbon content increased consistently at a rate of 6.4% from 5-10 years up to 15-20 years. Beyond this age group the increase observed was about 24% of the C present. Generally, OC tended to increase with the addition of pruned palm fronds to the soil across the ages. Organic Carbon was 40% higher in the 0-10 cm than the 10-20 cm layer. Some significant differences were observed when comparisons were carried out between layers ($p < 0.05$). Average C content in the 0-10 cm layer was 17.2±1.29 g C/kg soil with the lower layer was 10.3±0.64. With the exception of the 20-25 year group which had received a lot of pruned fronds over the years, the reference OC was significantly higher than the other age groups. All OC values obtained have a direct effect on C stocks for each layer and age group. C stocks decreased slightly at a rate of 1.22 % between the first two age groups and increased to 8.46% and further to 20.24% to attain the 25.2 Mg C/ha observed under the 20-25 year group. C stocks in the upper layer were significantly higher than those of the lower layer when the two were compared ($p < 0.05$). Results also showed significantly higher C stocks in the reference soil than in soils under prunnings for both layers (Tables 4.1, 4.4).

Average total N values for the 0-10 cm decreased between 3.3 and 36.4%. Between the 0-10 and 10-20 cm layers total N ranged between 0.91±0.15 and 1.40±0.07 gN/kg soil as shown in Table 4.4. Significant differences were observed among some means.

The carbon to nitrogen ratio (C:N) values ranged on average between 11.4±1.99 and 12.±0.92 depending on age and depth. Differences between means for both layers were quite small and insignificant. Increases in the 0-10 cm layer were very small with a significant rise taking place just beyond 20 years. Similar trend was observed in the 10-20 cm layer. Between the 0-10 and 10-20 cm layers there were no significant differences but within each layer no significant differences were observed ($p < 0.05$).

The Carbon saturation deficit (Csatdef) is an index that has been adopted from a similar study by van Noordwijk et al. (1997) and is used here to estimate approximately how much carbon had been accumulated and stored under each of the different oil palm age groups and how much more is needed to be added in order to attain C equilibrium under the plantation..

Averagely, the C saturation deficit for the 0-10 cm layer was 40.1±3.75 and 43.4±3.61 for the 10-20 cm layer. The C saturation deficit increased initially and decreased gradually at 10.2 % until a further decrease of about 34.8% was observed for 20-25 years. The 20-25 years group under prunnings was significantly different (higher) compared to each other group with the rest not showing any significant differences among the means for the 0-10 cm layer ($p < 0.05$). In the lower layer significant differences were observed among some age groups. Average increase in C saturation deficit with depth was 7.4%.

The data for C dynamics presented in Table 4.5 showed that there were no increases in carbon stored during the 5-10 and 10-15 years of pruning respectively but some increases were observed for the 0-10 cm soil layer. For the 10-20 cm consistent increases in the C stocks with age was obtained. The variation of Carbon storage was from -0.2 to 8 Mg/ha. This was equivalent to 30.8 and 42.8 Mg/ha. The average C stored per year with the prunnings varied from -0.04 to 1.6 Mg/yr.

4.5 Bulk density, Total N, C content and C stocks in soils within the alleys

The bulk density, total nitrogen content, OC content and C stock and C saturation deficits are presented in Table 4.6 while Table 4.7 shows the C dynamics with age and average incremental C additions per year.

A similar trend in bulk density was observed as under prunnings where bulk density increased with depth. Unlike the case of the prunnings, increases were observed under both layers with age of the oil palm plantation and were significant ($p < 0.05$). The results also show that the differences between means for both layers were significant in some cases i.e. $p < .05$ for the upper layer and $p < 0.05$ for the lower layer. From Table 4.1 it was observed that bulk density for the newly cultivated soil (0-5 yrs) was lower than that of the alleys for both depths.

There was a consistent increase in the OC of about 4.2% with age of the oil palm plantation up to 15-20 years for both 0-10 and 10-20 cm layers of the alleys. However, a sharp decrease was observed in both layers after 20 years. Carbon contents in the upper layer were significantly higher than those in the lower layer ($p < 0.05$). As noted, the OC content of the cultivated soils (0-5 yrs) was significantly higher than the means of the alleys in either layer (Tables 4.1, 4.6).

Table 4. 6 Bulk density, Total Nitrogen, C content and stocks for 0-10 and 10-20 cm layers under alleys.

No.	BD Mgm^{-3}	OC	TN	C:N	C Stocks Mgha^{-1}	Csatdef (%)	BD Mgm^{-3}	OC	TN	C:N	C Stocks Mgha^{-1}	Csatdef (%)	∑stocks Mgha^{-1}
		------gkg^{-1}------						-------gkg^{-1}--------					
	------------------------0-10 cm-------------------------						-----------------------------------10-20 cm-----------------------------						
1*	1.36a	13.7a	1.36a	10.1	18.6a	46.4c	1.49b	6.49b	0.70b	9.34	9.65b	61.1b	28.3
2*	1.33a	14.3a	1.52a	9.41	19.1ac	46.0ac	1.44c	6.83b	0.72b	9.49	9.82b	60.5b	28.9
3*	1.28d	16.9c	1.60a	10.6	21.5c	38.8a	1.51b	9.52d	0.88b	10.9	14.4d	42.3a	35.9
4*	1.35a	13.0a	1.37a	9.49	17.5a	49.3c	1.52b	8.68d	0.84ab	10.6	13.2d	46.9ac	30.7
Mean	**1.33±0.2**	**14.5±0.87**	**1.46±0.17**	**9.9±1**	**19.2±0.99**	**45.1±2.84**	**1.49±0.02**	**7.88±0.67**	**0.79±0.12**	**10.1±1.17**	**11.8±1.07**	**52.7±4.3**	**31.0**

*1= 5-10 years; 2= 10-15 years; 3= 15-20 years and 4= 20-25 years

∑stock= C stocks in 0-10 cm layer + C stocks in 10-20 cm layer

Means without the same letter are significantly different

Table 4. 7 Changes in C stocks under alleys with age of the oil plantations

Property	*1	2	3	4	1	2	3	4
		current				changes with time		
	---------------------------0-20 cm------------------------				-------------------------------0-20 cm------------------------------			
C stocks (Mgha^{-1})	28.3	28.9	35.9	30.7	**	0.6	7.0	5.2
Average increments/yr						0.12	1.4	-1.04

*1= 5-10 years; 2= 10-15 years; 3= 15-20 years and 4= 20-25 years

** Represents initial year from which additions took place later.

The C stocks also followed a similar trend as the C content. Increases were observed with age with a decrease beyond 20 years for both layers. Average C stocks were between 11.8±1.07 and 19.2±0.99 Mg/ha for soils under alleys. Comparison of the mean C content of soils under alleys (Table 4.6) to cultivated soils (Table 4.1) indicated that the latter was higher than the former for both layers.

Total N content in soils decreased with depth Table 4.6. Differences observed between 0-10 and 10-20 cm were significant ($p<0.05$) except for that of the 20-25 year which was not significant. The total N values increased between 5-18.2% in both layers and this reflected with increasing age of the plantations except that there was a decline beyond 20 years (Table 4.6).

Relatively high C: N ratio values were observed for some age groups in both layers. The trend decreased followed by an increase then a decrease in both layers with age. Differences observed among means for alleys were not significant for both layers compared to that under prunnings.

Carbon saturation deficit (Csatdef) in the 0-10 cm layer under alleys showed relatively higher values for the deficit. For the lower layer (10-20 cm) very high values of about 61 % were noted with the trend being similar to those of the upper layer. There were decreases in the deficit with time; The Csatdef concentrations decreased from 61% to 42.3% in the 10-20 cm layer. There were significant differences between some means for the 0-10 cm layer and also for the 10-20 cm layer ($p= 0.001$). Increases in Csatdef with depth were observed from 5 to 20 years.

From Table 4.7, carbon dynamics showed lack of consistency in C stock with age of the plantation. The annual increment varied from 0.6 to 5.2 Mg/ha and showed the Carbon stocks in the two different soil layers 0-10 cm and 10-20 cm under the oil palm alleys. The data showed that the C stored with age was not close to the C stored in the reference (uncultivated) soil.

CHAPTER FIVE

DISCUSSION

5.0 Introduction

This chapter focuses on discussing the results obtained from this research work and tries to make comparisons with reference to available data from elsewhere. The discussion would in the end come out with conclusions and make possible suggestions by way of recommendations for future studies under oil palm.

5.1 Soil characteristics of all sampled soils

5.1.1 Soil textural characteristics

Relatively higher values of sand were observed under both alleys and prunnings than silt and clay even though some increases and decreases were observed with depth. The increase in sand and clay fractions with decreasing silt observed with depth as seen under both conditions is partly due to downward movement of these fractions as a result of the heavy rainfall in the experimental area. Cultural practices like weed control also contributes to surface exposure of the soil to environmental and climatic effects. The increase in clay with depth could also be due to the type of parent material usually phyllites from which the soils were formed (Owusu-Bennoah et al., 2000).

5.1.2 Soil pH

The forest soil which served as the reference was highly acidic. Opening up the forest also caused a further drop in acidity. Similar results have been published by Nye and Greenland (1965) for this district. The low pH of the soils may be due to the nature of the parent materials and to the high rainfall (usually 2000mm and above) of the area (Tweneboah, 2000) which causes intense leaching of the basic cations in the forest soil. The pH which was recorded when determination was carried out in salt (0.01 M $CaCl_{2)}$ was depressed by about 0.5 (Δ pH is negative) compared to that in water. The added cation displaces H^+ into the solution and the dilution is counteracted (Rowell, 1988). The low pH values imply the presence of a positive charged colloidal surface. This also signifies that the soil has the potential to attract and hold negatively charged ions on its surface. The high rainfall is responsible for the leaching of the basic cations in the soil which also account for the low pH although the acid soil is suitable for oil palm.

The comparison of pH between soils sampled under prunnings and that from within the alleys also showed slightly higher pH values in soils under prunnings than those from the alleys. This could be partly attributed to the different amounts of organic material present at each location and also with increasing depth. Oxisols and Ultisols both highly weathered deep soils associated with this environment in addition to the low pH have contributed to successful growth of the oil palm industry (Mutert, et al., 1999; Tweneboah, 2000) in this area.

5.1.3 Exchangeable bases and cation exchange capacity (CEC)

The low values recorded for the basic cations could be due to quite low organic matter content and kaolinite dominating clay fraction (Owusu-Bennoah et al., 2000) even under the prunnings. This also reflected in the low per cent base saturation of less than 30%. Per cent base saturation (PBS) of the uncultivated decreased slightly with depth whiles a general increase was seen under both prunnings and alleys. Base saturation in some cases increased under prunnings with age but decreased with depth. The low PBS could also be explained by the high rainfall which leaches more bases out of the top layer.

