Soil Carbon Stock Dynamics of Hedgerow Intercropping and Conventional Soil Management Practices on a *Ferric Acrisol* in the Semi-deciduous Forest Zone of Ghana.

BY

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SOIL CARBON STOCKS DYNAMICS OF HEDGEROW INTERCROPPING AND CONVENTIONAL SOIL MANAGEMENT PRACTICES ON A FERRIC ACRISOL IN THE SEMI-DECIDUOUS FOREST ZONE OF GHANA.

A Thesis submitted to the Department of Agroforestry, College of Agriculture and Natural Resources, Kwame Nkrumah University of Science and Technology, Kumasi, in partial fulfilment of the requirements for the degree of

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IN

AGROFORESTRY

BY

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M. Sc. Soil Management

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DECLARATION

I declare that I have personally, under supervision, undertaken the study herein submitted.

Eric Owusu Adjei

September, 2012

We declare that we have supervised the student in undertaking the study submitted herein and confirm that the student has our permission to present it for assessment.

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Study Supervisor

September, 2012

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Head of Agroforestry Department

September 2012

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"For the ground is holy,

Being even as it came from the creator

Keep it, guard it, care for it.

For it keeps men, guards men, cares for men.

Destroy it and man is destroyed".

Alan Paton, *cry the beloved country*

This study has been successful through the effort of several people who contributed in various ways. I however, need to mention some key personalities who have been instrumental in planning and executing this study.

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Finally, I dedicate this thesis to my Mother, Madam Rosina Nyarko for her special love. Thanks Mum!

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ABSTRACT

Soil carbon (C) *storage* on croplands has been described as a developmental strategy because the accumulation of soil C improves cropland productivity for the production of the needed food to feed the ever-increasing population of tropical Africa. The storage of C in the soil also reduces carbon dioxide (CO_2) build up in the atmosphere with its attendant global warming reduction and other environmental benefits. In addition the accumulation of C in the soil provides that land users are able to benefit from C trading under the Clean Development Mechanism (CDM) as C stocks become a commodity for trading on the international market. The overall objectives of this study were to monitor soil C dynamics under hedgerow intercropping and other conventional cropland management practices, monitor the corresponding effect of soil C build up on cropland fertility and productivity as well as cropland quality as measured using Carbon Management Index (CMI) over the study period. This study was based on six seasons of field investigation on the carbon sequestration potential of the different soil management practices for the continuous production of maize on a *Ferric acrisol* within the semi-deciduous forest zone of Ghana. The hedgerow species studied under hedgerow intercropping (also known as alley cropping) was *Gliricidia sepium*. The types of cropland management systems studied included: continuous cropping with no fertilizer application and plant biomass burnt at the start of every season (CCBB); Continuous cropping with no fertilizer application and plant residue mulch (CCBM); Continuous cropping with full rate inorganic fertilizer application and plant residue mulch (CCMF); Alley cropping with pruning and plant residue mulch & no inorganic fertilizer application (ACPM); Alley cropping with pruning and plant residue mulch & half rate fertilizer application (ACPf); Alley cropping with pruning and plant residue mulch & full rate fertilizer application (ACPF); Alley cropping with pruning removed & full rate fertilizer application (ACPR). Soil C sequestration rate of 4.02 Mg C ha^{-1} $year^{-1}$ was attainable under hedgerow intercropping adopted for continuous maize production on a *Ferric acrisol*, within the semi deciduous forest zone of Ghana. Highest soil C sequestration was recorded under hedgerow intercropping with no inorganic fertilizers application (ACPM). Higher doses of inorganic fertilizer application under hedgerows reduced soil C sequestration potential whilst under non-hedgerow conditions, inorganic fertilizer use improved soil C sequestration potential. Regular biomass burning and the removal of high quality *Gliricidia* pruning at the beginning of every cropping season depleted soil C stocks. In terms of cropland productivity improvement, six-season mean maize grain yield was highest at 5.30 Mg ha^{-1} on the fertilized non-hedgerow plot (CCMF) which was comparable to 5.20 Mg ha^{-1} obtained on the hedgerow plot with full rate inorganic fertilizer application (ACPF). Maize grain yield levels on the CCMF plot had however started to record significant decline by the end of the sixth season as compared to the levels recorded at the start of the study. In addition, the adoption of hedgerow intercropping was also able to reduce the inorganic fertilizer requirement by half for comparable and sustainable higher maize production of 5.00 Mg ha^{-1} in the semi deciduous zone of Ghana. Hedgerow intercropping improved long term maize yield even under reduced application of inorganic fertilizers thereby conserving energy resources and the environmental impact of agricultural production. The burning of plant residues at the beginning of every cropping season however reduced cropland productivity over the season. Hedgerow intercropping enhanced soil available P but reduced soil pH and exchangeable bases. Cropland quality assessed using CMI was highest under hedgerow intercropping with reduced inorganic fertilization whilst the other forms of hedgerow intercropping led to CMI reduction. The studied non-hedgerow plots however recorded high CMI levels which were expected to decline if the study has continued for a longer period. Cropland quality improvement recorded during the study was closely related to other known soil quality

indicators as MBC/SOC ratio and LC. Therefore, the adoption of hedgerow intercropping for continuous and sustainable maize production improved soil C sequestration, ensured sustainable maize production and enhanced cropland quality of a *Ferric acrisol* within the semi deciduous forest zone of Ghana.

CHAPTER 1. INTRODUCTION AND STUDY BACKGROUND

1.0 Introduction and study background

The increase in the earth's near surface air and oceans temperature, commonly referred to as Global Warming is brought about primarily by the increase in atmospheric concentration of Green House Gases (GHG) such as Carbon Dioxide (CO_2), Nitrous Oxide (N_2O) and Methane (CH_4). The Intergovernmental Panel on Climate Change (IPCC) has recognized that human activities including accelerated fossil fuel burning and deforestation lead to the continued increase of atmospheric CO_2 concentration (IPCC, 2007; Malhi et al., 2008) compounding the problem of global warming. Global warming has however been described as the most serious environmental issue affecting the survival of human lives on a global scale. It has been associated with adverse effects on the stability of earth's climate system, human health, and the sustainability of socio-economic systems (Vagen et al., 2005). A major approach that has been identified with the potential to address the challenge of global warming is the reduction of CO_2 concentration in the atmosphere through the capture of carbon (C) from the atmosphere and storing it in reservoirs such as the oceans, forest biomass and soils commonly referred to as C sequestration (IPCC, 1990; 2000). In this thesis, I have used the terms of C storage, C sequestration and C stocks in soil interchangeably with the understanding that they all describe the maintenance and improvement of C concentration in soils.

The concept of Soil C sequestration, therefore refers to the removal of atmospheric CO_2 by plants and storage of the fixed C as Soil Organic Matter (SOM) (Lal, 2004). Globally, the soil contains approximately 1,500 Pg C (1 Pg = 1 X 10^{15} g) and can be either a net source or a net sink of atmospheric CO_2 depending on land use. However, during the last 200 years, land use changes and unsustainable agricultural practices have made the soil act as a net source of atmospheric CO_2 through organic matter decomposition and soil erosion (IPCC, 2001). It has contributed to the continuing rise in atmospheric CO_2 concentration and its potential adverse effects. This was therefore the basis that motivated the world leaders in 1997 to adopt the Kyoto Protocol to reduce the current levels of CO_2 emission.

The Kyoto Protocol requires that developed countries with GHG reduction commitment cut down their current CO_2 emission levels by investing in mitigation projects in developing countries. In the 1997 global climate agreement, policies related to deforestation and land degradation were excluded due to the complexity of measurements and monitoring for the diverse ecosystems and land use changes. Later, the IPCC recognized the potential for soil C sequestration as a GHG mitigation option (IPCC, 2000).

At the Bali United Nations Framework Convention on Climate Change (UNFCCC), Conference of Parties (COP -13) meeting in 2007, an agreement was reached on "the urgent need to take further meaningful action to Reduce Emissions from Deforestation and Forest Degradation (REDD)". The deadline for reaching an agreement on the specifics of an international REDD mechanism, at least as regards to its implementation in the short and medium term, was set at COP-15, which was held in Copenhagen in December 2009 (Richards, 2009). Also in Copenhagen, the international community including major CO_2 emitters such as the United States and China pledged to cut global CO_2 emission by 11-19 per cent by 2020 (Dellink et al., 2010).

In line with the above treaties, opportunities have therefore been created that allow developing countries to also sell C sequestration credits to the developed countries to offset their CO_2 emissions. The trading in carbon credits is being done through the Clean Development Mechanism (CDM) under the UNFCCC (IPCC, 2000; 2004; Richards, 2009;

UNFCCC, 2009). These protocols therefore, provide for the need to establish C sequestration projects in the developing countries for C credits trading purposes.

Though this facility is available, little information on the potential of the different land-use systems as possible C sources or sinks exists (Post and Kwon, 2000). Also lacking is information on the potential of the vast stretch of tropical croplands as possible carbon sinks. Even though evidence from long term experiments suggest that soil management practices that minimise soil disturbance and optimises plant yield through fertilization can result in significant increase in the rate of carbon input into the soil (Lal, 2004), studies on sustainable soil management have not focused on this new opportunity to explore the potential and benefits of soil C sequestration on croplands.

In Ghana and also in most tropical regions of the world, farmers have over the years, adopted bush fallow systems aimed at utilising SOM and nutrients accumulated during fallow periods for the production of the needed food to feed the growing population. After few years of cultivation when the fertility status of the croplands have been depleted, the land is left to fallow to accumulate SOM for soil fertility regeneration (Nye and Greenland, 1960) and the farmer clears a more fertile land for crop production. However with the current increase in population resulting in more demand for croplands to produce more food to feed the population, leaving lands in fallow for a long period of time in order to regenerate the lost fertility has become impractical. Fallow periods have therefore shortened leading to continuous cropping of croplands.

Consequently, there is reduced cropland productivity as a result of continuous soil nutrient mining resulting in soil and environmental degradation as well as increased rural poverty

(Bonsu et al., 1999). Similarly, under the low input agricultural systems in the tropics, the effect of low cropland productivity coupled with the changing global climate has been described by Vagen et al. (2005) as the main cause of food insecurity, malnutrition, poverty, diseases, deforestation, soil and environmental degradation, drying of streams and river bodies as well as loss of biodiversity. It has therefore become imperative to search for sustainable land use practices to address the above challenges.

In order to address the problem of low cropland productivity, Scientists have, over the years, developed and promoted to farmers the application of inputs such as fertilizers, chemical control of pest and diseases and the use of irrigation. This conventional soil management approach has been successful in certain parts of the world but has encountered serious problems in the tropical regions. One of these problems is the high cost of fertilizers to large numbers of resource-poor farmers coupled with the subsequent requirement of higher rates of use that also leads to environmental problems. Also, yield response to fertilizers has continued to decline because of low SOM, soil physical degradation or micronutrients deficiency (Young, 1997; Vagen et al., 2005).

These current problems of agricultural land shortage and soil fertility management in the tropics have led to a new paradigm shift in addressing soil fertility management issues. The new paradigm encourages the reliance on enhancing SOM, biological activity and soil health. It focuses on optimising nutrient cycling to reduce external inputs and maximize the efficiency of their use. Finally, it also explores the use of the positive attributes of trees and plant residues in sustaining cropland productivity (Young, 1997; Lal, 2000a; Vagen et al., 2005).

The capacity of trees to grow under difficult climatic and degraded soil condition, coupled with their potential for soil conservation, gives agroforestry, the integration of trees into crop landscape, a high potential in improving soil fertility and productivity. Tree litter and pruning are able to substantially maintain SOM, improve soil physical properties and at the same time nutrient supply. There is also a known potential of agroforestry in enhancing water-use efficiency of croplands (Young, 1997; Abunyewa et al., 2004).

One agroforestry technology for which the tree component is spatially zoned is hedgerow intercropping; also called alley cropping. Under hedgerow intercropping, hedges of woody perennials are planted in parallel rows usually 4-10 m apart and crops are grown in the alleys between them. The hedges are regularly pruned and the pruning may be either removed, as fodder or fuelwood, or retained on the soil. The effect of the trees in hedgerow intercropping in maintaining SOM levels through the supply of litter and root residues are a major cause for soil fertility improvement (Kang et al., 1990).

Young (1997) has classified the effect of SOM on soil properties into three groups: effects on soil physical properties, nutrient availability and biological activity. It is argued that the role of SOM in the supply of plant nutrient is more significant under tropical conditions where soils contain highly weathered clay minerals dominated by Kaolinite as well as iron and aluminium oxide with about 10 $cmol_c$ kg^{-1} of Cation Exchange Capacity (CEC) (Theng, 1980). Soil organic matter therefore becomes the major source of plant nutrients for crop growth as decomposition proceeds and also helps improve the ability of the soil to retain nutrient cations against leeching (Sanchez and Logan, 1992).

Consequently, the amount and quality of SOM has therefore often been used as an indicator of soil quality and productivity (Davidson, 2000). Based on this principle, in most agricultural ecosystems, land use practices that aim at increasing SOM content are often seen as desirable strategies (Madder et al., 2002; Loveland and Webb, 2003; Lal, 2004). Enhancing SOM build up is therefore considered as a developmental strategy with high potential in Sub-saharan Africa (SSA) where soil degradation has been linked to low crop yield, food crises and overall impoverishment (Vagen et al., 2005). This capacity of increased SOM in raising the productivity of tropical croplands also provides a very effective solution and strategy in addressing land use challenges associated with global warming such as change in rainfall pattern and distribution, hot temperatures and other extreme weather events (Hazell and Wood, 2008; Lal, 2010).