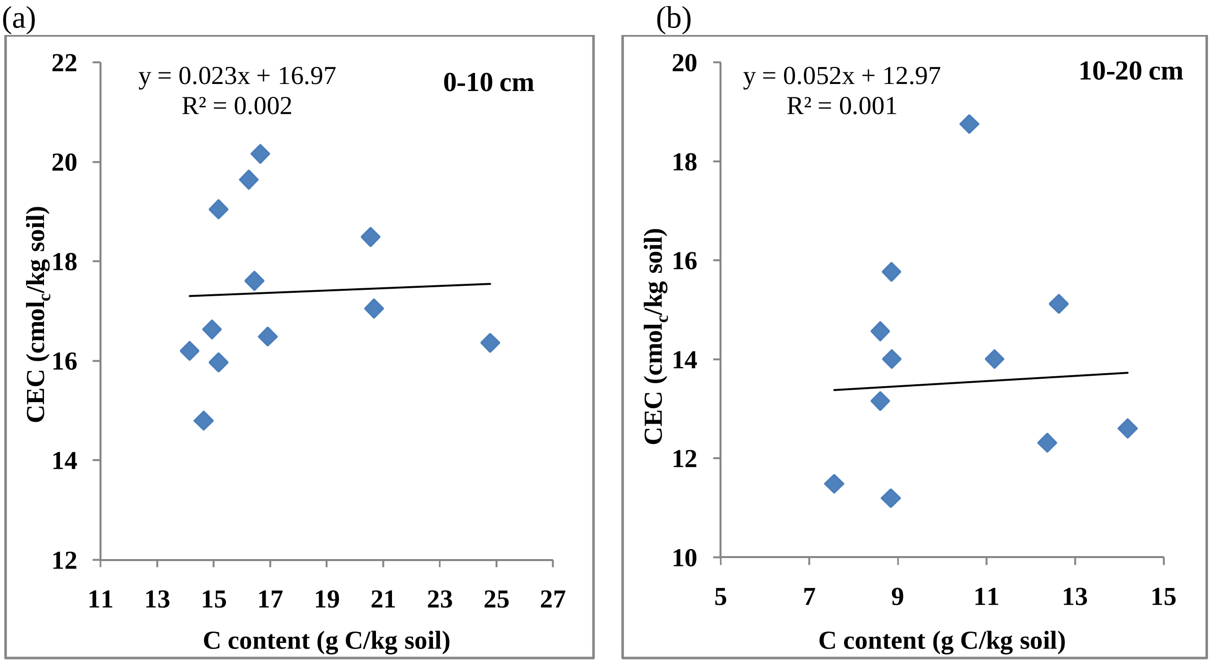

Fig. 5. 1 (a) and (b) show relationships between CEC (cmolc/kg soil) and C content (g C/kg soil) in the 0-10 and 10-20 cm layers respectively under prunnings.

Organic matter plays a role in the CEC of a soil (Pierzynski et al., 2000; Baddock and Nelson, 2000) as shown in Figs 5.1 and 5.2. This implies that low organic matter in the soil can give rise to equally low CEC values. Figure 5.2 shows that there is a positive correlation between CEC and organic C under alleys for both layers. This relationship though weak (R^2=0.126) is better than that under prunnings (R^2=0.002) giving an idea as to the different rates of decomposition present under both instances. According to Figs 5.1 and 5.2 a possible intercept values of approximately 17 and 12 for the 0-10 cm layers under prunnings and alleys respectively were obtained. Similarly, 7 and 13 intercept values for the 10-20 cm layers respectively under both scenarios were obtained.

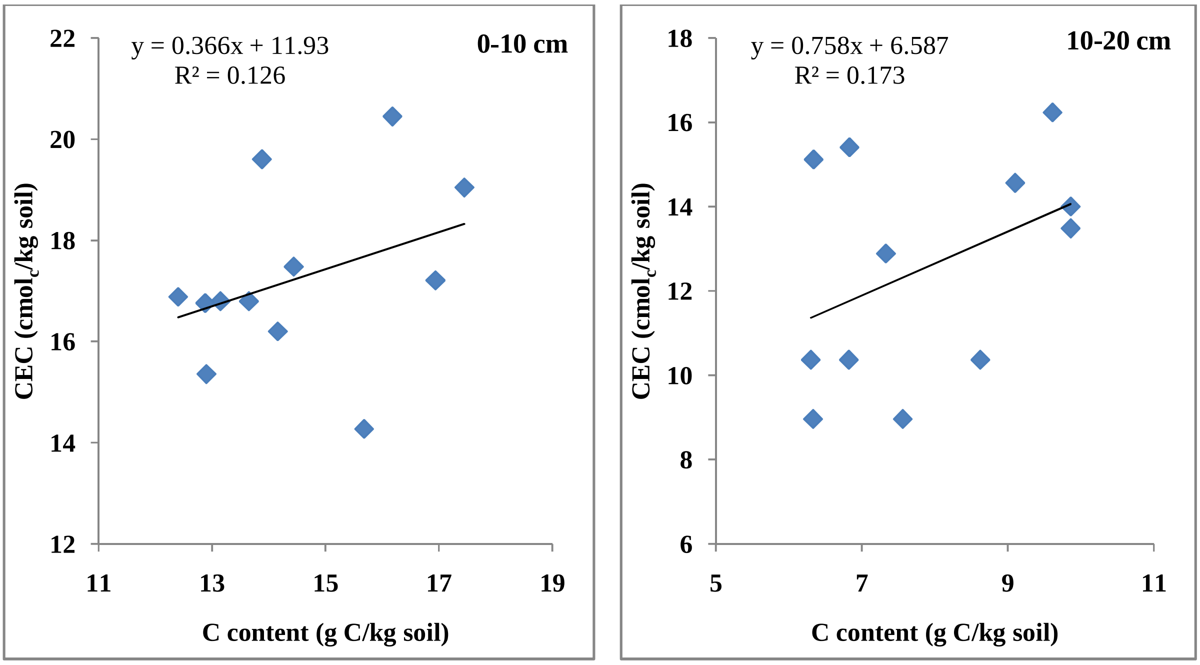

Fig. 5. 2 (a) and (b) show relationships between CEC (cmolc/kg soil) and C content (g C/kg soil) in the 0-10 and 10-20 cm layers respectively under alleys.

5.1.4 Bulk density

A general increase in bulk density with depth was observed under prunnings and alleys. This may be attributed to the increasing clay content with depth. Bulk Density values under prunnings were relatively lower than those of the alleys as a result of the influence of organic matter which made the soils in the 0-10 cm layer relatively loose as compared to those in the 10-20 cm layer where OM content was quite low. Organic matter under oil palm plantation play a key role in improving the physical properties of soil and thereby contributing to the structural stability of soils (Schnitzer and Khan, 1975) as has been observed in the bulk density values under prunnings (Table 4.4).

5.1.5 Organic carbon content

Establishment of oil palm plantations demands the removal of any existing forest vegetation cover or plant cover. The biomass produced after land clearing if not burnt is broken down by litter-feeding invertebrates such as termites, earthworms and beetles. Their actions while decreasing litter to tiny particles increases the surface for bacterial and fungal decomposition (MacKinnon et al., 1996) and account for the difference in OC values between the uncultivated and cultivated.

The high OC content of soils under prunnings as compared to those under alleys is due to the amount, location, quality and action of temperature and moisture on the pruned material (Kirschbaum, 2000; Raich and Tufekcioglu, 2000). The different C pools under the two scenarios could be as a result of the pool's size and its dependence on the productivity of the vegetation and decomposition of organic matter in the soil which are temperature dependent processes. This is because decomposition is generally considered to increase as temperature increases (Schimel et al., 1994; Kirschbaum, 2000). Higher temperature and precipitation more than 2000 mm/yr affect decomposition which could have led to increase losses of some C from some of the soils (Ågren and Hyvo¨nen, 2003).

When the forest was opened and exposed to the environment (cultivated) there was loss of C into the atmosphere from both soil and vegetation. The difference between the cultivated (0-5 yrs) and uncultivated was not much and also not significant. This could be partly due to quite a substantial amount of C remaining in the soil even after the vegetation had been removed which had not yet been lost (Table 4.1). However, periods beyond the initial years of cultivation were different such that when oil palm was established a notable drop in OC within the first 5 years was seen Guo and Gifford (2002). The subsequent drop in OC in the uncultivated from 10 years onwards was gradual (Lamade et al., 2005) when compared to the cultivated but less than 15 % of that for previous years as was observed under alleys with age. This trend was seen in both the 0-10 and 10-20 cm layers and could be due to disturbances resulting from agronomic practices such as weed control, insect control among others in the subsequent years.

The trend in OC observed under prunnings was an opposite of what was seen under alleys where palm fronds heaped underwent rapid decomposition especially in the 5-10 years period to release nutrient. However, as the age of the plantation moved towards the 20-25 years period, the rate of decomposition slowed down with decomposed material being protected by overlying palm fronds. It was therefore common to find heaps of varying heights with age of the plantation. Similar observations had been made in Benin (Henson 1999).

Soil moisture is a factor secondary to soil temperature that plays a very vital role in soil respiration (Rs) by making Rs very effective when it is adequate in soil (Conant et al., 2004; Luo and Zhou, 2006; Li et al., 2008; Litton and Giardina, 2008; Wang et al., 2011b). From field observations high OC was expected from soils which had received quite a lot of pruned materials particularly under older plantations beyond what was seen. This was not the case due to the fact that beneath the overlying fronds were very dry and warm layers, some of which were made up of fronds at different stages of decomposition. These layers were protected by the fronds above from moisture which was very much needed for decomposition to proceed. In addition, soils under these heaps had termites, beetles and other organisms except earthworms. This could be due to the vertical migration of these organisms to areas of more moisture and so affected C turnover in deeper layers instead (Briones et al. 1998a, 2010).

Analyses of the soils from the uncultivated site showed so much OM sitting on top of the soil but relatively low OC content (25.5 g C/kg soil for the 0-10 cm and 15.2 g C/kg soil for the 10-20 cm). The analyses did not show any significant difference between the uncultivated and the newly cultivated site (0-5 yrs) for the 0-10 and 10-20 cm layers. Even though moisture stress is limited in the forest reserve, temperature appears to exert a dominant control over seasonal variations in soil respiration (Janssens et al., 2001) and so may explain up to 72-96% of these variations in the forest (Keith et al., 1997; Boone et al., 1998; Rey et al., 2002; Subke et al., 2003) and may have accounted for the OC observed in the soil from the forest reserve.

5.1.6 Total nitrogen content

The decomposition of OM in soils provides nutrients for plant growth and it is also essential for the global cycling of elements such as C and N in soils (Pierzynski et al., 2000; Baddock and Nelson, 2000). From the results total N varied with amount of OM present in soils such that it increased along with changes in corresponding OM levels. However, some exceptions were associated with the uncultivated, cultivated and the 20-25 year group under prunnings for both depths where corresponding N contents did not appear to correspond with the OC values observed. This is because of the presence of relatively high OC content in these soils implying higher N release as well but was not the case. The relationship between N content and OC for the soils under prunnings with age is shown in Fig. 5.3 below.

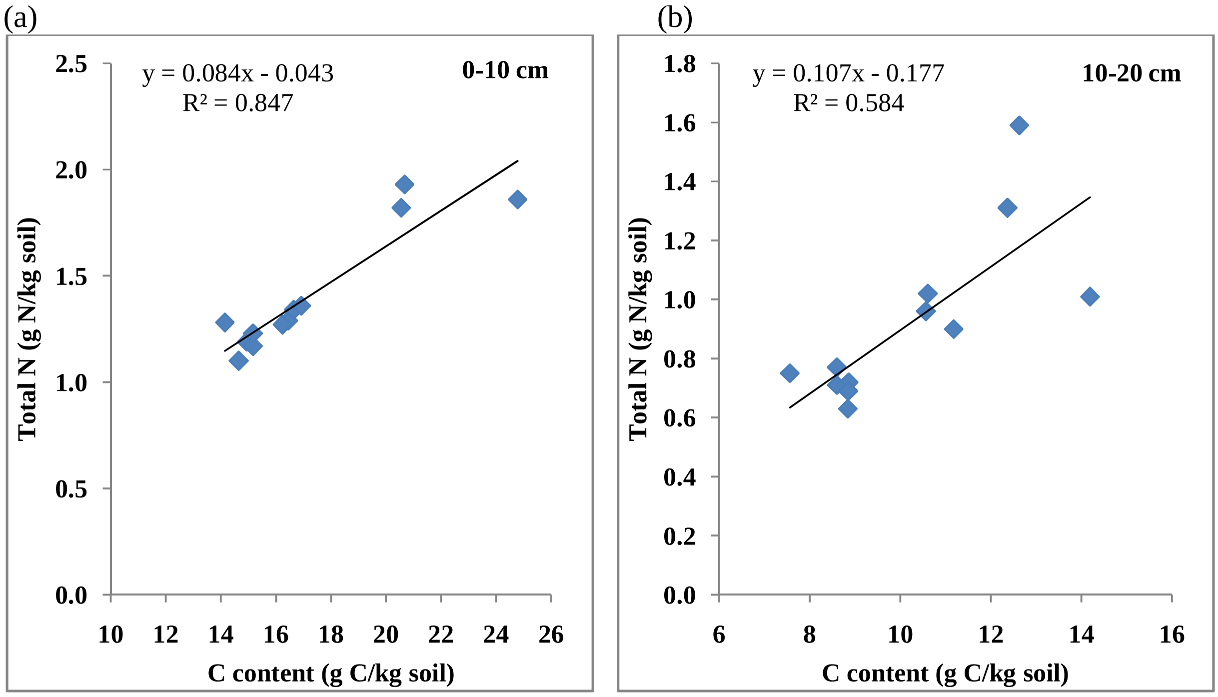

Fig. 5. 3 Relationships between Total N content (g/kg soil) and C content (g C/kg soil) in the (a) 0-10 cm layer and (b) 10-20 cm layer under prunnings.

From Fig.5.3 the soil N content under prunnings was observed to be increasing with increasing C content and age of the plantation for both the upper and lower layers with a strong correlation existing between N and C content especially in the 0-10 cm layer.

Under alleys, a similar trend was observed for both layers where increases occurred with increasing C content and age of the plantation as shown below in Fig. 5.4.

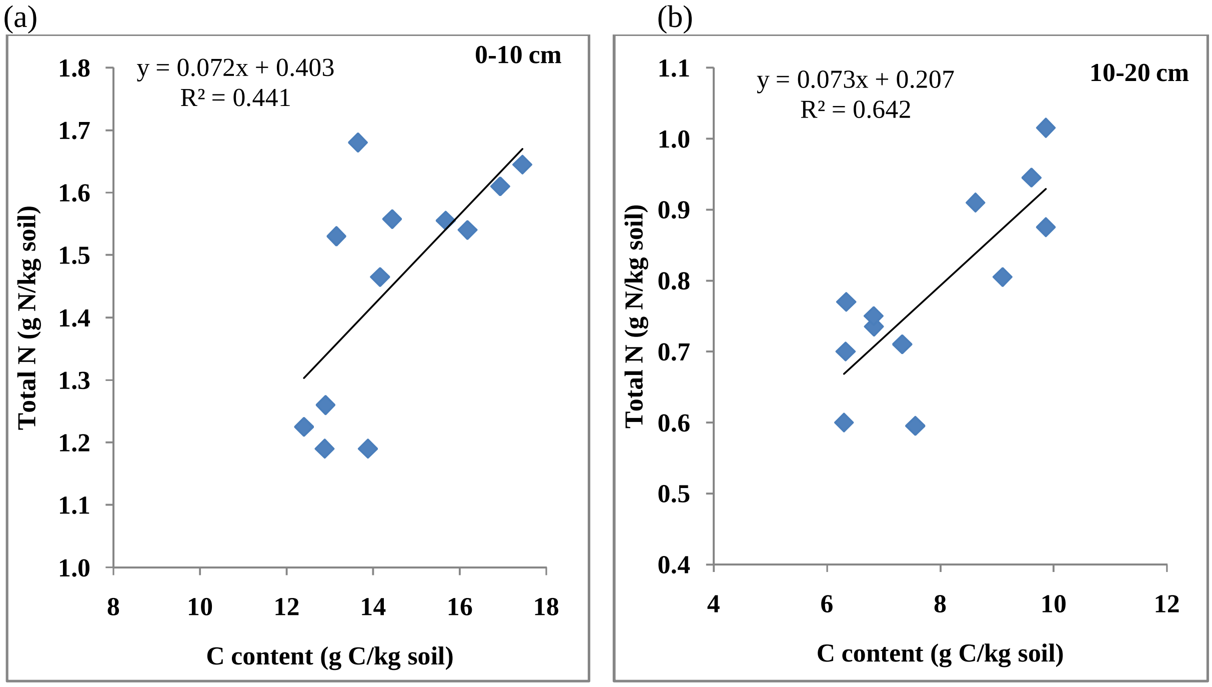

Fig. 5. 4 Relationships between Total N content (g/kg soil) and C content (g C/kg soil) in the (a) 0-10 cm layer and (b) 10-20 cm layer under alleys.

Total nitrogen in soils under prunnings though high could have been higher than those reported in Table 4.4 because of the relatively higher OC present but this was not so. It is possible that part of the N present in these soils (under prunnings) were immobilised as has been suggested that the “fresh” (i.e. younger) soil carbon is more sensitive to temperature changes, whilst the older fraction is not sensitive, as it includes hard-to-decompose materials and organic matter that is protected in the interior of soil particles (Giardina and Ryan, 2000; Thornley and Cannell, 2001; Davidson and Janssens, 2006). In addition to this is the fact that as a greater portion of SOM gets converted to such recalcitrant material, the temperature sensitivity and potential availability as a substrate for microbial respiration of this pool are of acute importance with respect to climate change (Biasi et al., 2005) and has been noted that late decomposition would be slower in systems with high initial mass loss rates (Berg et al. 1993) coupled with the absence of earthworms in these soils.

The increasing N with C content in soil observed under alleys with age of the plantation could be due to cultural practices such as occasional weeding which provided some residue under alleys. These materials were subjected to relatively faster rates of decomposition as excess heaping was absent in these soils to prevent materials from protection from the environment. This made more N available and so accounts for the increasing N content with age even in the presence of relatively low OM compared to the prunnings. The presence of earthworms in soils under alleys also promoted decomposition and N release faster than under prunnings since moisture was not limiting.

5.2 Carbon to nitrogen (C: N) ratio

The fixation of C through photosynthesis allows for N release in substrates within the rhizosphere. The C:N ratio increased when increases in C were not accompanied by N additions and this change in C:N ratio had a large potential effect on processes of mineralization, immobilization (Paterson, 2003). From Tables 4.4 and 4.6 a number of contrasting scenarios have been seen. Farmers under production systems are expected to keep C:N ratios below 12 to promote activities of soil microorganisms to release nutrients.

Results showed that the 20-25 years group under prunnings had C:N ratios less than 12 for both 0-10 and 10-20 cm layers respectively. The cultivated site also recorded fairly high C:N ratio values for both layers. Similarly, soils from the cultivated and the 20-25 years group also had significantly higher C content compared with the rest. The relatively lower C:N ratios observed for these two age groups compared to the rest under alleys promoted N mineralisation and more rapid soil N turnover (Cheng et al., 1996) with the higher C:N ratios possibly slowing down microbial activity and decomposition as N becomes limiting particularly under prunnings during initial periods (years) of decomposition of palm fronds. Increase in C content with age under prunnings was not accompanied by a corresponding increase in N especially for the 20-25 years group. This is partly due to different rates of decomposition of the two nutrients such that C appeared to be decomposing faster than N.

The very high C:N ratio observed under the uncultivated could be due to forest N use deficit as a result of C volatilisation.

The trend in C:N ratio with age for the top and lower layers under prunnings are presented in Figs. 5.5a and b.