Increased SOM on croplands also indicate that C is being sequestered in the soil medium instead of being emitted into the atmosphere in the form of CO_2. This is also the same strategy that ensures the sustainable use of croplands for food production which, eventually also reduces the need to convert more forestlands into croplands, that also leads to reduced emission of CO_2.

Unfortunately, knowledge on the C sequestration potential and the effect of increased soil C on tropical croplands quality and productivity is rudimentary. In this study, I propose to assess the potential of soil carbon sequestration in hedgerows intercropped with maize in the semi-deciduous forest zone of Ghana. I assume that efficient use of the biomass input from the pruning of the hedgerow species and maize stover plus the adoption of no-till could lead to the accumulation of SOM, improved soil quality and productivity compared to conventional soil management practices.

Study Objectives

The overall goal is to determine the effect of hedgerow intercropping and other conventional soil management practices on improving soil carbon over time by determining changes in:

i. Total soil organic carbon and mass (SOC_m) and its pools or fractions; microbial biomass carbon (MBC), labile carbon (LC) and non-labile carbon (non-LC)
ii. Maize yield and cropland productivity
iii. Carbon management index (CMI)

Study hypotheses

The study tested the following hypothesis:

Soil organic C build-up under hedgerow intercropping would not be significantly different from soil C build-up under conventional management practices and would not affect:

i. Total SOC and SOC_m, LC, non-LC and MBC;

ii. Maize yield and cropland productivity;

iii. CMI.

Thesis outline

Chapter 2 of this thesis reviews literature on prior research conducted on this topic and related literature. Chapter 3 compares the dynamics of total SOC and SOC_m, and the pools of MBC, LC and non LC, as affected by hedgerow intercropping and other conventional soil management practices over a three year period of continuous maize cultivation. Chapter 4 determines the effect improved soil carbon on cropland productivity and maize yield. Chapter 5 compares the changes in soil quality as affected by the adoption of hedgerow intercropping using the CMI as an index of soil quality. In chapter 6, information from earlier chapters is integrated to discuss the carbon sequestration potential of hedgerow intercropping.

In this thesis, I have used soil organic carbon (SOC) and soil organic matter (SOM) interchangeably with the understanding that SOC is only about 58 % of the SOM.

CHAPTER 2. LITERATURE REVIEW

2.0 Literature review

In this section, I explore the concept of the definition of soil carbon stocks build up, also referred to as C sequestration, and provide information on its potential and environmental services it provides for global well-being. I also review literature on the potential of soil and agroforestry systems as sinks for C sequestration. In addition, I review literature on the different soil organic carbon pools including soil microbial biomass carbon (MBC) and labile carbon (LC) as well as the measurement of these fractions as reliable indicators of SOC changes with time in response to soil management. Finally, I provide some information on the effect of improved SOM on sustainable land use.

2.1 The concept of soil carbon sequestration and global well being

Soil C sequestration refers to the removal of atmospheric CO_2 by plants and storage of the fixed C as soil organic matter. The underlying principle is to increase SOC content in the soil, improve depth distribution and stabilize SOC by encapsulating it within stable micro-aggregates so that C is protected from microbial processes or as stable C with long turnover time (Post and Kwon, 2000; Lal, 2004). This principle is however, based on the assumption that if soil management strategies are adopted that can promote sequestration, sequestration will continue until some steady condition (equilibrium concentration) is reached, as long as management strategies remain the same and weather conditions also remain similar (Hutchinson et al., 2007).

Globally, C storage in soils is the second largest in the biosphere (Lal, 2004), making the dynamics of SOC an important issue that must be understood if we are to fully comprehend global climate change. The soil is estimated to contain about 1500 Pg (1 Pg=10^{15} g = 1 billion tons) of C stored in the upper meter layer, most of which is found in the upper 0-20 cm of the soil. This is about three times the amount of 610 Pg C stored in the above ground biomass (including forests, savannas, grasslands, scrublands, tundra, desert, croplands and wetlands) and twice the amount of 770 Pg C as CO_2, in the atmosphere (Janzen, 2004). Lal (2001) even gives a higher estimate of Soil C as 2300 Pg C, made up of 1550 Pg SOC and 750 Pg Soil Inorganic Carbon (SIC). In principle however, the amount of C that can be sequestered at a site is a reflection of the long-term balance between C uptake and release mechanisms. This implies that the adoption of sustainable soil management practices that increase SOM such as conservation tillage, mulch farming, cover crops, agroforestry and fertilizer use is therefore an important instrument for soil C sequestration (Kuappi et al., 2001; Post and Kwon, 2000; Freibauer et al., 2004; Smith et al. 2000a; 2005).

In practice, the amount and quality of SOM is often used as an indicator of soil quality and productivity (Vieira et. al., 2007; De Bona et. al., 2008) and therefore in agricultural ecosystems, land use practices aimed at increasing SOM content is often seen as a desirable objective (Lal et al., 2004; Lal, 2010). However, as a result of human-induced land use change activities such as deforestation, biomass burning, conversion of natural to agricultural ecosystems, drainage of wetlands and soil cultivation, the soil emits CO_2 into the atmosphere. Consequently, the atmospheric concentration of CO_2 has increased by almost 31% since the industrial revolution from 280 ppmv in 1750 to 367 ppmv in 1999 from fossil fuel combustion and land use change. The global emission of carbon is estimated at 270 $\pm$ 30 Pg from fossil fuel combustion and 136 $\pm$ 55 Pg from land use change (IPCC, 2001).

It is the increase in atmospheric GHG and the attendant global warming, with severe consequences to mankind, that call for the identification of strategies to mitigate the threat of global warming with the current warming rate of $0.17^{o}C$ / decade (IPCC, 2001). The observed rate of increase of the global mean temperature is now in excess of the critical rate of 0.1^{o}C / decade beyond which the ecosystem cannot adjust (Lal, 2004).

The depletion of SOC pool has been identified to have contributed 78 $\pm$ 12 Pg C to the atmosphere. In some soils, the extent of depletion has reached one-half to two-thirds of the original SOC pool with a cumulative loss of 30-40 Mg C ha^{-1} (Mg = megagram = 10^6 g = 1 ton) every decade, as a result of soil degradation through poor landuse and soil management (Lal, 2004). This great loss of SOC pool therefore demonstrates the enormous potential of the soil to serve as a possible carbon sink. It is based on this principle that the sequestration of C in the soil has been identified by the IPCC as one of the main mitigation option for the rising concentration of GHG in the atmosphere (IPCC, 1990; 2000).

Agriculture and land-use change is estimated to contribute about 20% of the anthropogenic emissions of CO_2. When soil is converted from natural forest ecosystem into arable croplands, tropical soils lose about 50-75% of SOC within the first 20 years of conversion (Dumanski and Lal, 2004; Salinger, 2007). In addition, agricultural lands occupy larger portions of the global land area than any other human activity (Betts et al., 2007). There is therefore a great potential to regain some of the lost C by adopting best C sequestration practices on arable soils.

Moreover, because agricultural lands can be intensively managed by farmers, it is possible to control the release of these GHG to an extent that the land can be made to absorb more gases than they emit, by the adoption of recommended sustainable soil management practices for crops production (Lal, 2004; Naab et al., 2008).

The C sequestration potential of such improved land management techniques as agroforestry, has been shown to depend on the region specific interaction between climate, soil and management of resources (Janzen et al., 1999; Hutchinsom et al., 2007). It is estimated that if all best management practices were implemented, the C sequestration potential of US cropland could be about 24% of its commitment under the Kyoto Protocol, whilst Canadian soils can sequester 10% and China's soils sequester 47% of its annual fossil fuel emission. The European Union has C sequestration potential of about 90-129 Tg C year^{-1} whilst recent evidence from the humid tropics indicate that these regions have a considerable potential of soil C sequestration of as high as 50 Mg C ha^{-1} (Hutchinson et al., 2007).

A critical issue in the humid tropical region is that a sizeable part of the land mass remains under forest which is experiencing a high deforestation rate. Consequently the single most significant mitigation option is to reduce the pressure of converting a forested land to agriculture (Vagen et al., 2005). This can be achieved by improving the productivity of existing croplands by the adoption of improved management practices aimed at improving SOM upon which subsistence and low-input tropical agriculture is based. It is the same best management practices that will enhance C sequestration in soil that will also lead to greater net returns, reduced risk, more efficient energy use and often, improved environmental quality (Zentner et al., 2001)

In general, the global potential of soil C sequestration is estimated at 0.9 $\pm$ 0.3 Pg C year^{-1}. This amount is able to offset one-fourth to one third of the annual increase in atmospheric CO_2, which is estimated at 3.3 Pg C year^{-1}. In addition, enhancing the SOC pool would improve soil quality and agronomic/biomass productivity needed to meet the food demand of the growing population as an ancillary benefit of C sequestration. Furthermore, the adoption of the above soil management practices would lead to a 10-40% reduction of present agricultural energy requirement (Sauerbeck, 2001).

Therefore, C sequestration projects under the CDM have a dual mandate of reducing GHG emission and also contributing to sustainable development. For the industrialized countries, CDM offers a low cost emission credits whilst for the developing countries there is the hope that C sequestration will attract new and additional investment for sustainable development. For the subsistence farmers, there are two ways in which they can benefit from C sequestration projects. First of all, they would benefit from the gains in productivity associated with the adoption of C sequestration practices. Secondly they would also be compensated for the C they are able to sequester based on the quantity and the market price of C. Thus soil C sequestration is a win-win strategy (Hutchinson et al., 2007).

2.2 The potential of land management in soil C sequestration

A number of land management practices have been identified as having a great potential to increase C concentration in croplands. Hutchinson et al. (2007) identified land management practices including reducing tillage intensity and frequency, better crop residue management, efficient fertilizer use, and adopting agroforestry as having high potential for soil C sequestration on croplands. Post and Kwon (2000) and Lal (2004) also support this idea and termed such practices including mulch farming, reduced tillage, integrated nutrient management, integrated pest management, precision farming, as recommended management practices (RMP) for SOC improvement on croplands. They argued that with the adoption of such practices, tillage induced soil disturbances are eliminated, erosion losses are minimized, and large quantities of below and above ground biomass is returned to the soil.

The potential and benefits of these practices vary among geographical regions, antecedent level of SOC, soil taxonomy, soil texture and also climatic conditions (Hutchinson et al., 2007). It is however worth noting that most land users often adopt some of these practices in combination and their combined effect may or may not be additive.

In practice, the adoption of RMP conserves soil moisture and results in improved biodiversity which play very significant role in soil C dynamics (Young, 1997). Improved soil moisture associated with the adoption of no-till results in higher crop yield especially in the arid and semi arid regions and hence increase C input into soil. However, improved moisture is also believed to lead to rapid soil C decomposition thereby reducing SOC content. In contrast however, the presence of plant residue mulch under no-till coupled with lower soil temperatures and more limited soil aeration may lead to less soil C decomposition (Hutchinson et al., 2007).

With reference to soil biodiversity and its relationship with SOC and its dynamics, important members of soil biota including earthworms, termites, ants, some insect larvae and a few others of large soil animals are known to increase in numbers and activities with higher SOC. Activities of these animals have strong influence of soil physical and biological properties especially with regards to soil structure, porosity, aeration, water infiltration, nutrient cycling and organic matter pool and fluxes (Lal, 2004). The activity of soil biota also produces organic polymers which form and stabilize soil aggregates. Fungal hyphae and polysaccharides of microbial origin also play an important role in soil aggregation whilst earthworm and termites also positively impact on soil structure and enhance aggregation (Young, 1997).

In the following paragraphs, I present the potential of no-till and integrated nutrient management on soil C sequestration.

2.2.1 The potential of no-till on Soil C sequestration

It is universally acknowledge that soils of cropland can store more C when they are converted from conventionally tilled land management to no-till or conservation tillage (Lal, 2002). The reduced soil disturbance coupled with residue mulching have been shown to improve soil structure, lower bulk density and increase water infiltration capacity (Shaver et al., 2002; Lal, 2004; Hutchinson et al., 2007). However, these effects depend on soil clay content, and vary with soil zone and cropping frequency (Campbell et al., 2005). Hao et al. (2002) in their work also endorsed the role of no-till and concluded that the potential of conservation tillage to sequester SOC is greatly enhanced when soils are amended with organic manures.

Usually, the adoption of no-till is supported by the provision and judicious management of plant residue mulch. Holland and Coleman (1987) have reported a slower rate of surface litter decomposition due to the presence of higher fungal population in mulch litter as compared to the decomposer community present in soils. They argued that increased fungal decomposition may promote organic matter retention because fungi retain a higher proportion of metabolised C than bacteria. Moreover, fungal decomposition leads to the production of a more recalcitrant organic fraction than bacteria.

The adoption of no-till and its effect on SOC has been identified by many authors from many geographical regions such as Brazil, North America, Africa and Argentina, as having a great influence on soil C sequestration in both temperate and tropical conditions (Lal, 2002; Sa et al., 2001). Under semi-arid conditions of Canadian Prairies, Hutchinson et al. (2007)

reported that SOC gains under no-till were about 0.25 Mg C ha^{-1} $year^{-1}$ greater than for tilled systems regardless of cropping frequency, whilst under sub-humid environments on the prairies, the advantage was about 0.5 Mg C ha^{-1} $year^{-1}$ for rotations with fallow, but 0.25 Mg C ha^{-1} $year^{-1}$ with continuous cropping. Bruce et al. (1998) in their work on Canadian soils also have suggested the similar potential rate of 0.20 Mg C ha^{-1} $year^{-1}$ for all soil across Canada upon the conversion of agricultural land under no-till.