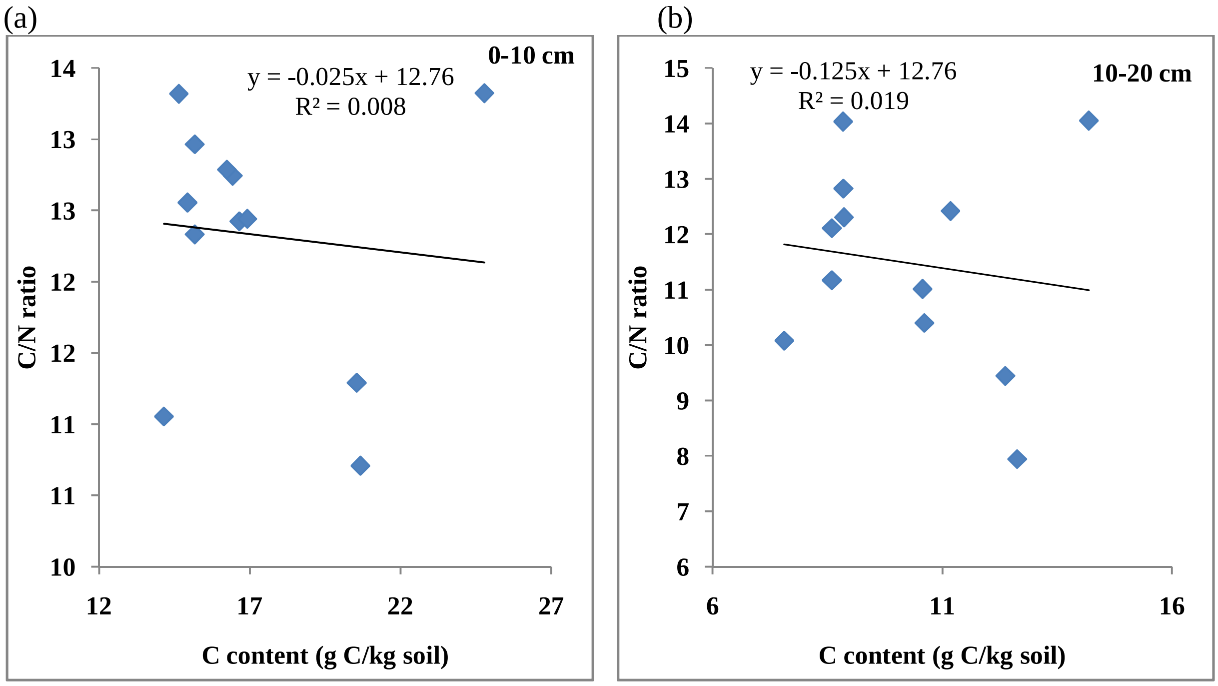

Fig. 5. 5 Relationships between C/N ratio and C content (g C/kg soil) in the (a) 0-10 cm layer and (b) 10-20 cm layer under prunnings.

The Figures 5.5 a and b show that C:N ratio decreased with increase in C content in both layers. Quite a similar trend was observed in soils under alleys (Fig.5.6) even though results in Table 4.6 showed an inconsistency in the C: N ratios.

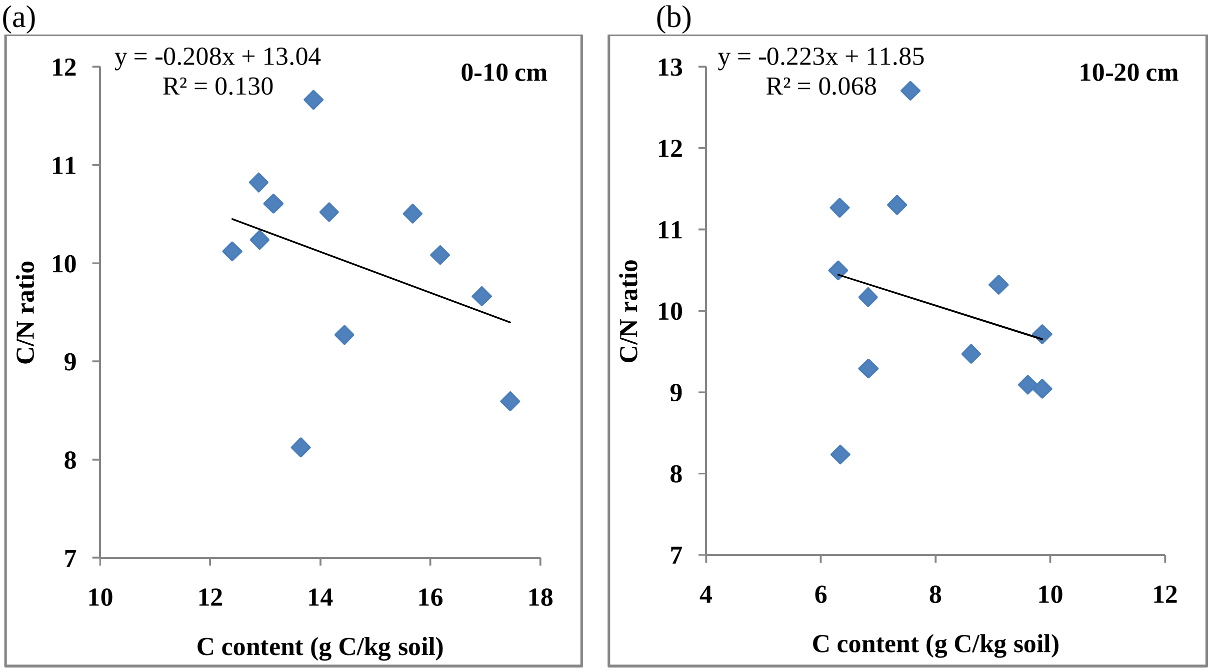

Fig. 5. 6 Relationships between C/N ratio and C content (g C/kg soil) in the (a) 0-10 cm layer and (b) 10-20 cm layer under alleys.

The relatively lower C:N ratios under alleys compared to the prunnings could be due to the nature and quality of weeds grown in the alleys as compared with the highly lignified oil palm fronds added to soils under pruning (Cheng, 1999). The conclusion may be that soils analysed that had relatively high C:N ratios (>12) may contain residue of low quality having insufficient N and as such the prunnings may not after all be so beneficial from the fertility point of view as quality materials for mulching and nutrient recycle even though oil palm prunnings and heaping may play a significant role in reducing C emissions into the atmosphere.

A linear relationship has usually been shown to exist between soil organic C content and C input from crop residues (Paustian et al., 1997c; Duiker and Lal, 1999). Paustian et al. (1992) found a positive effect on soil C with the use of residues containing higher lignin contents. It is important to note that C:N ratio of residues have been shown to be very important in C sequestration in soil (Paustian et al., 1997a; Drinkwater et al., 1998). Studies by previous scientists suggest that even low C:N ratio materials can be beneficial for C sequestration and has been proven by Lal *et al.* (1999) in an experiment involving two different sources of residue materials where they indicated the beneficial effects of grass cover crops compared with leguminous ones in sequestering C.

5.3 Carbon stocks

Carbon stocks in soils from uncultivated, cultivated, prunnings and alleys followed a similar trend as C content. Stocks in the uncultivated soils were significantly higher than all the rest. When C stocks for both layers were summed up, it was observed that soils under prunnings showed higher values than the alleys particularly for the 20-25 year group.

The value of 59.6 Mg C/ha calculated for the 0-20 cm layer under forest conditions (uncultivated) in this work falls within the range 5-180 t/ha for the 0-30 cm layer as put out for humid tropical forests (IPCC, 1997).

5.4 Relationship between C and management options:

Carbon in the soils sampled under alleys was statistically lower than C in uncultivated. Cultural activities such as weeding and in some cases spraying with herbicides could be responsible for this through making C available for rapid decomposition. The different plant species present as undergrowth could also be responsible for contributing to C input (when cut and left on soil surface) and at the same time C removal when the oil palm trees absorb part of dissolved organic carbon from the soil. In addition the effect of erosion which could cause losses of OC on one side and additions at another side may contribute to the loss of the OC in the alleys. The occasional flooding of the farms in the district could also be a contributing factor .to the reduced OC in the alleys as compared with the reference soil.

Carbon under prunnings was relatively higher than under alleys. The system of adding pruned materials as residue to soil seems to improve the storage of carbon particularly in the surface horizon. Since no significant difference actually exists in terms of texture for the two systems, soil management could be responsible for the differences and this could prove as a very good option of controlling C losses to the environment to offset atmospheric balance. These are shown in Figs 5.7 and 5.8.

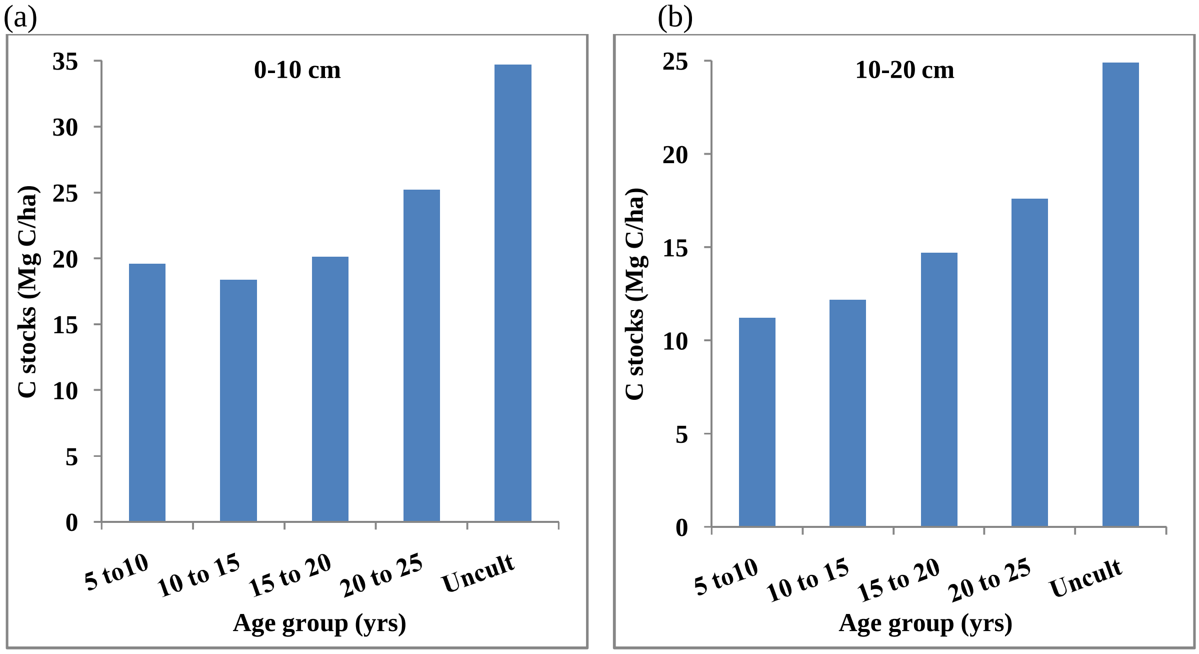

Fig. 5. 7 shows carbon stocks in the (a) 0-10 cm layer and (b) 10-20 cm layer under prunnings for the different age groups.

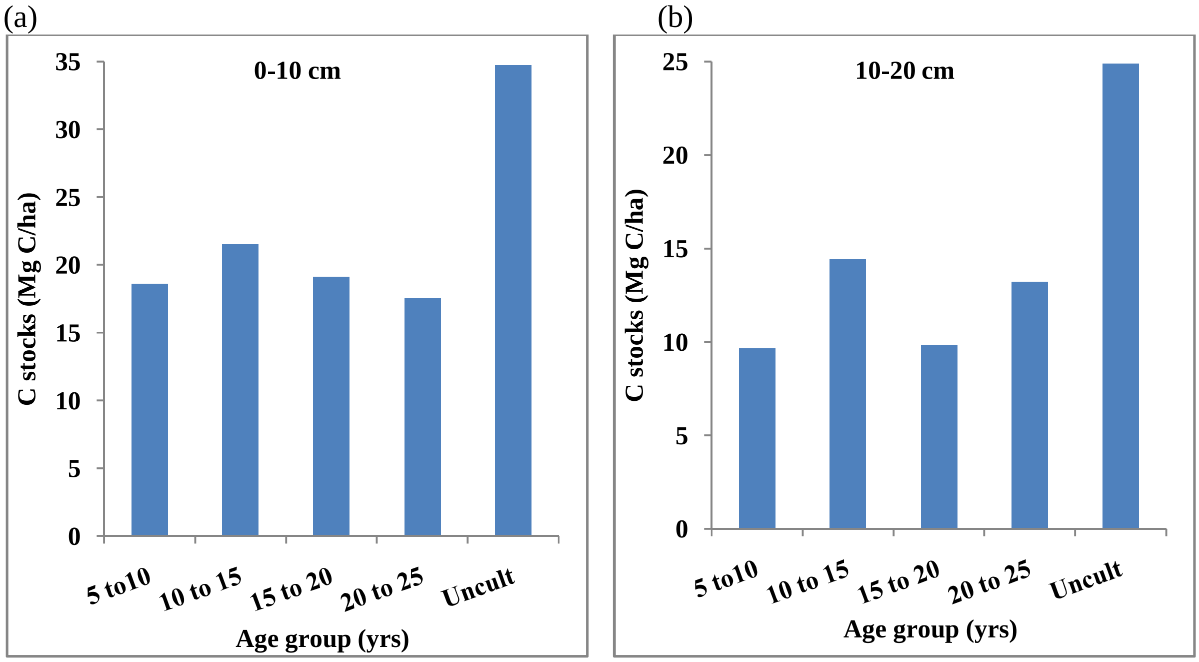

Fig. 5. 8 shows carbon stocks in the (a) 0-10 cm layer and (b) 10-20 cm layer under alleys for the different age groups.

Management actions taken may most likely affect stocks in the 0-10 cm layers as compared to the 10-20 cm layers as seen from the graph above. The potential of these soils in holding more C stocks might be limited due to intrinsic limitations imposed by climatic factors (Ingram and Fernandes, 2001). Below the 20 cm layer it would be a bit difficult to tell how management (heaping of pruned frond) would affect C stocks but for stocks in the surface layers (0-10 and 10-20 cm) the management system can be seen as being the main factor affecting stocks. This is evident from the results obtained under prunnings for the 20-25 years group when compared with that of the cultivated site where the difference between the two was just 0.3 Mg C/ha.

5.5 C saturation deficit (Csatdef)

Based on the Csatdef, the higher the index the more OC is needed to sequester C. The results of the present study seem to suggest that the soil under the prunnings for 20-25 years would require less organic matter for the 0-10 cm layer than the soil under young oil palm plantations to reach the OC level at the reference point. The 20.3 % obtained for the cultivated site has shown that although the soil had lost some C due to removal of vegetation, decomposition of litter and in some cases through burning, good management practices could restore such a soil to its equilibrium or even beyond.

The results in Tables 4.4 and 4.6 showed Csatdef but in order to have an idea as to how much has been accumulated with time, the C saturation was calculated. This was done by subtracting the Csatdef from 100 (the uncultivated). The C saturation that had taken place in the soils under prunnings and alleys with time relative to the reference are presented in Figs. 5.9 and 5.10 below.

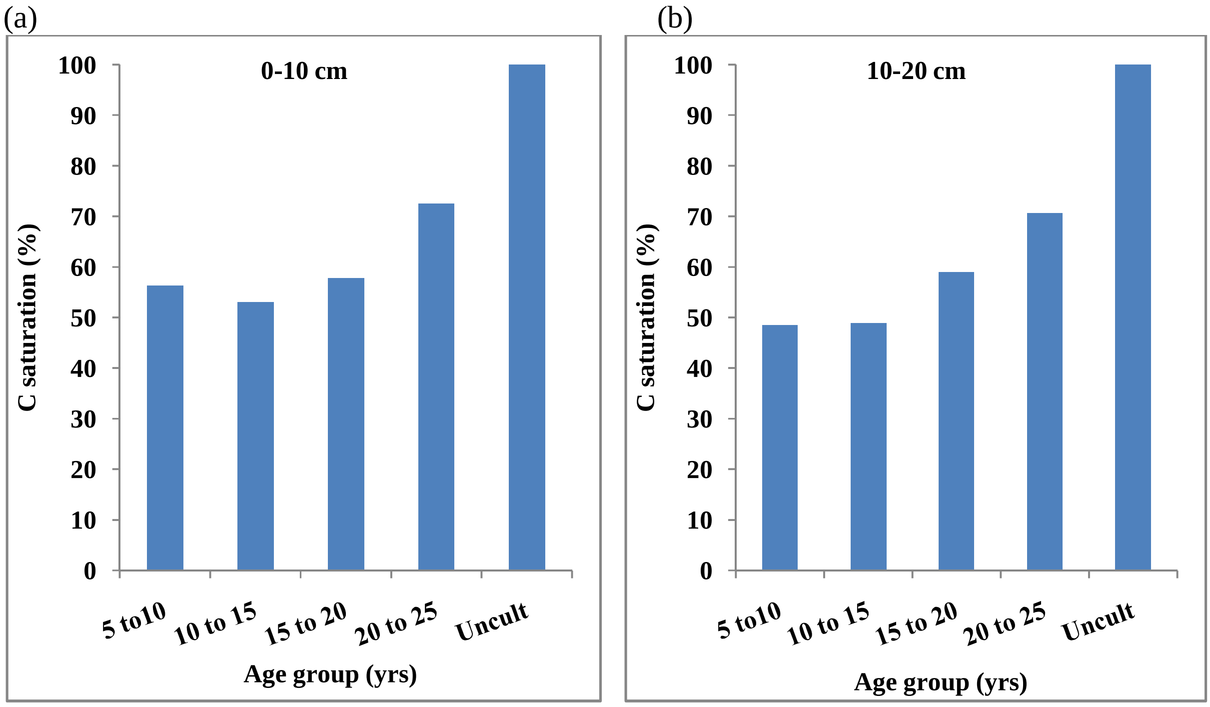

Fig. 5. 9 Carbon saturation in the (a) 0-10 cm layer and (b) 10-20 cm layer under prunnings for the different age groups.

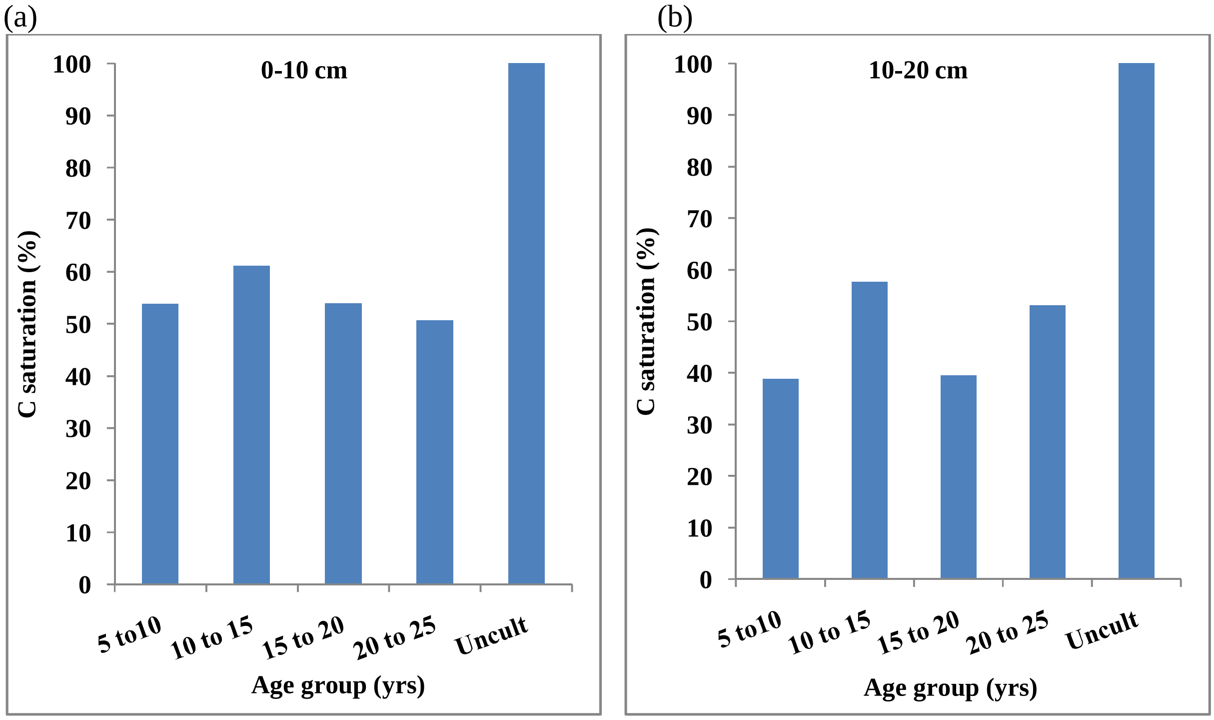

Fig. 5. 10 Carbon saturation in the (a) 0-10 cm layer and (b) 10-20 cm layer under alleys for the different age groups.

It can be seen that the presence of pruned materials influenced C stocks in the upper layer of soils under prunnings compared to the same layer under alleys. Although the difference in saturation appeared not to be so much it was significant. The lower layer under alleys appeared to be fluctuating whiles a steady increase was observed under prunnings with age. If bulk densities had remained constant under both cases then a significantly higher amount of C stock would have been noted under prunnings and this would have resulted in quite lower saturation deficits under prunnings than what is seen in Table 4.4.

In the end it is also imperative to note that the results under prunnings showed that some C was added to the soil with time under each plantation (Table 4.4). The additions observed in some cases might be small but it is possible that beyond the 25 year period, these soils could reach the control (uncultivated) or even go beyond it. Another important thing to note is that in addition to the annual increases in stocks under prunnings, some organic materials are still present on the farm that have still not either fully decomposed or are yet to undergo decomposition depending on the age of the plantation. The undecomposed materials serve as a means to trap and hold C and other gases (released via decomposition) which otherwise would have been emitted into the atmosphere contributing to greenhouse gases that play a key role in global climate change issues.