On European soils, Smith et al. (1998, 2000a,b) reported of the great potential of soil C sequestration under no-till. Smith et al. (1998) estimated that adoption of conservation tillage has the potential to sequester 23 Tg C $year^{-1}$ in the European Union or about 43 Tg C $year^{-1}$ in the wider Europe including the former Soviet Union. In addition to enhancing SOC pool, up to 3.2 Tg C $year^{-1}$ may also be saved in agricultural fossil fuel emission. They concluded that the 100% conversion to no-till agriculture could mitigate all fossil fuel C emission from agriculture in Europe.

Under a Savannah ecosystem in western Nigeria, Lal (2000a) reported a change of 16 and 20 Mg C ha^{-1} when maize was continuously cropped for three years under plow-till and no-till treatment respectively on an Alfisol. On cultivated soils of the Sub-Saharan African (SSA) region, Vagen (2005) reported attainable C sequestration in a range of 0.05-0.36 Mg C ha^{-1} $year^{-1}$ upon conversion from traditional cultivation techniques (with tillage) to no-till systems where a combination of animal manure and fertilizers were applied. This translates into a sequestration of 1.0-7.5 Tg C $year^{-1}$ on the total permanent cropland area of 20.9 million ha of the SSA region.

It is worth noting that no-till may also increase SOC at a given site by preventing soil erosion though this does not represent a net removal of C from the atmosphere but ultimately enhance soil quality and productivity associated with improved SOC (Hutchinson et al., 2007). In addition no-till is accompanied by a reduction in fossil fuel emissions because of reduced machinery and tractor use (Dyer and Desjardins, 2003).

2.2.2 Integrated nutrient management

The integrated nutrient management (INM) concept refers to the maintenance of soil fertility through the use of nutrients from all possible sources including: mineral fertilizers, animal manure, green manure, crop residue, biological nitrogen fixation, compost, city waste, sludge and household waste in an integrated manner (FAO, 1993). In general, many agricultural ecosystems are nutrient limited and therefore the addition of plant nutrients usually result in increased crop production. In relation to improving SOM in croplands, Gregorich et al. (2001) and Lal (2004) have observed that the use of organic manures and compost enhances the SOM more than application of the same amount of nutrients as inorganic fertilizers. They argue that the fertilizer effects on SOM are related to the amount of biomass C produced/returned to the soil and its humification. Gilley and Risse (2000) as well as Compton and Boone (2000) also observed similar effect and noted that the long term application of organic manure increased SOM and improved soil aggregation and this effect could persist for a century or longer.

Under European conditions, Smith and Powlson (2000) reported that only 54% of manure produced in Europe is applied to croplands. They estimate that if all manures were incorporated into arable land in the European Union, there will be a net sequestration of 6.8 Tg C $year^{-1}$, which is equivalent to 0.8% of the 1990 CO_2-C emission for the region.

In a study conducted in the Netherlands by Reijneveld et al. (2009), they observed that despite the farmers' perception about decreasing SOC on croplands in recent years, following the implementation of the manure policy, which restricts the use of animal manure and compost on croplands, SOC in croplands in the Netherlands is indeed increasing. Their study explored over 2 million digitally available SOC data from 9 regions in the Netherlands and concluded that despite the general decrease of SOC in agricultural lands in Europe (Bellamy et al., 2005; Sleutel et al., 2003), SOC in the Netherlands continues to increase due to the application of relatively large amount of animal manure, because of high livestock density (Oenema and Brentsen, 2004).

On the contribution of inorganic fertilization to SOC build-up, it is however important to consider that about 1 Kg C is emitted in the manufacture and transportation of 1 kg N fertilizer and must also be accounted for in any C balance. Nonetheless, in a long term experiment conducted in the Saskatchewan, Campbell et al. (2001) recorded significant increase in C sequestration even after allowing for the expenditures of C from fertilizer N manufacture and transportation. The general principle is that the application of inorganic fertilizers on cropland generally increases crop production thereby increasing above ground and below ground biomass input into such soils. This therefore is expected to enhance the potential of such soils to accumulate more organic carbon. In practice however, the long term observation of continuous inorganic fertilizer application has yielded some contrasting results especially in the tropical regions.

Within the tropical agro-ecosystems where farmers practice low input agriculture, the judicious and combined use of organic and inorganic nutrient sources has been suggested as a reliable means both to improve crop yields (Vanlauwe, et al., 2001; Kramer et al., 2002) and also to reduce SOC depletion (Vanlauwe et al., 2001; Bationo et al., 2007).

In a study conducted in Ghana by Yeboah et al. (2005) the application of 120 kg/ha N fertilizer for three cropping seasons of maize monocropping resulted in lower SOC. They attributed the reduced SOC to enhanced C mineralization associated with soil aggregates breakdown. Similarly, in a the same study, to understand the effect of plant residue quality on the formation of SOM pools and also how residue interact with inorganic fertilizers to affect the long term SOM dynamics, they observed that inorganic nitrogen fertilization decreased soil aggregate stability and the capacity of soil to stabilize SOM in soil aggregates.

The combination of grasses and legumes in rotation has also been observed to result in the production of large quantities of biomass of different quality with the potential of improving soil productivity and also enhanced SOC especially under no-till management conditions (Zentner et al., 2001; Yeboah et al., 2005). The contribution of legumes in rotation to cropland productivity is evident in the fact that legumes are also able to reduce inorganic fertilizer requirement thereby reducing the net fossil fuel requirements and the C cost of manufacturing N fertilizers (Zentner et al., 2001). Similarly, Tetteh (2004) studied the effect of applying plant residues of varying qualities on cropland productivity in the semi deciduous forest zone of Ghana. He attributed the enhancement in cropland productivity associated with the combined use of legumes with grasses to improvement on the enhanced synchronization of nutrients released from the mixture of plant residues to the uptake requirement of the planted crops.

2.3 Agroforestry and soil C sequestration

2.3.1. Definition and Concept

Agroforestry has been defined by many authors including Young (1997), Sanchez (2000) and Nair et al. (2008). Nair et al. (2008) refer to a practice of purposefully growing trees and crops, and/or animals in an interacting combination, for a variety of benefits and services. It has been described as an age-old practice, revived in the recent past with a renewed scientific interest to maintain the sustainability of agroecosystems (Batish et al., 2007). The classical definition by Young (1997) stated that "Agroforestry is a collective name for land-use systems in which woody perennials (trees, shrubs, etc.) are grown in association with herbaceous plants (crops, pastures) or livestock, in a spatial arrangement, a rotation, or both; there are usually both ecological and economic interactions between the trees and other components of the system".

The agroforestry concept is based on the premise that land-use systems that are structurally and functionally more complex than either crop or tree monocultures result in a greater efficiency of resource (nutrient, light, water) capture and utilization, and greater structural diversity that entail close nutrient cycling. While the above and below ground diversity provide more system stability, and resilience at the site level, the system provides connectivity with forests and other landscape features at the landscape and watershed level. Agroforestry is therefore recognized as an integrated applied science that has the potential to address many of the land management and environmental problems of the developing and developed countries (Nair, 2007; Nair et al., 2008).

2.3.2 Benefits of Agroforestry

Agroforestry systems have been shown to provide many benefits over traditional agriculture systems. In terms of improving soil productivity, several authors including Young (1997); Degrande and Duguma (2000); and Vagen et al. (2005) have all demonstrated that agroforestry has beneficial effect upon soil productivity and conservation and hence have the potential to reverse land degradation in the tropics. They suggested that the presence of trees improve the soil in the following several ways: The woody species are mostly fast growing leguminous trees that fix nitrogen and coppice vigorously to provide high quality plant biomass to fertilize the agricultural crops whilst the underground root systems also provide beneficial interaction to enhance the productivity of the crops. In addition, litter fall and fine root turnover increase SOM concentration.

In terms of weed and pest management, Agroforestry has been recognized to help reduce weed population through the effect of shading and litter cover, and also decrease insect attacks by providing a physical barrier to airborne pests and pathogens (Batish et al., 2007). Agroforestry also has been shown to help maintain water quality, reduce the levels of pollution and soil erosion. This occurs more effectively in riparian buffer zones by reducing runoff to rivers and streams. The adequate tree cover over soil also helps to increases the soil water holding capacity, reduce evaporation, and increase water infiltration (Degrande and Duguma, 2000).

Agroforestry has also been proven to offer a number of biodiversity conservation benefits by providing a protective tree cover within, or alongside fields thereby creating secondary habitat for species, reducing rate of conversion of primary habitats, and creating an acceptable transition zone between primary habitats (Batish et al., 2007).

Economically, agroforestry has been shown to help low income farmers to increase their income by providing valuable marketable products such as food they need to feed their families, while also having a source for a much needed export of timber, wood fiber, fuel, and medicine (Degrande and Duguma, 2000).

From the standpoint of SOM placement and build-up, agroforestry systems are known to affect the morphology and chemical composition of soil as a result of above and below ground tree litter inputs. The chemical and physical nature of leaf, bark, branch and roots alter decomposition and nutrient availability via controls on soil water and the soil fauna involved in litter breakdown. In addition, the extensive lateral root systems are able to scavenge soil nutrients from large volume of soil and redistribute them near soil surface beneath the tree canopies (Brown, 2002; Schroth et al., 2007).

Following the realization of the significant role of trees in the capture and storage of atmospheric CO_2 in vegetation, soil and biomass products, agroforestry has been recognized as a C sequestration activity under the afforestation and reforestation activities that have been approved as a GHG – mitigating strategy under the Kyoto Protocol (Malhi et al., 2008). Under agroforestry systems, there is the belief that tree incorporation in croplands and pastures would result in a greater net above ground as well as below ground C sequestration (Palm et al., 2004; Haile et al., 2008).

The estimates of C sequestration potential under agroforestry are therefore derived from combining the above ground values and the soil carbon values which also depend on factors such as climate, soil type and depth, previous and current land use, selection of species, level of soil disturbance as well as the initial size of SOC stock. This therefore makes quantifying changes in SOC content under agroforestry very complex (Szott et al., 1999; Paul et al., 2002).

It has therefore been suggested by Brown (2004) that agroforestry has the potential to reduce the hazards of soil erosion and desertification as well as to rehabilitate the over 1.9 billion ha of land that has been degraded due to erosion, salinization, fertility depletion, and advancing desert. It must however be noted that agroforestry is not without its downfalls, which include: shade, competition, allelopathy, harbouring of harmful pests, and threat from invasive potential of trees (Batish et al., 2007). In addition, Palm et al. (2004) list high start-up cost, credit limitations, cash flow limitations, and higher cost of labour as major limitations to the widespread adoption of agroforestry in the tropics.

2.3.3 Carbon Sequestration under Agroforestry

In the following paragraphs, I present some information on the potential of agroforestry in belowground C capture in tropical agro-ecosystems. In practice, most recorded values of the different agroforestry systems have been determined using different methodological approaches as well as soil C measured at different levels of soil depth. The result is that there are such variable soil C values reported in literature, ranging from as low as 1.25 Mg ha^{-1} to as high as 173 Mg ha^{-1} (Nair et al., 2009).

In a study under a silvopastorial system of *Acacia mangium* and *Arachis pintoi* in Costa Rica Amezquita et al. (2005) reported 173 Mg C ha^{-1} in the top 100 cm of soil under a 10-16 years old plot. In Togo, Dossa et al. (2008) reported soil C value of 97 Mg C ha^{-1} within the top 40 cm soil layer under a shaded coffee with *Albizia adianthifolia* system of about 13 years old whilst in Kenya, Impala Project (2001) reported SOC stock ranging from 2.6-3.7 Mg C ha^{-1} (0-20 cm) on a *Ferralsol.*

Under a 26 year old cocoa agroforests in Cameroon, Duguma et al. (2001) reported a mean C sequestration potential of 5.85 Mg C ha^{-1} yr^{-1} whilst in Mali, under the sahelian conditions of West Africa, a 35 year old parkland had a C sequestration potential of 1.09 Mg C ha^{-1} yr^{-1} (Takimoto et al., 2008b). In general, these values are similar to the attainable rate of soil C sequestration for the Sub-Saharan Africa region suggested by Vagen et al. (2005) in the range of 0.1-5.3 Mg C ha^{-1} yr^{-1} under agroforestry.

Other workers have however, observed no difference in SOC dynamics between agroforestry and other forms of soil management systems. Tornquist et al. (1999) after five years of establishing agroforestry systems on an unmanaged pasture sited on a *Haplic Acrisol* and *Dystic Fluvisol*, observed no difference in SOC in the agroforestry system and the pasture. The pasture soils even maintained relatively higher SOC status despite the fact that they received less organic matter input than the agroforestry systems. Lugo and Brown (1993) in their study also arrived at a similar conclusion and argued that grass root biomass and turnover may have had a greater role in SOC accumulation than surface inputs.

2.3.4 Carbon sequestration under hedgerow intercropping

Under hedgerow intercropping, a few examples of soil C sequestration potential have also been reported in literature. Under alley cropping conditions in Malawi, Makumba et al. (2007) reported a 123 Mg C ha^{-1} under a 10 year old *Gliricidia sepium* and maize alley plot within the top 200 cm soil depth whilst Lal (2005) reported under a five year old *Leucaena* alley plot in Western Nigeria, an amount of 13.6 Mg C ha^{-1} within the top 10 cm soil layer. In Costa Rica, Oelbermann et al. (2006) reported a 1.62 Mg C ha^{-1} within the 0-40 cm soil layer under a 19 year old alley cropping system of *Erythrina poeppigiana* and maize with *Phaseolus vulgaris*, all indicating the potential of hedgerow intercropping in maintaining higher levels of SOC under non hedgerow plots.

Similarly, under alley cropping conditions of both leguminous and non-leguminous trees, Mulongoy et al. (1993) observed SOC content of at least 46 % less under maize on non-hedgerow plot than on hedgerow plots. In this study, even the non-leguminous hedgerow tree were able to maintain similar levels of SOC as leguminous trees, ranging from 6,4 – 7,0 g Kg^{-1}, confirming the hypothesis that levels of SOM depended largely on both quality and quantity of plant materials as litter returned to the soil. Yamoah et al. (1986) reported that prunings of *Senna siamea*, a non-nitrogen fixing tree, maintained higher SOC levels than N-rich pruning of *Gliricidia sepium* and *Flemingia macrophylla*.

The application of inorganic fertilizers under hedgerow intercropping conditions has however resulted in variable effect on SOM build-up. Many authors including Kramer (2002); Yeboah et al. (2007); and Hutchinson et al. (2007) have observed that within the tropical agro-ecosystems where farmers practice low input agriculture, the judicious and combined use of organic and inorganic nutrient sources has the potential both to improve crop yields and also to reduce SOC depletion. On the contrary, many other authors including Vanlauwe et al. (2001); Bationo et al. (2007); Naab et al. (2008) and Fonte et al. (2009) have observed that the effect of inorganic fertilizer application even though could lead to improved biomass yield, may not necessarily lead to higher soil C sequestration. In a study conducted in Ghana by Fonte et al. (2009), the application of plant residues and 120 kg/ha N fertilizer for three cropping seasons on maize resulted in lower SOC. They attributed the reduced SOC to enhanced soil C mineralization associated with decreased soil aggregate stability and the capacity of soil to stabilize SOM in soil aggregates upon the application of inorganic fertilizers.

2.4 Soil organic matter and conceptual pools.

2.4.1 Definitions and Functions

Soil organic matter refers to all forms of SOC constituents consisting of intact plant and animal tissues, micro-organisms, dead roots and other detritus as well as humus. It is a very important component of soil and influences soil physical and chemical properties as well as provides an important store and source of plant nutrients (Young, 1997). The soil OM and its related soil properties have been described as the most acknowledged indicators of soil quality by Wander and Drinkwater (2000). On the global scale, the soil contains about 1500 Pg (1 Pg=10^{15} g = 1 billion tons) of C stored in the upper meter layer, most of which is found in the upper 20 cm of the soil. This is estimated to be about three times the amount of 610 Pg C stored in the above ground biomass and twice the amount of 770 Pg C as CO_2, which is a major green house gas, in the atmosphere (Janzen, 2004).

In terms of its functions, SOM serves numerous valuable on-site and off-site functions. The principal on-site functions described by Lal (2004) include: source and sink of principal plant nutrients (e.g., N, P, S, Zn, Mo); source of charge density and responsible for ion exchange; absorbent of water at low moisture potentials leading to increase plant available water capacity; promoter of soil aggregation that improve soil tilth; cause of high water infiltration capacity and reduced losses due to surface run off; substrate providing energy for soil biota leading to increase in soil biodiversity; source of strength for soil aggregates leading to reduction in susceptibility to erosion; cause for high nutrient and water use efficiency because of reduction in losses by drainage, evaporation and volatilization; buffer against sudden fluctuations in soil reaction (pH) due to application of agricultural chemicals; and moderator of soil temperature through its effect on soil colour and albedo. He also described the important off-site functions of SOC to include: reducing sediment load in stream and rivers; filtering of pollutants and agricultural chemicals; reactors for biodegradation of contaminants; and buffering the emission of GHGs from the soil to the atmosphere.

The role of SOM in sustaining cropland productivity has been reported in literature by many authors including Pan et al. (2009) who established the relationship that 1 % increase in SOM on average will lead to an increase in total cereal productivity of 0.43 Mg ha^{-1} and a decrease of yield variability against climatic disturbances by 3.5 %. Quantitatively, the effect of increased SOC in the root zone has been assessed by Lal, (2006) to influence agronomic production (kg grain ha^{-1} Mg C^{-1}) of various crops at the rate of 200-300 for maize, 30-60 for beans (*Phaseolis vulgaris*), 20-40 for wheat, 20-50 for soybean and 20-50 for rice. Similarly, Zentner et al. (2001) observed that improving cropland C could lead to greater net returns on inputs, reduced risk, more efficient energy use and often, environmental quality.

However, the nature of organic matter in soil is described as very complex and is allocated to different conceptual pools or fractions, which are differentially responsive to management and land-use practices. As a result, several authors have proposed different concepts / models of describing the different conceptual pools or fractions of SOM.

2.4.2 Conceptual Pools

Soil organic matter is described by Oades (1988) as a heterogeneous, dynamic substance that varies in C and N content, molecular structure, decomposition rate, and turnover time. Brady and Weil (1999) described SOM as consisting of intact plant and animal tissues, micro-organisms, dead roots and other recognizable plant residues (detritus) and also amorphous colloidal mixtures of highly decomposed materials no longer identifiable as tissues (humus). Several authors including Doran and Smith (1987) have conceptualized the existence of living and non-living SOM pools. They stated that the living pool constituted a small portion of the total SOM (1-8%) and included soil microorganisms and fauna. They described the living pool as a labile pool which functions as an important catalyst for transformations of C, N and other plant nutrients. The non-living pool was divided into active and inactive or new and old fractions. This pool constituted the major proportion of SOM and was described as important because it defined the physical environment within which soil organisms function and also confers stability to the soil ecosystem.

Young (1997) also described SOM as consisting of the active and stable fractions. He described the active fraction as not true humus but finely divided plant litter and the labile humus, which is fully decomposed soil humus. The active and labile humus fractions are responsive to soil management; whereas the stable fraction is stabilized soil humus remaining in the soil for decades. Other authors including Schimel et al. (1994) and Torn et al. (2005)

endorsed the concept of SOM consisting of different conceptual pools of varying decomposability and further suggested that SOM can be viewed as having an active labile pool of (mean residence time [MRT] approx. 1-2 years), a slow pool (MRT approx. 25 years) and a passive recalcitrant pool (MRT approx. 100-1000 years).

In terms of SOM dynamics, the protection of SOM from decomposition by silt and clay particles thereby enhancing the capacity of soil to sequester C has also been discussed by many authors including Ladd et al. (1985); Feller and Beare (1997); von Lutzow et al. (2006) and (2007). Similarly, other authors including Elliott and Coleman (1988) conceptualized that SOM is composed of a mineral-associated organic C (MOC) and a particulate organic C (POC) fraction. They further suggested that the POC can be subdivided into a free (POC_f), located between the soil aggregates and an occluded (POC_o) sub-fraction located within the soil aggregates. Based on this premise, they proposed that the POC_o fraction could be more protected against physico-chemical attack than the POC_f. The encapsulation of organic matter within soil aggregates, especially the micro-aggregates has also been suggested to provide greater protection against decomposition than those located outside the aggregates (Elliott and Coleman, 1988; Six et al., 2000).

It is however important to note that the amount of both labile and recalcitrant SOM are sensitive to land management, especially in agricultural systems which reduce inputs to SOM through removal of plant biomass. Tillage also decreases SOM through physical disturbance of soil structure which expose organic matter to oxidation by microbes and promotes erosion (Ding et al., 2002; McLauchlan and Hobbie, 2004).

2.4.3 Total Soil Organic Matter

In general, total SOM refers to all forms of SOC constituents. Under natural undisturbed forest ecosystems, SOM is at near steady state with annual input of detritus materials from below-and above-ground sources equal to annual respiration, but begins to decrease when natural ecosystems are converted to agricultural ecosystems (Vagen, 2005). Agricultural activities including forest clearance and burning, ploughing, drainage of wetlands and low input farming or shifting cultivation enhance SOM decomposition or soil respiration leading to the emission of CO_2 to the atmosphere (Schlesinger, 2000; Tiessen et al., 2001). It has been estimated that when soil is converted from natural forest ecosystem into arable croplands, temperate soils lose about 20-30% of the original SOC as CO_2 whilst tropical soils loose even larger proportion of about 50-75% within the first 20 years of conversion (Dumanski and Lal, 2004).

In practice, since SOM has no definite chemical composition, SOC which is the most dominant elemental constituent of SOM, is more commonly measured based on the understanding that SOC is 58% of the SOM (Weil et al., 2003). In the laboratory, total SOC can be readily determined by several methods including the wet acid dichromate oxidation method also known as the modified Walkley and Black procedure as described by Nelson and Sommers (1982); measuring the CO_2 released by dry combustion using the Laboratory Equipment Corporation (LECO) CHN Analyser and also monitoring the loss of mass on ignition (Magdoff, 1996).

2.4.4 Soil Labile Carbon and its dynamics

The soil labile C (LC), also referred to as the light fraction (LF) or the particulate organic carbon (POC), is basically constituted by partially decomposed plant, animal and fungal residues and therefore is referred to as being a labile fraction which is more sensitive to soil management regime than the total soil organic matter (Young, 1997; Torn et al., 2005)

Several workers have over the years developed protocols aimed at quantifying the LC fraction for early detection and accurate evaluation of the effect of land management on SOC dynamics based on the specific chemical or physical properties of the fractions. Schnitzer (1978) adopted the chemical separation method based on the solubility of organic fractions in different reagents such as water, acids, and bases. In the proposal of Blair et al. (1995) based on the susceptibility of organic fractions to oxidation, the LC fraction was considered as that oxidized with 333 mM $KMnO_4$. Recent studies by Weil et al. (2003) and Vieira et al. (2007) modified the $KMnO_4$ procedures and proposed the use of a much lower concentration of 20 - 60 mM. They observed that such lower concentrations were more sensitive to detect changes in C lability among some tropical soils as well as being more closely related to soil productivity and biologically mediated soil properties such as respiration, microbial biomass and aggregation.

Wiesenberg et al. (2004) adopted the macromolecular technique for estimation of proteins, polysaccharides and lipids whilst Smernik et al. (2000) adopted the “virtual fractionation” technique using solid state ^{13}C NMR spectroscopy to quantify LC. Others have proposed the use of particulate organic matter isolated through physical fractionation based either on density (Diekow et al., 2005; Vieira et al., 2007) or granulometric (Skjemstad et al., 2006) as the labile C fraction. All these procedures have been developed to assist scientists and researchers to predict or detect SOC change in an early stage as a result of land management change so as to make informed decision to reduce fertility decline, erosion, and GHG emission.

In a study by Dalal and Mayer (1986), it was observed that C losses were 11 times greater in the light fraction than the heavy fraction after conversion of virgin land into agriculture. Similarly, soil tillage has been shown to significantly affect the LC composition than the other stable fractions (Bayer et al., 2002; Friexo et al., 2002). Tillage reduces LC whilst cessation of tillage causes LC to increase (Six et al., 2000) and Balesdent et al. (2000) have also reported higher concentration of LC in no-till than in conventionally tilled soil because of the lower soil disturbance and SC decomposition rate due to no-till soil management.

The role of the LC in soil management is suggested to be directly related to soil quality because it plays a role to stabilize microaggregates (Six et al., 1999) and determines the soil microbial activity (Gregorich et al., 1994). It also indicates that physical protection of organic matter in stable aggregates is functioning and therefore decreasing SOM mineralization rates (Balesdent et al., 2000; De Bona et al., 2008). Soil aggregation also provides physical protection to LC from microbial decomposition and is at least partially responsible for the increase in LC with reduction in tillage (Six et al., 2000). Although LC inside aggregates is theoretically and chemically equivalent to unprotected LC, physical protection of LC confers a longer residence time. Soil aggregation therefore enhances the potential of soil to sequestration C.

2.4.5 Soil microbial biomass carbon

The soil microorganism population is described as the living components of SOM and form a component of the labile fraction of SOM. They are noted to be responsible for mineralisation of nutrients, decomposition and degradation or transformation of toxic compounds. In terms of its dynamics, soil microbial biomass is described as a useful early indicator of organic matter dynamics and soil development (Sparling and Ross, 1993; Wang et al., 2007). In addition, the proportion of microbial C in soil organic C (MBC/SOC) has been described as an index for monitoring soil development, changes under different cropping systems and land uses as well as soil degradation and recovery (Mandal, 2007; Wang et al., 2007).

The most frequently used procedures for determining microbial biomass carbon (MBC) include the chloroform fumigation and incubation (CFI) procedure and the chloroform fumigation and extraction (CFE) procedure (Vance et al., 1987). In recent times, the CFE has been the preferred procedure over the CFI because of the following advantages: no microbial mineralization stage is required; problems of selecting appropriate controls associated with the incubation method is avoided; CFE is applicable to soils of low moisture content; and is more accurate (Jenkinson et al., 2004).

The microbial biomass in soil comprises of a substantial pool of nutrients (Anderson and Domsch, 1980), which can be either a source or sink of plant nutrients, depending on the stage of growth (Duxbury et al., 1989, Mandal et al., 2007). It has been known to exert a key controlling influence on the rate at which N, C and other nutrients cycle through agricultural and other ecosystems (Jenkinson, 1988). The turn over time for N derived from microbial biomass is known to be 10 times faster than that returned in plant residue (Smith and Paul, 1990). Such fast rate of N transmission may play an important role in determining N flows in agricultural systems, determine the supply rates to crops under low input management and influence the availability of soil mineral N for uptake or loss in high fertilizer input systems (Lovell et al., 1994). Monitoring the size and turnover of microbial biomass is therefore useful to determine the effect of management on the SOM levels.