From the discussions so far prunnings have improved the soil physical properties particularly bulk density and have also provided enough C on top of the soil with age of the plantation. From an environmental point of view, the holding of C in organic resources serves as a means to sequester C emitted into the atmosphere (Paustian et al., 1998a) to affect global climate change.

5.6 Carbon dynamics and increments

The carbon dynamics in soils under pruned branches showed a gradual increase in C even though there was a slight decline at age 10-15 years. Between age groups 10-15 and 15-20 years there was an increase of about 6 Mg/ha of C and a further addition of 8 Mg/ha of C to the previous to get to 12 Mg C/ha as shown in the results in Table 4.5.

A loss of about 0.04 in OC was observed annually between the 5-10 and 10-20 years groups when average increments were calculated. This could be attributed to losses from the upper to the lower layer during heavy rainfall in addition to that lost through surface run-off. Beyond the 10-15 years there were increases in C storage as a result of increases in the accumulation of the heaped prunnings. This is reflected by the large C storage at 20 - 25 years. If further increases take place with age, it is possible that soils under pruned branches could reach C equilibrium level of the reference soil.

Under alleys there was an addition of about 7 Mg C/ha to that of 10-15 years age group. However, there was a sharp decline beyond 20 years of 5.2 Mg C/ha which could be attributed to losses by runoff or use of C as dissolved organic carbon by oil palm and undergrowth species. The relatively higher C values in some instances under alleys could also be due to contributions from the undergrowth species when they are cut and allowed to decompose.

Average increment per year in soils under alleys was gradual with age but decreased towards the 20-25 years period. The rate of decline observed between the 15-20 and 20-25 years was 1.04 Mg C/yr. If this rate of loss should continue then oil palm production would be affected especially in systems where external inputs in the form of fertiliser are absent. From field observations, oil palms trees in the relatively younger plantations had higher and better yields than the older ones which could be due to different nutrient content in addition to OM quantities.

CHAPTER SIX

SUMMARY, CONCLUSION AND RECOMMENDATION

6.1 Summary

The removal of forest cover for oil palm has raised concerns especially in the wake of issues and discussions revolving around climate change and its associated effects. Arguments have been advanced to the effect that oil palm does not have what it takes to contribute significantly to climate change mitigation since it is a high C emitter. This has been based on the fact that unlike other perennial cash crops litter fall under oil palm is not natural but comes about as result of management practices undertaken by farmers. The nature of the pruned materials do not make them suitable for use as mulch cover on the whole farm but are heaped at some areas on farms. In order to ascertain the validity of these claims and assumptions the objectives of this study were (1) to assess the differences in soil C content and stocks under already established oil palm plantations of different maturity ages; (2) to examine changes in soil C stocks over time under these oil palm plantations.

Oil palm plantations of different ages (5-10, 10-15, 15-20 and 20-25 years) were chosen based on similar land history. Sites selected were fairly located at the bottom slope on Oda soil Series (Aeric Endoaquent). On the same farm two different samples were taken; first under alleys; and secondly under pruned branches. A reference site (uncultivated) also located on Oda soil Series was selected from a forest reserve and used as a standard (control). In addition to this was the inclusion of a cultivated site with age 0-5 years to allow for investigations after forest removal and replacement with oil palm trees.

Particle size analyses showed that all soils were all of sandy loam texture. All soils were acidic with pH below 5.5, relatively low CEC and with low per cent base saturation. Bulk density values varied with age and depth. Soils under prunnings had relatively lower bulk densities than those under alleys. Nitrogen content was largely dependent on C content since it was derived from the mineralisation of OM which served as the main source of N supply in the absence of external input.

The C content determined showed that OC under alleys fairly decreased with age whiles that under prunnings increased with age. Against the uncultivated plot there were significant differences with the other soils. Carbon stocks calculated followed a similar pattern as C content. In order to determine the quality of the prunnings, C:N ratios were calculated. Quite high C:N ratios (>12) were seen in some soils under prunning especially in the initial years of heaping and in the cultivated soils. The C:N ratio under alleys were fairly below 12. The use of carbon saturation deficit gave an idea as to how much each soil needed to add in order to get to the current state of the uncultivated soil. Currently, none of the ages has been able to get to the target. The closest has been the 20-25 years group under prunnings indicating a positive feedback compared to the rest when pruned materials were added.

An examination of the forest floor revealed a lot of litter fall which had not been decomposed and this shows the ability of forests to store C for relatively longer time until deforestation takes place. Oil palm plantations have the ability to sequester C when residue materials in the form of pruned palm fronds are added to the soil.

6.2 Conclusion

The low C content and corresponding low N content of the soils are expected since tropical soils have been found to be low in organic matter. High temperatures promoted the rate of decomposition where nutrient release was faster than could be immediately absorbed and used by plants. These nutrients were at times subject to losses associated with high precipitation which is very typical of the study area.

Prunnings improved soil structure to the point that bulk density values in soils under heaps were relatively lower than their corresponding bulk densities under alleys on the same farm. The higher bulk densities under alleys could be attributed to human activities such as walking during harvesting among other farm activities and partly to the low C content of the soils.

Oil palm does well when intercropped with other annual and perennial crops such as maize, plantain, cassava, cocoyam, etc until full canopy cover sets in later at about 10 years.

From sequestration point of view, materials with high C:N ratios are good since they would persist longer in soil and so contribute to C storage. The basic criteria for increasing soil organic C is that the amount of C added in residues, including plant roots, exceeds the amount of C lost in decomposition. Thus quantifying the effects of individual management practices such as prunning and heaping of fronds and their combinations on C sequestration is vital for improving the potential of farming systems to sequester C.

The practical implications of this research would be to encourage prunning and heaping of palm fronds within rows of palm trees at well designated spots continually. This action would not only provide nutrients to the crops but would with time contribute to building C levels in the soils in addition to the pruned materials that would remain on top of the soil.

6.3 Recommendations

Similar studies under other plantation crops in Ghana could be carried out.

After 20 years the carbon saturation deficit is improved. There is the need to investigate what can be done to improve decomposition of palm residue to enhance the fertility of the mineral soil. This may require determining the standard height for heaping or the need for external additions in the form of fertilisers to improve decomposition.

In order to be sure of the amount of nutrient contained in oil palm pruned branches, total nutrient analyses should be carried out to determine the various nutrient elements present and their proportions.

There is also the need to quantify CO_2 emissions under various oil palm plantations as a means to ascertain C additions and losses under oil palm plantations.

From the fertility point of view, research could be conducted on how to effectively use pruned branches to prepare compost which could later be applied as fertiliser in rings around the oil palm trees. To enhance soil fertility and speed up nutrient release there should be a way to get water to the soil under the heaps if heaping would be continued. This is necessary since irrigation water in the form of rain does not percolate through the heaps to the lower layers but trickle off from the sides unto the ground creating dry and warm conditions underneath.

Research could be undertaken to investigate the contribution of different leguminous crop species to C buildup under oil palm. This would be very necessary as Ghana seeks to expand its oil palm industry which has the potential of affecting existing forests and other vegetations.

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APPENDICES

Appendix A: Summary information of selected sites

Plot number	Age (yrs)	Depth (cm)	Longitude	Latitude
3	0-5	0-10	06° 03, 828′	000° 51, 791′
		10-20		
2		0-10	06° 01, 502′	000° 51, 898′
		10-20		
1		0-10	06° 13, 930′	000° 55, 691′
		10-20		
6	5-10	0-10	06° 06, 295′	000° 51, 257′
		10-20		
5		0-10	06° 03, 313′	000° 52, 217′
		10-20		
4		0-10	06° 13, 947′	000° 55, 675′
		10-20		
9	10-15	0-10	06° 03, 471′	000° 51, 321′
		10-20		
7		0-10	06° 14, 016′	000° 55, 791′
		10-20		
8		0-10	06° 02, 329′	000° 52, 057′
		10-20		
10	15-20	0-10	06° 14, 054′	000° 56, 555′
		10-20		
11		0-10	06° 02, 685′	000° 51, 301′
		10-20		
12		0-10	06° 04, 962′	000° 53, 195′
		10-20		
14	20-25	0-10	06° 14, 074′	000° 55, 694′
		10-20		
15		0-10	06° 12, 394′	000° 58, 160′
		10-20		
13		0-10	06° 03, 170′	000° 51, 664′
		10-20		
16	Uncult	0-10	06° 09, 328′	000° 55, 333′
		10-20		

Uncult: Forest reserve used as reference soil

Appendix B:

Analysis of variance (ANOVA) tables

B1: Summary of ANOVA for Calcium (cmol$_c$/kg) of soil under prunning in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	0.66667	0.22222	11.11	0.003
Residual	8	0.16000	0.02000		
Total	11	0.82667			

SE: 0.14 Lsd: 0.27 %CV: 8.5 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25	3	1.8667	A
10 to 15	3	1.8000	A
15 to 20	3	1.7333	A
5 to 10	3	1.2667	B

Means that do not share a letter are significantly different.

B2: Summary of ANOVA for Bulk Density (Mg/m^3) between 0-10 and 10-20 cm layers for each age group under alley

Age (yrs)	class*	means	lsd	cv (%)	α (%)
Cultivated	1	1.24±0.03 A	0.068	2.2	5
	2	1.48±0.03 B			
5-10	1	1.36±0.017 A	0.039	1.2	5
	2	1.49±0.017 B			
10-15	1	1.33±0.026 A	0.059	1.9	5
	2	1.44±0.026 B			
15-20	1	1.28±0.019 A	0.042	1.3	5
	2	1.51±0.019 B			
20-25	1	1.35±0.013 A	0.029	0.9	5
	2	1.52±0.013 B			
Uncultivated	1	1.36±0 A	0	0.0	5
	2	1.64±0 B			

*Classes: 1 = 0-10; 2 = 10-20 cm; Means without the same letter are significantly different

B3: Summary of ANOVA for Bulk Density (Mg/m^3) between 0-10 and 10-20 cm layers for each age group under pruned branches

Age (yrs)	class*	means	lsd	cv (%)	α (%)
5-10	1	1.34±0.02 A	0.045	1.4	5
	2	1.43±0.02 B			
10-15	1	1.21±0.013 A	0.030	1.0	5
	2	1.36±0.013 B			
15-20	1	1.18±0.015 A	0.034	1.2	5
	2	1.40±0.015 B			
20-25	1	1.15±0.018 A	0.040	1.4	5
	2	1.34±0.018 B			

*Classes: 1 = 0-10; 2 = 10-20 cm; Means without the same letter are significantly different

B4: Summary of ANOVA for Bulk Density (Mg/m^3) of soil under alleys in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	0.0123630	0.0041210	10.02	0.004
Residual	8	0.0032889	0.0004111		
Total	11	0.0156519			

SE: 0.020 Lsd: 0.038 %CV: 1.5 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
5 to 10	3	1.35667	A
20 t0 25	3	1.35111	A
10 to 15	3	1.33222	A
15 to 20	3	1.27556	B

Means that do not share a letter are significantly different.