The size and activity of SOM has been described as directly related to the amount and quality of carbon and other nutrients available from plant residues, organic amendments and root exudates (Wang et al., 2007). Accordingly the application of organic manure and chemical fertilizers, have been shown to maintain or increase soil microbial biomass, thereby improving soil quality than that achieved with chemical fertilization alone (Graham et al., 2002; Mandal et al., 2007; Mabuhay et al., 2006). They attributed the general increase in MBC to the application of easily biodegradable organic materials, which stimulate microbial activity of the soil. Similar results were also found by Goyal et al. (2006) in a field experiment in Japan. They observed that the microbial biomass C and N increased significantly with the addition of organic manure along with inorganic fertilizers, as compared to unfertilized soil.

In terms of the ratio of soil MBC/SOC, Wang et al. (2007) reported the ratio of 1–5% for tropical soils and described it as an effective early warning of the improvement or deterioration of soil quality as a result of different management practices.

2.5 Carbon management index

In croplands, enhancing soil quality or its relative sustainability has been the desirable objective of land users. Several authors have therefore suggested different methods of assessing soil quality dynamics. Doran and Parkin (1994) suggested the evaluation of soil quality through the establishment and assessment of a minimum dataset (MDS) including soil properties such as bulk density, infiltration rate, total C and N content, pH, and electric conductivity. Other authors such as Gregorich et al. (1994) have however proposed the inclusion of SOM in the MDS not only as a single parameter but as an integrative attribute related to the soil properties.

Blair et al. (1995) in agreement with the previous authors proposed the use of carbon management index (CMI) to assess soil quality based on information related to SOC dynamics that recognizes the separation of total soil carbon into conceptual pools. They argued that in practice, the use of total SOC as an index of soil health and productivity is of limited value just as the use of total nutrient concentration in soils. The expression of soil quality using the CMI therefore compares increments in the total soil C (expressed by the carbon pool index - CPI) in proportion to labile soil C (expressed by the lability index - LI) to a reference soil under native vegetation as follows:

$$CMI = CPI \times LI \times 100 \qquad \text{Eqn. 1}$$

where the CPI represents the ratio between the total SOC concentration of the treatment plot and the total SOC concentration of the reference system; the LI represents the ratio between the C lability of the treatment plot and the C lability in the reference system; whilst the C lability is the ratio of the concentration of labile and non-labile C of individual plots.

The CMI concept therefore improves the soil productivity/sustainability assessment by comparing changes that occur in the total and also the rapidly changing labile C as a result of an agricultural practice. In this comparison, increased importance is even attached to the changes in the labile, as opposed to the non-labile component of SOM. The total SOC pool and the C lability directly influence soil physical, chemical and biological attributes as well as its self organization (Blair and Crooker, 2000). Therefore the integration of both total SOC pool and C lability into the CMI can provide a useful parameter to assess the capacity of a cropland management system to promote soil quality (Blair et al., 1995, 2006; Diekow et al., 2005; Vieira et al., 2007).

Carbon Management Index (CMI) has therefore been adopted and used as a more sensitive indicator of the rate of change of carbon in agricultural soils (Blair et al., 1997 and De Bona et al., 2008). It is therefore recommended for sustainability evaluation of a wider range of land management systems in different agro-ecological zones. The system with a higher value of CMI is considered as a measure of greater resilience (Blair et al., 1997).

Carbon Management Index determination

The CMI expresses soil quality in terms of changes in the total SOC content and in the proportion of labile C fraction compared to the same reference soil, generally under adjacent undisturbed natural vegetation, which is arbitrarily given a CMI of 100. When the objective is to compare a number of experimental treatments, Blair et al. (1997) suggested that one treatment can then be selected as a relative standard for all other treatment. They also suggested that there is no value of CMI that can be considered good or bad. The index only provides a measure of the rate of change of the system relative to a comparatively more stable reference area. Therefore, the objective of every land management should be to increase CMI and hence provide the system with greater resilience.

In his proposal for adoption of the CMI as a measure of soil quality, Blair et al. (1995) used 333 mM $KMnO_4$ treatment to predict the rapidly changing LC in a land-use system as discussed above. Vieira et al. (2007) however, used a lower concentration of 60 mM $KMnO_4$ and compared it with the 333 mM $KMnO_4$ as well as with physical fractionation based on density (NaI 1.8 Mg m^{-1}) and particle size separation (53 um mesh). They observed that the use of 60 mM $KMnO_4$ correlated strongly with the physical fractionation method based on density, especially in assessing the quality of tropical soils. Some other studies have also used POM isolated through physical fractionation based on density (Diekow et al., 2005) or the granulometric method (Skjemstad et al., 2006) to estimate the CMI.

It is worth noting that the principles of chemical oxidation and physical fractionation are different and the labile C determined by the two methods are also different. The main idea is that both methods provide a relative index of LC to assess the quality of a land use system.

In their study to evaluate the influence of no-till and irrigation on soil quality in tropical and subtropical regions, De Bona et al. (2008) observed that soil quality was improved with the adoption of no-till but not with the adoption of irrigation. They also found that LI was more sensitive than the CPI in reflecting the influence on management systems on soil quality as assessed using CMI. They however emphasized that the CMI should only be considered as a soil quality indicator and not as a general soil quality index, because several other aspects associated to the capacity of soil to function must be considered when assessing soil quality. They also suggested that in assessing the quality and sustainability of an agro-ecosystem, it would be reasonable to consider, for example, that irrigation could increase biomass production including food production.

In another study to evaluate the influence of long-term no-till and N fertilization on soil quality using the CMI, Vieira et al. (2007) observed that the introduction of legume cover crops or the application of fertilizer N improved the capacity of the management system to promote soil quality on a subtropical *Acrisol*. The sensitivity of CMI in this study was evident in the close correlation obtained with the physical, chemical and biological soil attributes that also served as indicators of soil quality.

2.6 Effect of soil organic matter on soil productivity

Over the years, many authors such as Madder et al. (2002); Loveland and Webb (2003) and Lal et al. (2004; 2010) have discussed the positive effect of SOM on soil productivity. These include: improved nutrient supply, enhanced CEC, better nutrient and moisture retention, Phosphorus availability and buffer against acidity. Brady and Weil (1999) however described the role of SOM on soil productivity in relation to the different SOM fractions/pools. They attributed the provision of readily available substrate for soil organisms and readily mineralizable nitrogen to the presence of active/labile pool of SOM. The labile pool has also been considered to be responsible for most of the beneficial effect of organic matter on soil structure such as: enhanced infiltration of water, resistance to erosion and ease of tillage. They described the passive/stable fraction as closely associate with the colloidal properties of soil humus that govern cation exchange capacity and water holding capacity of soils.

Lal (2010) elaborated the following relationship that exists between agronomic production and improved SOM pool under low input agriculture conditions. He indicates that enhanced

SOM positively affects the following soil productivity parameters such as: soil structure and aggregation, water retention, nutrient retention, biotic activity including the microbial biomass, erosion control, non-point source pollution abatement, sedimentation reduction and control of hypoxia, C sequestration, increase in use efficiency of inputs, increase in biomass production. It has therefore been proposed as a desirable objective to adopt land use practices aimed at increasing SOM content in agricultural ecosystems, (Madder et al., 2002; Loveland and Webb, 2003; Lal et al., 2004). Enhancing SOM is therefore considered as a developmental strategy with high potential in SSA where soil degradation has been linked to low crop yield, food crises and overall impoverishment (Vagen et al., 2005).

CHAPTER 3: DYNAMICS OF SOIL ORGANIC CARBON AND FRACTIONS UNDER HEDGEROW INTERCROPPING AND CONVENTIONAL SOIL MANAGEMENT PRACTICES

3.1 INTRODUCTION

Agriculture has been identified as one of the major sources of large quantities of green house gases (GHG) into the atmosphere accounting for 25% of CO_2, 50% of CH_4 and 70% of N_2O released to the atmosphere (Salinga, 2007) contributing to the warming of the earth's surface with severe consequences to mankind. Over the years, some tropical agricultural lands have lost over 75% of the SOC content to the atmosphere (Dumanski and Lal, 2004) as a result of deforestation and the adoption of unsustainable soil management practices. Consequently, this has led to loss of cropland productivity, malnutrition, poverty as well as soil and environmental degradation. However, because agricultural lands can be intensively managed by farmers, it is possible to control the emission of these GHG to an extent that the land can be made to conserve more gases (especially CO_2) than they emit through the adoption of recommended sustainable soil management practices for crop production (Lal, 2004; Naab, 2008). This is the underlying principle of soil C sequestration in croplands.

The potential for soil C sequestration as a GHG mitigation option has been recognized by the IPCC as significant (IPCC, 2000). For example, in the European Union, the potential for soil C sequestration in croplands is approximately 90-120 Tg C $year^{-1}$ whilst China has the potential of 105-198 Tg C $year^{-1}$. India's potential of 39-49 Tg C $year^{-1}$ is about 47% of current fossil fuel emissions whilst in the humid tropics of sub-Saharan Africa, the potential of soil C sequestration is about 50 Mg C ha^{-1}(Hutchinson et al., 2007). This potential of croplands to sequester C is enhanced by the adoption of recommended sustainable soil and crop management practices as reduced tillage, agroforestry and increasing residue input from higher yields into the soil whilst practices as biomass burning, deforestation and soil tillage deplete soil C (Lal., 2004; Hutchinson et al., 2007).

In addition to the GHG mitigation role of soil C sequestration, SOC is a very important natural resource that plays a major role in maintaining cropland productivity. Enhanced SOC on tropical croplands is known to improve soil quality and agronomic/biomass productivity needed to meet the food demand of the growing population. Furthermore, the adoption of the above soil management practices would lead to a 10-40% reduction of present agricultural energy requirement (Sauerbeck, 2001). Carbon sequestration is therefore described as a development strategy with high potential in SSA where soil degradation is related to low crop yield, food crises and overall impoverishment (Vagen et al., 2005).

To be able to realise such benefits of soil C sequestration in croplands in Ghana, it would be relevant to assess the dynamics and potential of soil C sequestration of the different soil management practices proposed by farmers in Ghana, compared to some of the recommended management practices including agroforestry. In practice however, the effectiveness of hedgerow intercropping adopted for the continuous production of maize, compared with the traditional soil management practices within Ghana's smallholder farming system has largely been assessed for their C sequestration potential (Lal, 2000b; Vagen et al., 2005).

A few authors including Fonte et al. (2009) and Naab et al. (2008) have monitored SOC dynamics in Ghana under different management practices including agroforestry in recent years. However, the evaluation of the impact of different levels of inorganic fertilization under hedgerow intercropping and also under conventional soil management for soil C sequestration assessment are scarce (Hutchinson et al., 2007). For example, Fonte et al. (2007) in their study focused on the role of biomass transfer from several organic sources including *Crotolaria juncea* and *Leucaena leucocephala* plus inorganic fertilization, in improving soil productivity and SOC dynamics. They observed that the quantity of plant residue, rather than residue quality, served as a major determinant in soil aggregation that could influence SOC. Their study however, did not monitor the presence of the hedgerow species on the same croplands, as occurs under hedgerow intercropping, with its attendant potential competition for nutrients and moisture on soil C and maize yield dynamics. Other studies have however proposed that organic resource quality might be important for controlling soil aggregation (Six et al., 2000)

This study was therefore established to monitor the dynamics of SOC and its fractions under hedgerow intercropping compared with other conventional soil management practices to assess the potential of the practices to sequester SOC on a *Ferric Acrisol* in the semi-deciduous forest zone of Ghana.

The specific objective was to assess the changes in total SOC, weight of SOC per unit area (SOC_m), LC, non-LC, MBC as well as MBC/SOC ratio within the 0-15 cm soil depth, as affected by hedgerow intercropping, compared with the conventional soil management practices over the six seasons of continuous maize cropping on a *Ferric Acrisol*.

The hypothesis tested was that hedgerow intercropping and the other conventional soil management practices used for the cultivation of maize have no effect of SOC, SOC_m, LC, non-LC and MBC as well as MBC/SOC ratio.

3.2 MATERIALS AND METHODS

3.2.1 General description and history of study site

The study was located at the Faculty of Renewable Natural Resources farm at the Kwame Nkrumah University of Science and Technology (KNUST) located at latitude 1°, 40/ North and longitudes 6°, 45/ West of the Greenwich meridian in the semi deciduous forest zone of Ghana.

Soil and climate

The soil of the study site belongs to *Asuansi series* classified by Adu, (1992) as *Ferric Acrisol* according to FAO (1990) or *Typic haplustult* according to USDA (1998). It occurs at the upper and middle slope sites of the Kumasi-Asuansi/Nta-Ofin Compound Association. This soil has been formed on a weathered granitic parent material with a moderately well drained moisture regime solum in the upper slope portion in the landscape. The area experiences a bimodal rainfall pattern with peaks in June and October, separated by a dry period from December to February. The mean annual rainfall ranges between 1300 and 1600 mm whilst the mean annual temperature ranges from 22 to 31^{o}C with an average of 26.6^{o}C (Adu, 1992).

Land use history

This study was superimposed on a fallowed Alley Farming Research Network for Africa (AFNETA) fallow management experiment established in 1990 but left to fallow from 1999 to 2005. The hedgerow species of *Gliricidia sepium,* (Jack) Walp were planted at 4 m between rows. Each plot had three rows of hedgerow species and measured 10 x 12 m.

The AFNETA experiment had the following objectives:

i. To explore the effect of short fallow on sustainability of agroforestry,

ii. To explore optimum rotation system in agroforestry which will integrate small ruminants,

iii. To provide information on management requirements on fallow management in alley farming.

The AFNETA experiment had the following treatments arranged in randomised complete block design with three replications:

1. Continuous cropping, no trees and no fertilizer application - (CCf)
2. Continuous cropping, no trees with fertilizer application - (CCF)
3. 2 years of continuous cropping, followed by 2 years fallow - (CC_2c)
4. 2 years alley cropping, followed by 2 years of unmanaged fallow (AC_2m)
5. 2 years alley cropping, followed by 2 years of managed fallow (AC_2M)
6. Continuous alley cropping with 50% pruning and 50% as feed (ACP_{50})
7. Continuous alley cropping with 100% pruning application - (ACP_{100})

3.2.2 Field Procedures of Current Study

Study treatment and experimental layout

The cropland management practices tested in the current study were:

1. Continuous cropping with no fertilizer application and plant biomass burnt (CCBB)
2. Continuous cropping with no fertilizer application and plant residue mulch (CCBM)
3. Continuous cropping with full rate fertilizer application and residue mulch (CCMF)
4. Alley cropping with pruning and plant residue mulch, and no fertilizer (ACPM)
5. Alley cropping with pruning and plant residue mulch, and half rate fertilizer (ACPf)
6. Alley cropping with pruning and plant residue mulch, and full rate fertilizer (ACPF)
7. Alley cropping, pruning removed but plant residue and full rate fertilizer applied (ACPR)

A Randomised Complete Block Design (RCBD) was used for the study was arranged in three replications.

Test Crop

Seed maize of variety *Mamaba* (Local name) was obtained from the Crops Research Institute of the Council for Scientific and Industrial Research (CSIR) and used as the test crop. Maize was planted during the major and minor seasons of 2005, 2006 and 2007 with spacing 80 x 40 cm planted at 3 seeds per hill and later thinned to 2 plants per hill to achieve a plant population of 62,500 ha^{-1}.

Inorganic fertilization

Inorganic fertilizer rate of $N\text{-}P_2O_5\text{-}K_2O$ kg ha^{-1}: 70-40-40, which is the recommended fertilizer rate for maize production in the ecological zone, was applied to the maize crop on the plots that received full rate fertilizer application. This generally amounts to 5 bags of 50 kg each NPK 15-15-15 and 2.5 bags Sulphate of Ammonia applied per ha. Fertilizer rate of N-P_2O_5-K_2O kg/ha 35-20-20 was applied to the maize crops on the plots that received half rate fertilizer application. All the required amount of NPK 15-15-15 fertilizers were applied to the maize plants at 2 weeks after planting whilst the sulphate of ammonia application was done at 6 weeks after planting.

Land Preparation

No-till land preparation was adopted for all plots. At the beginning of the study, the land was initially slashed with a cutlass, after which the following biomass management practices were assigned to the following plots: On the CCBB plot, all plant biomass were burnt after about 20 days of drying. This practice is similar to the traditional bush burning practice which is the most adopted method of land preparation for maize by most farmers in Ghana. On the remaining plots, the plant biomass was left to decompose as surface mulch. In addition, the hedgerow species were pruned at 30 cm from the ground with the pruning spread evenly on the plot also as surface mulch whilst the woody components were removed from the plots. On the ACPR plot, all hedgerow pruning were removed from the field at all pruning events.

During land preparation for the second and subsequent seasons, hedgerow pruning and maize stover were quantified and evenly spread on all the mulched plots as surface mulch. Maize seed was planted through the mulch at the beginning of each cropping season on all the mulched plots, whilst seeds were planted on a bare ground on the CCBB plot.

3.2.3 Soil Sampling and Laboratory Analyses

Field sampling

Bulk soil samples were taken at 0-15 and 15-30 cm soil depth from each plot for analyses before the treatments were imposed at the beginning of every cropping season from 2005 to 2007. During each sampling, a screw auger was used to collect soil samples from randomly located points across each plot. On the hedgerow plots, samples were collected in between the hedgerows and also within the hedgerows. Soil samples were bulked for each plot and placed in polythene bags, labelled and transported to the Soil Research Institute's laboratory for processing and analyses.

Soil investigations on the levels of SOC and its fractions were conducted at the following periods corresponding to the cropping seasons described as follows:

1. Major season of 2005 (Maj. 2005);
2. Minor season of 2005 (Min. 2005);
3. Major season of 2006 (Maj. 2006);
4. Minor season of 2006 (Min. 2006);
5. Major season of 2007 (Maj. 2007);
6. Minor season of 2007 (Min. 2007) and
7. Final level at the end study in 2008 (Fin. 2008)

Laboratory analyses

i. Total Soil Organic Carbon

Total Soil Organic Carbon (SOC) was determined by the modified Walkley and Black procedure as described by Nelson and Sommers (1982) for 0-15 cm and 15-30 cm soil depth. This is a procedure of wet combustion of the organic matter with a mixture of potassium dichromate and sulphuric acid. After the reaction, excess dichromate was titrated against ferrous sulphate.

One gram of soil was weighed into an Erlenmeyer flask. A reference sample and a blank were also included. Ten millilitres of 1.0 N (equivalent to 0.1667 M) potassium dichromate solution were added to the soil and the blank flask. To this, 20 ml of concentrated sulphuric acid was carefully added from a measuring cylinder, swirled and allowed to stand for 30 minutes in a fume cupboard. Distilled water (250 ml) and concentrated orthophosphuric acid (10.0 ml) were added and allowed to cool. One millilitre of diphenylamine indicator was added and titrated with 1.0 M ferrous sulphate solution.

<u>Calculation</u>

The percent organic C content of soil was calculated as follows:

$$\text{\% Organic C} = \frac{M * 0.39 * mcf\,(V_1 - V_2)}{s} \qquad \text{Eqn. 2}$$

where

M = molarity of ferrous sulphate solution

V_1 = ml ferrous sulphate solution required for a blank

V_2 = ml ferrous sulphate solution required for sample

s = weight of air dry sample in gram

mcf = moisture correcting factor (100 + % moisture) / 100

0.39 = 3 * 0.001 * 100 % * 1.3 (3 = equivalent weight of C)

1.3 = a compensation factor for the incomplete combustion of the organic matter

The % SOC value obtained was converted to SOC concentration expressed in kg C Mg^{-1} soil by multiplying the % SOC value by a factor 10.

Soil organic carbon mass

The total SOC concentration values were subsequently converted into mass (i.e. weight of SOC per unit area) expressed in Mg C ha^{-1} using soil depth, soil bulk density and weight of soil in 1 ha. The Soil Organic Carbon Mass (SOC_m) was therefore computed as:

$$SOC_m \text{ (Mg C ha}^{-1}\text{)} = \text{SOC (kg C Mg-1)} * BD * SD * 10\,000 \text{ m}^2 \text{ ha}^{-1} * 0.001 \text{ Mg kg}^{-1}. \quad \text{Eqn. 3}$$

Where: BD is soil bulk density (Mg m^3)

SD is soil depth (m)

0.001 is conversion factor for kg C Mg soil to Mg C ha^{-1}.

Soil Labile Carbon fraction separation

The total SOC pool was separated into labile and non-labile fractions using the chemical oxidation method earlier proposed by Blair et al. (1995) and modified by Weil et al. (2003).

Labile C was analysed for 0-15 cm soil depth by placing 1.0 g of air-dried soil samples into 100 mL capped plane shaking bottles (wrapped in aluminium foil to prevent photo-oxidation) and 20 ml of slightly alkaline 20 mM $KMnO_4$ solution was added. The suspension was horizontally shaken for 15 minutes at 200 cycles min^{-1} and centrifuged at 3000 cycles min^{-1} for 5 minutes to separate soil particles from solution. Thereafter, 0.02 ml of the clear supernatant solution was transferred to a glass cuvette tube, diluted with 10 ml of distilled water, and then it's absorbance at 550 nm light was measured with a spectrophotometer (SPECTRONIC 20 Genesys).

Absorbance readings were compared to a standard curve constructed using different concentrations of the $KMnO_4$ solution by the following equation for a straight line as described by Weil, (2003) as shown below.

$$\text{molarity} = a + b * \text{absorbance} \qquad \text{Eqn. 3}$$

(where a represents molarity at concentration 0, and b represent the slope)

The non-labile C concentration was obtained by the subtraction of the LC concentration from the total SOC concentration, using data from the 0-15 cm soil depth, as follows:

$$\text{Non-LC (kg C Mg}^{-1}\text{)} = \text{SOC (kg C Mg}^{-1}\text{)} - \text{LC (kg C Mg}^{-1}\text{)} \qquad \text{Eqn. 4}$$

Microbial biomass carbon analysis

The microbial biomass C concentration for the 0-15 cm soil depth was determined using the Chloroform Fumigation and Extraction (CFE) method as described by Ladd and Amato (1989). Two 10 g of field moist soil samples, after passing through a 4 mm mesh, were each put in a 50 ml beaker and placed in a large jar (1.0 L) with a small beaker containing 10 ml of chloroform. A soil sample without chloroform served as control. The jars were covered and allowed to stand at room temperature for 48 h. Immediately after fumigation, a 100 ml 0.5 M K_2SO_4 solution (Tate et al., 1988; Jeorgenson and Brooks, 1990) was used to extract microbial biomass carbon from the lysed microorganisms. The amount of microbial carbon in solution was determined after an aliquot of the extract had been evaporated to dryness. The dichromate oxidation method was used to determine microbial biomass carbon.

For microbial biomass carbon calculation, k-factors of 0.35 (Sparling et al., 1990) was used. The following equation was used to estimate microbial carbon and nitrogen from the extracted carbon:

$$\text{Microbial C } (\mu g) = Ec/k \qquad \text{Eqn. 5}$$

Where Ec = the extracted carbon following fumigation

K = the fraction of the killed biomass extracted as carbon or nitrogen under laboratory conditions

Proportion of microbial biomass carbon as total soil organic carbon

The proportion of MBC as total SOC (%) was computed using the data from SOC within the 0-15 soil depth as:

$$MBC/SOC = MBC\ (kg\ C\ Mg^{-1} soil)\ /\ SOC\ (kg\ C\ Mg^{-1} soil) * 100. \qquad \text{Eqn. 6}$$

3.2.4 Statistical Analyses

This study determined the effect of cropland management practice, season and soil depth (0-15 and 15-30 cm) for total SOC (kg C Mg^{-1}) only, and cropland management practice and season on SOC_m (Mg C ha^{-1}), LC (kg C Mg^{-1}), non-LC (kg C Mg^{-1}), MBC (kg C Mg^{-1}) and MBC/SOC ratio (0-15 cm) for the entire study period. Separate analysis of variance tests were done and significance of hypothesis for both main and interaction effects was set at probability level of less or equal to 0.05 ($p \leq 0.05$). Means were separated when ANOVA indicated significant differences at $p \leq 0.05$ using Tukey's test for means separation. The SAS software package was used. Described below are the effects tested and the statistical designs used:

Statistical designs

Cropland Management Practices

The effect of cropland management practices of CCBB, CCBM, CCMF, ACPM, ACPf, ACPM and ACPR were determined on mean SOC, SOC_m, LC, non-LC, MBC and MBC/SOC at 0-15 cm soil depth as a randomized complete block design.

Cropland management practice and seasons

The effect of cropland management practices of CCBB, CCBM, CCMF, ACPM, ACPf, ACPM and ACPR at 0-15 cm soil depth and seasons of Maj. 2005; Min. 2005; Maj. 2006; Min. 2006; Maj. 2007; Min. 2007; and Fin. 2008, and their interactions, was determined on SOC, SOC_m, LC, non-LC, MBC and MBC/SOC as a split plot in a randomised complete block design. Whole plot factors were the seven cropland management practices and sub-plot factors were the seven seasons.

Cropland management practice, soil depth and seasons

The effect of cropland management practices of CCBB, CCBM, CCMF, ACPM, ACPf, ACPM and ACPR; soil depth of 0-15 cm and 15-30 cm and seasons of Maj. 2005; Min. 2005; Maj. 2006; Min. 2006; Maj. 2007; Min. 2007; and Fin. 2008; and interactions, was determined on total SOC concentration as a split-split plot in a randomised complete block design. Whole plot factors were the seven treatments. Sub-plot factors were the two levels of soil depth whilst the sub-sub plot factors were the seven seasons.

3.3 RESULTS

3.3.1 Initial levels of soil organic carbon and its fractions

The levels of total SOC, SOC_m, LC, non-LC, MBC and MBC/SOC ratio varied ($p<0.05$) among the study plots at the start of the current study based on dominant vegetation during the six-year fallow period and also the management practices imposed during the nine years of AFNETA study (Table 3.1). In general hedgerow plots did not indicate any superior accumulation of total SOC and its variants except for LC and MBC/SOC ratio which recorded higher levels on hedgerow plots.

Total SOC of the study plots, ranged from 12.80 to 17.37 kg C Mg^{-1} soil within the 0-15 cm soil depth and 7.07 to 9.70 kg C Mg^{-1} soil within the 15-30 cm soil depth. The highest SOC ($p < 0.05$) was recorded on both non-hedgerow plot (CCMF) and hedgerow plots (ACPM) within the 0-15 cm and also the 15-30 cm soil depth.

The level of SOC_m ranged from 16.20 to 20.44 Mg C ha^{-1} within the 0-15 cm soil depth. Labile C and non-LC levels ranged from 0.70 to 1.72 kg C Mg^{-1} and from 12.32 to17.02 kg C Mg^{-1} respectively. Microbial biomass C ranged from 0.62 to 0.89 kg C Mg^{-1} whilst the proportion of MBC as SOC ranged from 3.47 to 7.13 %.