B5: Summary of ANOVA for Bulk Density (Mg/m^3) under alleys in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	0.0116991	0.0038997	12.00	0.002
Residual	8	0.0026000	0.0003250		
Total	11	0.0142991			

SE: 0.018 Lsd: 0.034 %CV: 1.2 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25	3	1.52111	A
15 to 20	3	1.50778	A
5 to 10	3	1.48667	A
10 to 15	3	1.43889	B

Means that do not share a letter are significantly different.

B6: Summary of ANOVA for Bulk Density (Mg/m^3) of soil under prunning in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	0.0658546	0.0219515	129.55	<.001
Residual	8	0.0013556	0.0001694		
Total	11	0.0672102			

SE: 0.013 Lsd: 0.025 %CV: 1.1 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
5 to 10	3	1.34111	A
10 to 15	3	1.20778	B
15 to 20	3	1.18000	B
20 t0 25	3	1.14556	C

Means that do not share a letter are significantly different.

B7: Summary of ANOVA for Bulk Density (Mg/m^3) of soil under prunning in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	0.0148667	0.0049556	12.90	0.002
Residual	8	0.0030741	0.0003843		
Total	11	0.0179407			

SE: 0.020 Lsd: 0.037 %CV: 1.4 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
5 to 10	3	1.43444	A
15 to 20	3	1.40222	A B
10 to 15	3	1.36111	B C
20 t0 25	3	1.34444	C

Means that do not share a letter are significantly different.

B8: Summary of ANOVA for BD for soil under prunnings and alleys in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	7	0.1511847	0.0215978	74.40	<.001
Residual	16	0.0046444	0.0002903		
Total	23	0.1558292			

SE: 0.017 LSD: 0.029 %CV: 1.3 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
5 to 10b	3	1.35667	A
20 t0 25b	3	1.35111	A
5 to 10a	3	1.34111	A
10 to 15b	3	1.33222	A
15 to 20b	3	1.27556	B
10 to 15a	3	1.20778	C
15 to 20a	3	1.18000	C D
20 t0 25a	3	1.14556	D

Means that do not share a letter are significantly different.

B9: Summary of ANOVA for BD for soil under prunnings and alleys in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	7	0.0902884	0.0128983	36.37	<.001
Residual	16	0.0056741	0.0003546		
Total	23	0.0959625			

SE: 0.019 LSD: 0.033 %CV: 1.3 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25b	3	1.52111	A
15 to 20b	3	1.50778	A
5 to 10b	3	1.48667	A B
10 to 15b	3	1.43889	B C
5 to 10a	3	1.43444	B C
15 to 20a	3	1.40222	C D
10 to 15a	3	1.36111	D E
20 t0 25a	3	1.34444	E

Means that do not share a letter are significantly different.

B10: Summary of ANOVA for Soil Organic Carbon (g/kg) between 0-10 and 10-20 cm layers for each age group under alley

Age (yrs)	class*	means	lsd	cv (%)	α (%)
Cultivated	1	22.25±1.060 A	2.403	6.4	5
	2	10.96±1.060 B			
5-10	1	13.74±0.589 A	1.336	5.8	5
	2	6.49±0.589 B			
10-15	1	14.33±0.967 A	2.193	9.1	5
	2	6.83±0.967 B			
15-20	1	16.86±0.528 A	1.198	4.0	5
	2	9.52±0.528 B			
20-25	1	12.98±0.928 A	2.104	8.6	5
	2	8.68±0.928 B			
Uncultivated	1	25.54±0 A	0	0	5
	2	15.17±0 B			

*Classes: 1 = 0-10; 2 = 10-20 cm; Means without the same letter are significantly different

B11: Summary of ANOVA for Soil Organic Carbon (g/kg) between 0-10 and 10-20 cm layers for each age group under pruned branches

Age (yrs)	class*	means	lsd	cv (%)	α (%)
5-10	1	14.58±0.598 A	1.355	5.2	5
	2	8.42±0.598 B			
10-15	1	15.59±0.528 A	1.198	4.4	5
	2	8.68±0.528 B			
15-20	1	16.60±0.342 A	0.775	2.5	5
	2	10.79±0.342 B			
20-25	1	22.00±1.840 A	4.170	10.5	5
	2	13.06±1.840 B			

*Classes: 1 = 0-10; 2 = 10-20 cm; Means without the same letter are significantly different

B12: Summary of ANOVA for Soil Organic Carbon (g/kg) under alleys in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	25.4358	8.4786	11.17	0.003
Residual	8	6.0711	0.7589		
Total	11	31.5069			

SE: 0.871 Lsd: 1.640 %CV: 6.0 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
15 to 20	3	16.8567	A
10 to 15	3	14.3300	B
5 to 10	3	13.7400	B
20 t0 25	3	12.9767	B

Means that do not share a letter are significantly different.

B13: Summary of ANOVA for Soil Organic Carbon (g/kg) under alleys in 10-20cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	19.1465	6.3822	14.09	0.001
Residual	8	3.6247	0.4531		
Total	11	22.7712			

SE: 0.673 Lsd: 1.267 %CV: 8.5 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
15 to 20	3	9.5233	A
20 t0 25	3	8.6800	A
10 to 15	3	6.8267	B
5 to 10	3	6.4900	B

Means that do not share a letter are significantly different.

B14: Summary of ANOVA for Soil Organic Carbon (g/kg) under prunning in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	98.525	32.842	19.86	<.001
Residual	8	13.229	1.654		
Total	11	111.754			

SE: 1.286 Lsd: 2.421 %CV: 7.5 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25	3	22.000	A
15 to 20	3	16.603	B
10 to 15	3	15.593	B
5 to 10	3	14.580	B

Means that do not share a letter are significantly different.

B15: Summary of ANOVA for Soil Organic Carbon (g/kg) under prunning in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	42.0170	14.0057	33.73	<.001
Residual	8	3.3220	0.4152		
Total	11	45.3390			

SE: 0.644 Lsd: 1.213 %CV: 6.3 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25	3	13.0633	A
15 to 20	3	10.7867	B
10 to 15	3	8.6833	C
5 to 10	3	8.4200	C

Means that do not share a letter are significantly different.

B16: Summary of ANOVA for OC for soil under prunnings and alleys in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	7	168.297	24.042	19.93	<.001
Residual	16	19.300	1.206		
Total	23	187.597			

SE: 1.098 LSD: 1.901 %CV: 6.9 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25a	3	22.000	A
15 to 20b	3	16.857	B
15 to 20a	3	16.603	B C
10 to 15a	3	15.593	B C D
5 to 10a	3	14.580	B C D
10 to 15b	3	14.330	B C D
5 to 10b	3	13.740	C D
20 t0 25b	3	12.977	D

Means that do not share a letter are significantly different.

B17: Summary of ANOVA for OC for soil under prunnings and alleys in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	7	94.5339	13.5048	31.10	<.001
Residual	16	6.9467	0.4342		
Total	23	101.4806			

SE: 0.659 LSD: 1.141 %CV: 7.3 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25a	3	13.0633	A
15 to 20a	3	10.7867	B
15 to 20b	3	9.5233	B C
10 to 15a	3	8.6833	C D
20 t0 25b	3	8.6800	C D
5 to 10a	3	8.4200	C D
10 to 15b	3	6.8267	D E
5 to 10b	3	6.4900	E

Means that do not share a letter are significantly different.

B18: Summary of ANOVA for Soil Carbon Stocks (t/ha) between 0-10 and 10-20 cm layers for each age group under alley

Age (yrs)	class*	means	lsd	cv (%)	α (%)
Cultivated	1	27.67±1.419 A	3.218	6.5	5
	2	16.19±1.419 B			
5-10	1	18.63±0.625A	1.416	4.4	5
	2	9.65±0.625 B			
10-15	1	19.07±1.006 A	2.281	7.0	5
	2	9.82±1.006 B			
15-20	1	21.51±0.879 A	1.992	4.9	5
	2	14.36±0.879 B			
20-25	1	17.53±1.435 A	3.252	9.3	5
	2	13.22±1.435B			
Uncultivated	1	34.73±0 A	0	0	5
	2	24.88±0 B			

*Classes: 1 = 0-10; 2 = 10-20 cm; Means without the same letter are significantly different

B19: Summary of ANOVA for Soil Carbon Stocks (t/ha) between 0-10 and 10-20 cm layers for each age group under pruned branches

Age (yrs)	class*	means	lsd	cv (%)	α (%)
5-10	1	19.55±0.830 A	1.883	5.3	5
	2	12.08±0.830 B			
10-15	1	20.05±0.549 A	1.244	3.2	5
	2	14.68±0.549 B			
15-20	1	18.40±0.526 A	1.193	3.4	5
	2	12.17±0.526 B			
20-25	1	25.18±1.936 A	4.388	9.1	5
	2	17.56±1.936 B			

*Classes: 1 = 0-10; 2 = 10-20 cm; Means without the same letter are significantly different

B20: Summary of ANOVA for Soil Carbon Stocks (t/ha) under alleys in 0-10cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	25.3580	8.4527	8.72	0.007
Residual	8	7.7577	0.9697		
Total	11	33.1158			

SE: 0.986 Lsd: 1.854 %CV: 5.1 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
15 to 20	3	21.5066	A
10 to 15	3	19.0673	A B
5 to 10	3	18.6291	B
20 t0 25	3	17.5297	B

Means that do not share a letter are significantly different.

B21: Summary of ANOVA for Soil Carbon Stocks (t/ha) under alleys in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	51.378	17.126	14.94	0.001
Residual	8	9.172	1.147		
Total	11	60.550			

SE: 1.071 Lsd: 2.016 %CV: 9.1 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
15 to 20	3	14.362	A
20 t0 25	3	13.215	A
10 to 15	3	9.816	B
5 to 10	3	9.648	B

Means that do not share a letter are significantly different.

B22: Summary of ANOVA for Soil Carbon Stocks (t/ha) under prunning in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	81.129	27.043	15.92	<.001
Residual	8	13.593	1.699		
Total	11	94.722			

SE: 1.303 Lsd: 2.454 %CV: 6.3 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25	3	25.176	A
10 to 15	3	20.055	B
5 to 10	3	19.553	B
15 to 20	3	18.396	B

Means that do not share a letter are significantly different.