Table 3.1. Initial levels of total SOC, SOC_m, LC, non-LC, MBC and MBC/TOC ratio of the study plots

Cropland Management		SOC	SOC	SOC_m	LC	non-LC	MBC	MBC/TOC
Current Study	AFNETA Study	0-15 cm (kg C Mg^{-1})	15-30 cm (kg C Mg^{-1})	0-15 cm (Mg C ha^{-1})	0-15 cm (kg C Mg^{-1})	0-15 cm (kg C Mg^{-1})	0-15 cm (kg C Mg^{-1})	0-15 cm
CCBB	CCf	15.03bc	9.07a	18.75b	0.93cd	14.66bc	0.87a	5.83b
CCBM	CCF	15.33bc	7.87b	19.42ab	0.97cd	14.94bc	0.73ab	4.87c
CCMF	CC_2c	17.37a	9.70a	20.44a	0.87cd	17.02a	0.80ab	4.63c
ACPM	AC_2m	17.10ab	8.07a	19.27ab	1.43ab	16.53ab	0.62c	3.47d
ACPf	AC_2M	16.07b	9.63b	16.64c	0.70d	15.79ab	0.64c	4.00cd
ACPF	ACM_{50}	14.17cd	7.93b	16.42c	1.72a	13.48d	0.85a	6.00b
ACPR	ACM_{100}	12.80e	7.07c	16.20c	1.21bc	12.32d	0.89a	7.13a

where for the current study, CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch & no fertilizer; ACPf - alley cropping with pruning and plant residue mulch & half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch & full rate fertilizer; ACPR - alley cropping with pruning removed & full rate fertilizer;
and for the AFNETA study CCf represents continuous cropping, no trees and no fertilizer application; CCF - continuous cropping, no trees with fertilizer application; CC_2c - 2 years of continuous cropping followed by 2 years fallow; AC_2m - 2 years alley cropping, followed by 2 years of unmanaged fallow; AC_2M - 2 years alley cropping, followed by 2 years of managed fallow; ACM_{50} - Continuous alley cropping with 50% pruning and 50% as feed; ACP_{100} - Continuous alley cropping with 100% pruning application.
Columns means followed by different letters are significantly different at $p < 0.05$

3.3.2. Dynamics of soil organic carbon and its fractions

3.3.2.1. Effect of cropland management

Cropland management significantly influenced ($p < 0.05$) mean levels of total SOC, SOC_m, LC and non-LC; whilst mean MBC and MBC/SOC ratio were not affected ($p > 0.05$) during the study period (Table 3.2). Mean levels of SOC within the 0-15 cm soil depth ranged from 13.36 kg C Mg^{-1} soil on the CCBB plot to 17.36 kg C Mg^{-1} soil on the ACPM plot over the six seasons of continuous maize cultivation. Highest mean SOC ($p < 0.05$) was attained on both the non-fertilized, mulched hedgerow intercropping plot (ACPM) as well as on the fertilized and mulched non-hedgerow plot (CCMF). Similarly, highest level of SOC_m levels ($p < 0.05$) was attained on ACPM and CCMF plots with the mean SOC_m ranging from 17.62 kg C ha^{-1} on the ACPR plot to 22.62 kg C ha^{-1} on the ACPM plot (Table 3.3).

Labile C levels ranged from 0.87 kg C Mg^{-1} soil on the ACPR plot to 1.38 kg C Mg^{-1} soil on the CCMF plot and formed 6.5 – 10.2 % of SOC. Higher mean LC ($p < 0.05$) was also recorded on the fertilized and mulched hedgerow plots of ACPf and ACPF as well as on the mulched non-hedgerow (CCBM) plot within the 0-15 cm soil depth. The level of non-LC ranged from 12.99 kg C Mg^{-1} soil on the ACPR plot to 17.44 kg C Mg^{-1} soil on the ACPM plot (Table 3.3).

Table 3.2. Summary of p values of ANOVA results for the effects of cropland management practice, season, as well as cropland management practice and season interaction on total SOC, SOC_m, LC, non-LC, MBC, and MBC/SOC ratio.

Source[1]	Df	p-value						
		SOC 0-15 cm	SOC 15-30 cm	SOC_m 0-15 cm	LC 0-15 cm	non-LC 0-15 cm	MBC 0-15 cm	MBC/SOC 0-15 cm
Cropland Management	6	0.0001	0.0002	0.0001	0.02	0.0001	0.31	0.93
Season	6	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Cropland Management * Season	36	0.18	0.57	0.009	0.04	0.06	0.14	0.10

[1]Cropland management practice * season * soil depth interaction did not influence total SOC

Table 3.3. Means of total SOC, SOC_m, LC, non-LC, MBC, MBC/SOC ratio within 0-15 cm soil depth under the different cropland management practices of the current study

Cropland Management	SOC 0-15 cm (kg C Mg^{-1})	SOC 15-30 cm (kg C Mg^{-1})	SOC_m 0-15 cm (Mg C ha^{-1})	LC 0-15 cm (kg C Mg^{-1})	nonLC 0-15 cm (kg C Mg^{-1})	MBC 0-15 cm (kg C Mg^{-1})	MBC/SOC 0-15 cm
CCBB	13.58d	8.71bc	18.01bc	1.20b	13.10d	0.69c	4.94bc
CCBM	13.65d	8.26bc	18.29bc	1.26ab	13.15d	0.68c	4.97bc
CCMF	16.71ab	10.16a	21.48a	1.38a	16.33ab	0.81b	4.78c
ACPM	17.36a	10.13a	22.16a	1.07c	17.44a	0.90a	5.20b
ACPf	15.59bc	9.83a	18.54bc	1.24ab	15.57b	0.79b	5.11bc
ACPF	15.25c	8.92b	19.33b	1.34a	14.72c	0.71c	4.78c
ACPR	13.33d	8.13c	17.62c	0.87d	12.99d	0.75bc	5.60a

where for the current study, CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch & no fertilizer; ACPf - alley cropping with pruning and plant residue mulch & half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch & full rate fertilizer; ACPR - alley cropping with pruning removed & full rate fertilizer.

Columns means followed by different letters are significantly different at $p < 0.05$

3.3.2.2. Effect of cropland management and seasons interaction

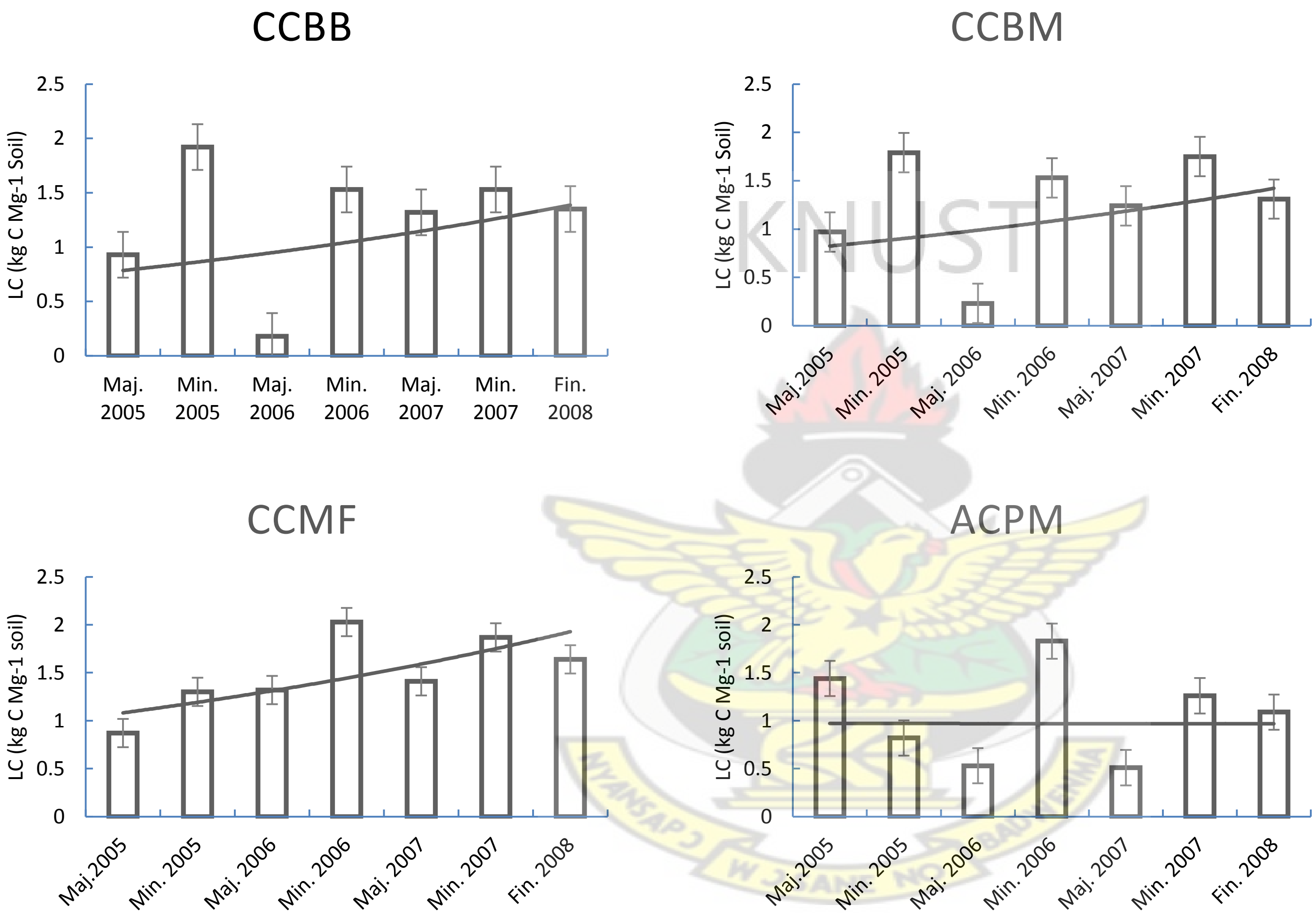
At the end of three years of experimentation, made up of six seasons of continuous maize cultivation, cropland management practices and season interaction influenced LC and SOC_m ($p < 0.05$) but did not influence SOC, non-LC, MBC and the proportion of MBC as SOC ($p > 0.05$) dynamics during the period (Table 3.2).

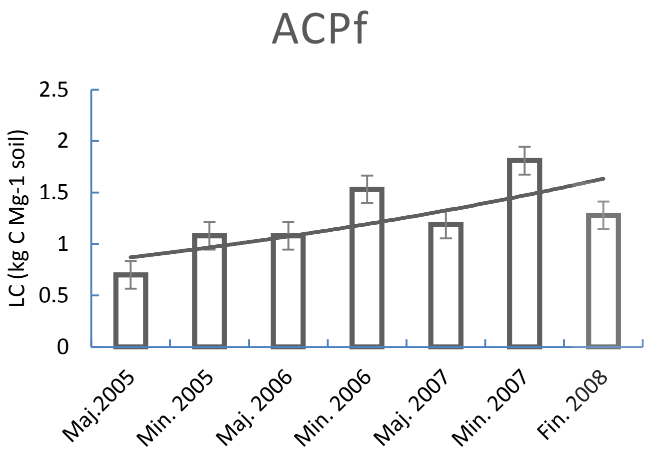
Labile C dynamics over the seasons

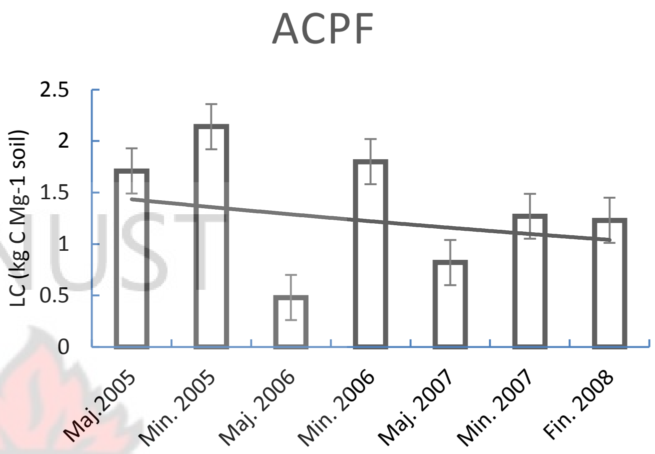
Labile C levels on all the non-hedgerow plots significantly improved ($p < 0.05$) by the end of the study period whilst on the hedgerow plots, only ACPf recorded improvement in LC levels ($p < 0.05$) (Figure 3.1).

There was a significant improvement in LC on the continuous cropping plot that received no fertilizer application with biomass burnt at the beginning of every cropping season (CCBB) during the second season over the initial level but this improvement was not sustained by the third season. Labile C was however kept a steady state in the subsequent four seasons indicating some level of stability. On the mulched non-hedgerow plot (CCBM), LC exhibited similar trends as the CCBB plot but the level during the subsequent four seasons were not always similar. On the mulched and fertilized non-hedgerow plot (CCMF), LC improved significantly over the initial levels throughout the study period. The highest LC level was attained by the fourth season but this level could not be sustained.

Under hedgerow conditions, the ACPM and ACPR plots recorded significant reduction ($p < 0.05$) in LC during the first three seasons whilst the ACPf and ACPF plots recorded LC improvement ($p < 0.05$) during the first two seasons. The Labile C improvement over the initial level on the ACPf plot was sustained over the study period whilst on the ACPF plot, LC improvement in the first two seasons could not be sustained (Figure 3.1).