B23: Summary of ANOVA for Soil Carbon Stocks (t/ha) under prunning in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	60.3977	20.1326	24.91	<.001
Residual	8	6.4655	0.8082		
Total	11	66.8631			

SE: 0.899 Lsd: 1.693 %CV: 6.4 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25	3	17.5627	A
10 to 15	3	14.6831	B
15 to 20	3	12.1747	C
5 to 10	3	12.0758	C

Means that do not share a letter are significantly different.

B24: Summary of ANOVA for Soil Carbon Stocks (t/ha) between 0-10 cm layer under alley and 0-10 cm layer under prunning for 15 to 20 year period

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age15	1	14.7041	14.7041	17.51	0.014
Residual	4	3.3589	0.8397		
Total	5	18.0630			

SE: 0.916 Lsd: 2.077 %CV: 4.6 α= 0.05

Grouping Information Using Tukey Method

Age15	N	Mean	Grouping
15 to 20a	3	21.5268	A
15 to 20b	3	18.3959	B

Means that do not share a letter are significantly different.

B25: Summary of ANOVA for Soil Carbon Stocks (t/ha) between 10-20 cm layer under alley and 10-20 cm layer under prunning for 10 to 15 year period

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age10	1	35.192	35.192	31.42	0.005
Residual	4	4.480	1.120		
Total	5	39.671			

SE: 1.058 Lsd: 2.399 %CV: 8.6 α= 0.05

Grouping Information Using Tukey Method

Age10	N	Mean	Grouping
10 to 15b	3	14.669	A
10 to 15a	3	9.825	B

Means that do not share a letter are significantly different.

B26: Summary of ANOVA for Soil Carbon Stocks (t/ha) between 10-20 cm layer under alley and 10-20 cm layer under prunning for 15 to 20 year period

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age15	1	7.0443	7.0443	26.39	0.007
Residual	4	1.0677	0.2669		
Total	5	8.1120			

SE: 0.517 Lsd: 1.171 %CV: 3.9 α= 0.05

Grouping Information Using Tukey Method

Age15	N	Mean	Grouping
15 to 20a	3	14.3516	A
15 to 20b	3	12.1845	B

Means that do not share a letter are significantly different.

B27: Summary of ANOVA for C stock for soil under prunnings and alleys in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	7	122.073	17.439	13.07	<.001
Residual	16	21.351	1.334		
Total	23	143.423			

SE: 1.155 LSD: 1.999 %CV: 5.8 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25a	3	25.176	A
15 to 20b	3	21.507	B
10 to 15a	3	20.055	B C
5 to 10a	3	19.553	B C
10 to 15b	3	19.067	B C
5 to 10b	3	18.629	B C
15 to 20a	3	18.396	B C
20 t0 25b	3	17.530	C

Means that do not share a letter are significantly different.

B28: Summary of ANOVA for C STOCK for soil under prunnings and alleys in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	7	145.3035	20.7576	21.24	<.001
Residual	16	15.6379	0.9774		
Total	23	160.9414			

SE: 0.989 LSD: 1.711 %CV: 7.6 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25a	3	17.563	A
10 to 15a	3	14.683	B
15 to 20b	3	14.362	B
20 t0 25b	3	13.215	B
15 to 20a	3	12.175	B C
5 to 10a	3	12.076	B C
10 to 15b	3	9.816	C
5 to 10b	3	9.648	C

Means that do not share a letter are significantly different.

B29: Summary of ANOVA for soil Total Nitrogen (g/kg) between 0-10 and 10-20 cm layers for each age group under alley

Age (yrs)	class*	means	lsd	cv (%)	α (%)
Cultivated	1	1.90±0.20 A	0.454	15.6	5
	2	0.66±0.20 B			
5-10	1	1.34±0.159 A	0.361	15.7	5
	2	0.69±0.159 B			
10-15	1	1.61±0.182 A	0.414	14.8	5
	2	0.86±0.182 B			
15-20	1	1.60±0.159 A	0.361	13.1	5
	2	0.84±0.159 B			
20-25	1	1.36±0.247 A	0.561	22.4	5
	2	0.84±0.247 A			
Uncultivated	1	1.44±0 A	0	0	5
	2	0.53±0 B			

*Classes: 1 = 0-10; 2 = 10-20 cm; Means without the same letter are significantly different

B30: Summary of ANOVA for soil Total Nitrogen (g/kg) between 0-10 and 10-20 cm layers for each age group under pruned branches

Age (yrs)	class*	means	lsd	cv (%)	α (%)
5-10	1	1.19±0.0775 A	0.1756	8.6	5
	2	0.70±0.0775 B			
10-15	1	1.23±0.0516 A	0.1171	5.3	5
	2	0.72±0.0516 B			
15-20	1	1.32±0.0540 A	0.1224	4.7	5
	2	0.96±0.0540 B			
20-25	1	1.87±0.2088 A	0.4734	13.2	5
	2	1.30±0.2088 B			

*Classes: 1 = 0-10; 2 = 10-20 cm; Means without the same letter are significantly different

B31: Summary of ANOVA for Total N for soil under prunnings in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	0.899200	0.299733	70.39	<.001
Residual	8	0.034067	0.004258		
Total	11	0.933267			

SE: 0.0653 LSD: 0.1229 %CV: 4.7 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 to 25	3	1.87000	A
15 to 20	3	1.32333	B
10 to 15	3	1.23000	B
5 to 10	3	1.19000	B

Means that do not share a letter are significantly different.

B32: Summary of ANOVA for Total N for soil under prunnings in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	0.70683	0.23561	10.09	0.004
Residual	8	0.18673	0.02334		
Total	11	0.89357			

SE: 0.1528 LSD: 0.2877 %CV: 16.6 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 to 25	3	1.3033	A
15 to 20	3	0.9600	A B
10 to 15	3	0.7233	B
5 to 10	3	0.7000	B

Means that do not share a letter are significantly different.

B33: Summary of ANOVA for soil Carbon to Nitrogen ratio between 0-10 and 10-20 cm layers for cultivated and uncultivated soils

Age (yrs)	class*	means	lsd	cv (%)	α (%)
Cultivated	1	11.63±2.508 A	5.684	18.0	5
	2	16.23±2.508 A			
Uncultivated	1	17.80±0 A	0	0	5
	2	28.90±0 B			

*Classes: 1 = 0-10; 2 = 10-20 cm; Means without the same letter are significantly different

B34: Summary of ANOVA for Carbon saturation deficit in 0-10 cm layer under alley.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
age2	3	210.236	70.079	8.72	0.007
Residual	8	64.317	8.040		
Total	11	274.552			

SE: 2.835 Lsd: 5.339 %CV: 6.3 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25a	3	49.526	A
5 to 10a	3	46.360	A
10 to 15a	3	45.098	A B
15 to 20a	3	38.075	B

Means that do not share a letter are significantly different.

B35: Summary of ANOVA for Carbon saturation deficit in 10-20 cm layer under alley.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
age2	3	829.99	276.66	14.94	0.001
Residual	8	148.18	18.52		
Total	11	978.17			

SE: 4.304 Lsd: 8.103 %CV: 8.2 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25a	3	46.89	A
5 to 10a	3	61.22	B
10 to 15a	3	60.558	B
15 to 20a	3	42.28	A

Means that do not share a letter are significantly different.

B36: Summary of ANOVA for Carbon saturation deficit in 0-10 cm layer under pruned branches.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	672.62	224.21	15.92	<.001
Residual	8	112.69	14.09		
Total	11	785.31			

SE: 3.753 Lsd: 7.067 %CV: 9.4 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
15 to 20	3	47.032	A
5 to 10	3	43.701	A
10 to 15	3	42.255	A
20 t0 25	3	27.508	B

Means that do not share a letter are significantly different.

B37: Summary of ANOVA for Carbon saturation deficit in 10-20 cm layer under pruned branches.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	3	975.71	325.24	24.91	<.001
Residual	8	104.45	13.06		
Total	11	1080.15			

SE: 3.613 Lsd: 6.803 %CV: 8.4 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
5 to 10	3	51.464	A
15 to 20	3	51.066	A
10 to 15	3	40.984	B
20 t0 25	3	29.410	C

Means that do not share a letter are significantly different.

B38: Summary of ANOVA for C saturation deficit for soil under prunnings and alleys in 0-10 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	7	1012.07	144.58	13.07	<.001
Residual	16	177.01	11.06		
Total	23	1189.08			

SE: 3.326 LSD: 5.757 %CV: 7.8 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
20 t0 25b	3	49.526	A
15 to 20a	3	47.032	A B
5 to 10b	3	46.360	A B
10 to 15b	3	45.098	A B
5 to 10a	3	43.701	A B
10 to 15a	3	42.255	A B
15 to 20b	3	38.075	B
20 t0 25a	3	27.508	C

Means that do not share a letter are significantly different.

B39: Summary of ANOVA for C saturation deficit for soil under prunnings and alleys in 10-20 cm layer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Age	7	2347.34	335.33	21.24	<.001
Residual	16	252.63	15.79		
Total	23	2599.96			

SE: 3.974 LSD: 6.878 %CV: 8.3 α= 0.05

Grouping Information Using Tukey Method

Age	N	Mean	Grouping
5 to 10b	3	61.220	A
10 to 15b	3	60.548	A
5 to 10a	3	51.464	A B
15 to 20a	3	51.066	A B
20 t0 25b	3	46.886	B
15 to 20b	3	42.275	B
10 to 15a	3	40.984	B
20 t0 25a	3	29.410	C

Means that do not share a letter are significantly different.

Appendix C

Questionnaire

1. Is this the first time oil palm is being planted on this land?
   Yes ☐ No ☐
2. Has the land been previously cultivated for any other crop apart from oil palm?
   Yes ☐ No ☐
3. Was it a fallow farmland?
   Yes ☐ No ☐
   If yes, can you tell how long?
   ………………………………………………………………………………………..........
4. Was it an abandoned farmland?
   Yes ☐ No ☐
   If yes, can you tell how long?
   ……………………………………………………………………………………………
5. Was it a virgin forest that was converted to oil palm or a logged off forest?
   Virgin forest ☐ logged off forest ☐
6. Where do you get seedlings from?
   ……………………………………………………………………………………………
7. How old do they reach before transplanting?
   …………………………………………………………………………………………....
8. When is transplanting normally done?
   ……………………………………………………………………………………………
9. Do you apply any form of fertiliser?
   Yes ☐ No ☐
   If yes, what type?
   ……………………………………………………………………………………………
10. Do you undertake weed control on your farm?
    Yes ☐ No ☐
11. How do you control weeds on your farm?
    Cultural ☐ Chemical ☐
12. When you prune, what do you do with the cut branches?
    ……………………………………………………………………………………………