CCBB
LC (kg C Mg-1 Soil)
2.5
2
1.5
1
0.5
0
Maj. 2005
Min. 2005
Maj. 2006
Min. 2006
Maj. 2007
Min. 2007
Fin. 2008
CCBM
LC (kg C Mg-1 Soil)
2.5
2
1.5
1
0.5
0
Maj.2005
Min. 2005
Maj. 2006
Min. 2006
Maj. 2007
Min. 2007
Fin. 2008
CCMF
LC (kg C Mg-1 soil)
2.5
2
1.5
1
0.5
0
Maj.2005
Min. 2005
Maj. 2006
Min. 2006
Maj. 2007
Min. 2007
Fin. 2008
ACPM
LC (kg C Mg-1 soil)
2.5
2
1.5
1
0.5
0
Maj.2005
Min. 2005
Maj. 2006
Min. 2006
Maj. 2007
Min. 2007
Fin. 2008





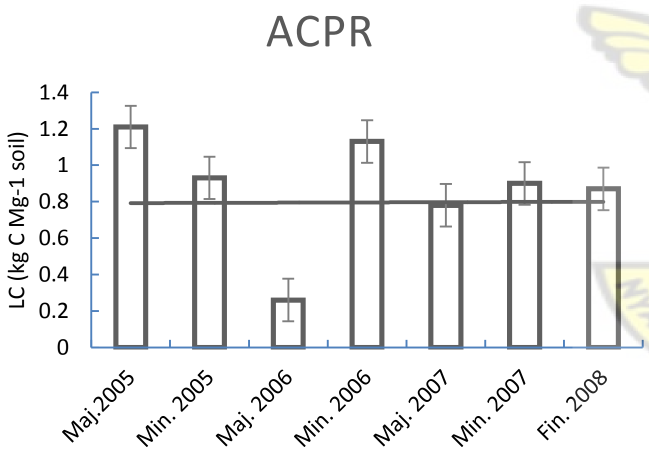


Figure 3.1. Labile Carbon dynamics over the six seasons from the major season of 2005 to the end of the sixth season at the beginning of 2008 on the studied cropland management practices; where CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, and full rate fertilizer.

Soil organic carbon mass dynamics over the seasons

After six season of continuous maize cropping on these plots, SOC_m levels ranged from18.87 Mg C ha^{-1} on the ACPR plot to 31.29 Mg C ha^{-1} on the ACPM plot. The resultant absolute soil C sequestration over the three year period ranged from 0.67 Mg C ha^{-1} on the CCBB plot to 12.06 Mg C ha^{-1} on the ACPM plot (Figure 3.2).

Regular plant residue burning at the beginning of every cropping season on the non-hedgerow plot (CCBB) resulted in the least ($p<0.05$) soil C sequestration potential, which was similar to the potential of the hedgerow plot that had its pruning regularly removed (ACPR) within the 0-15 cm soil depth. Full rate inorganic fertilizer application on the non-hedgerow plot (CCMF) improved C sequestration potential significantly ($p < 0.05$) but caused a reduction under hedgerow conditions on the ACPF plot compared to the non-fertilized and mulched hedgerow plot (ACPM) during the period (Fig. 3.2). The application of lower doses of inorganic fertilizer under hedgerow conditions was able to sustain higher soil C sequestration potential than the application of full rate inorganic fertilizer.

The overall trend in soil C sequestration potential on the studied cropland management practices were in the following order: ACPM = ACPf > CCMF = ACPF > CCBM = ACPR > CCBB.

Annual soil C sequestration potential of the studied management practices therefore, ranged from 0.22 Mg C ha^{-1} $year^{-1}$ on the CCBB plot to 4.02 Mg C ha^{-1} $year^{-1}$ on the ACPM plot.

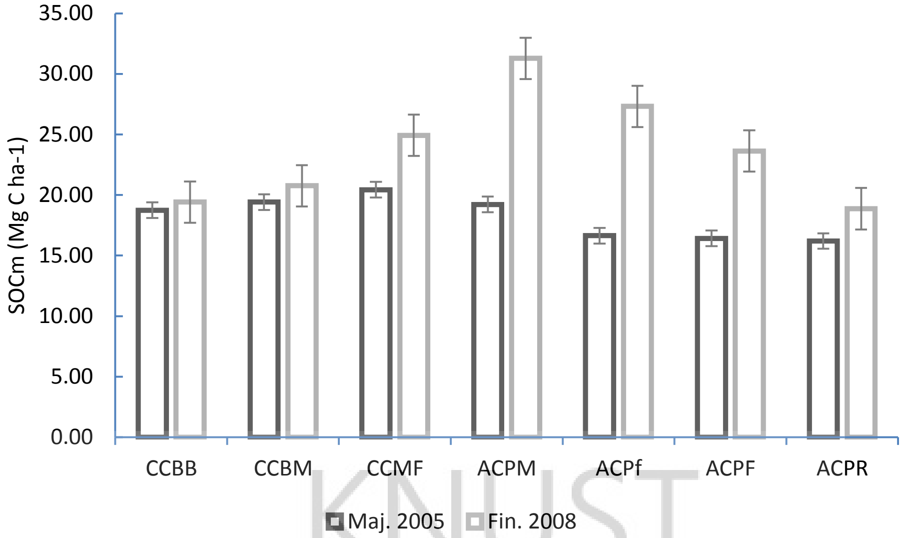


Figure 3.2. Comparison of the initial (Maj. 2005) and the final (Fin 2008) organic carbon mass levels of the studied cropland management practices after 3 years of continuous maize cultivation; CCBB - continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, and full rate fertilizer;

3.4 DISCUSSIONS

The presence of hedgerow species with N fixing potential, coupled with the judicious management of the different qualities of plant resources as surface mulch has been described in scientific literature as having the potential to sustain long term cropland productivity. Similarly, the application of inorganic fertilizers under both hedgerow intercropping and non hedgerows for maize production has also been described as having the potential to sustain the long term productivity of croplands. Further investigation regarding the influence of these soil management practices on SOM dynamics however is vital to be able to assess the overall sustainability of these soil management practices. In this study, the dynamics of the different fractions of SOC as influenced by hedgerow intercropping and the other studied non-hedgerow cropland management practices are discussed below:

3.4.1 *Initial SOC Status*

Initial levels of total SOC between 12.80 to 17.37 g C kg^{-1} were rated as low to moderately low (Quansah, 2010) for such tropical soils within the 0-15 cm soil layer. He rated SOC levels of < 15 g C kg^{-1} soil as low, whilst levels between 16 and 30 g C kg^{-1} soil were rated as moderate for effective agriculture on Ghana soils. Total SOC levels were similar to the levels reported by Fonte et al. (2009), Vagen et al. (2005) and Hutchinson et al. (2007) under similar conditions. Although the presence of hedgerow species did not indicate any superior total SOC status on the plots throughout the AFNETA study and also in the fallow period, it is assumed that the superior levels of LC and MBC/SOC ratio under some of the hedgerows plots demonstrate the potential of *Gliricidia* species in improving SOC status if the fallow period had lasted longer. This is because LC dynamics have been identified as reliable indicators of future SOC dynamics in response to management (Friexo et al., 2002; Wiesenberg et al., 2004; De Bona et al., 2008). Similarly, the MBC/SOC ratio has also been described as reliable indicators of future SOC dynamics. The recorded MBC/SOC ratio of 3.47 to 7.13% was similar to the 1-5% recorded by Wang et al. (2007) for tropical soils. The superior MBC/SOC ratio on the ACPR could be attributed at the start of the study to the judicious application of all hedgerow pruning on these plots during the nine years of the AFNETA study which was also followed by the improved *Gliricidia* fallow period.

3.4.2 *Mean SOC and its fractions dynamics (Effect of cropland management)*

Superior mean total SOC and SOC_m on the non-hedgerow mulched and fertilized plot (CCMF) as well as on the non-fertilized and mulched hedgerow plots (ACPM) confirmed the potential of hedgerow intercropping without inorganic fertilizer application in sustaining the SOC status on tropical croplands. Many authors including Palm et al. (2004) and Haile et al. (2008) have observed similar SOC sequestration potential. The results obtained supports the observation that the application of plant residues of varying qualities, as occurs on the ACPM plots under three years of continuous maize production on tropical croplands, provides a better condition for sustaining SOC levels (Tetteh, 2004). He argued that the application of low quality maize stover in combination with a high quality *Gliricidia* pruning as surface mulch as well as the presence of the hedgerow species that also has a nitrogen fixing potential could ensure better synchronization of nutrient release and uptake. This is believed to result in improved cropland productivity and also enhance SOC especially under no-till management conditions (Vagen et al., 2005).

The maintenance of similar superior levels of mean total SOC and SOC_m on the fertilized and mulched non-hedgerow (CCMF) plot also confirmed the potential of judicious plant residue management with inorganic fertilizer application in sustaining SOC levels of tropical croplands (Yeboah et al., 2005). Many other authors have all observed that within the tropical agro-ecosystems where farmers practice low input agriculture, the judicious and combined use of organic and inorganic nutrient sources has the potential both to improve crop yields (Vanlauwe, et al., 2001; Kramer, 2002; Yeboah et al., 2005 and 2007) and also to reduce SOC depletion (Vanlauwe et al., 2001; Bationo et al., 2007). However, the inability of biomass burning under non hedgerow (CCBB) conditions to sustain similar levels of soil C sequestration as the CCMF plot could be attributed to the loss of organic resources that could have converted into SOM as well as increased SOM mineralization under such conditions as observed by Lal (2004). Similar low soil C sequestration under hedgerow conditions with pruning removed (ACPR) could also be attributed the loss of nutrient rich organic resources that could have contributed to increased SOM accumulation and also could have improved cropland productivity. Increased cropland productivity could have returned larger volumes of plants biomass to sustain higher SOM levels as reported by Young (1997) and Hutchinson et al. (2007)

Mean Labile Carbon dynamics

The maintenance of higher mean LC levels on the fertilized and mulched hedgerow plots (ACPf and ACPF) as well as on the fertilized and non-fertilized non-hedgerow plots (CCBM and CCMF) as shown in Table 3.3 confirmed the potential of integrated soil fertility management principles in sustaining SOC status. It is argued that the judicious application plant resources as surface mulch in combination with inorganic fertilizer application under both hedgerow and non-hedgerow conditions could have positively influence cropland productivity and also provided larger volumes of readily decomposing LC. Increased soil LC could eventually have contributed to sustain higher SOC levels as has been reported by many authors including Blair et al. (1995); Wiesenberg et al. (2004); Hutchinson et al. (2007); De Bona et al. (2008). The inability of the ACPM plot to maintain similar high LC level could be attributed to the possible competition of hedgerow species for nutrients and moisture that could have affected the productivity and SOC dynamics of the mulched hedgerow plot (Young, 1997; De Bona et al., 2008).

In practice, variations in LC levels at the early stages on the adoption of a soil management practice has been identified as reliable indicators of future SOC dynamics (Balesdent et al., 2000; Wiesenberg et al., 2004; De Bona et al., 2008). However other authors including Blair et al. (1995) and Bayer et al. (2002) have caution that lower labile C levels in soils does not necessarily mean lower total C stock in soil. It only provides a measure of rapid assessment of the dynamics of soil C as a result of management change in agricultural systems with the understanding that soils with improving labile C would eventually accumulate more organic C with time.

The proportion of LC as a component of SOC ranging from 6.5 to 10.2% obtained in this study, was consistent with the observation of De Bona et al. (2008) who proposed the range of 4 - 19% for tropical soils. Vieira et al. (2007) in their work using 60 mM $KMnO_4$ to determine LC reported a similar range of 7.3 - 10.5% LC as a component of the C pool.

3.4.3. *Effect of cropland management and season on LC*

Improvement in the LC status on the non-hedgerow plots over initial levels during the second seasson could be atributed to the addition of larger volumes of plant residues obtained from the six years of fallow prior to the start of the study (Figure 3.1). This large quantities of plant residues could have provided partially decomposed plant resource, which is described as LC (Young, 1997; Torn et al., 2005) that is more sensitive to soil management regime than the whole SOM pool. The improved LC during the first few seasons under the non-hedgerow conditions could only be sustained upon the addition of inorganic fertilizers (CCMF) confirming the potential of integrated nutrient management in promoting SOM (Vanlauwe et al., 2001; Bationo et al., 2007).

Under hedgerow conditions, the significant reduction of LC on the ACPM in the first three seasons could be attributed to the severe competition for plant nutrients and moisture by the hedgerow species (Young, 1997; De Bona et al., 2008) whilst the similar LC reduction on the ACPR could be attributed to the removal of high quality pruning, coupled with enhanced competition of the hedgerow species for nutrients and soil moisture. The regular removal of the hedgerow pruning on the ACPR could have deprived the plot sizeable quantity of plant nutrient (chapter 4) which could have improved cropland productivity for both the maize and hedgerow species. This could have reduced the effect of competition for nutrients and moisture between the maize crops and hedgerow spacies and improved LC.

The sustenance of higher level of LC on the ACPf throughout the seasons could be attributed to the combined effect of judicious use of plant resorces with lower doses of inorganic fertilzer to sustain the productivity of tropical croplands. It has been augued that the application of higher doses of inorganic fertilizers could reduce the nitrogen fixing potential of leguminous hedgerow species as occured on the ACPF plot (Lal, 2004). Higher doses of inorganic fertilizer application could have also reduced LC through enhanced soil C mineralization associated with decreased soil aggregate stability and the capacity of soil to stabilize SOM in soil aggregates (Yeboah et al., 2007; Fonte et al., 2009).

3.4.4. *Effect of cropland management and season on* SOC_m

Improved accumulation of SOC_m of 12.06 Mg C ha^{-1} over the study period, which is equivalent to soil C sequestration rates 4.02 Mg C ha^{-1} $year^{-1}$ on the hedgerow plots with pruning applied as surface mulch with no inorganic fertilizer application (ACPM), was similar to estimates of Vagen (2005) for the SSA region. He reported attainable C sequestration in a range of 0.1-5.3 Mg C ha^{-1} yr^{-1} under agroforestry and 0.05-0.36 Mg C ha^{-1} $year^{-1}$ upon conversion from traditional cultivation techniques (with tillage) to no-till systems where a combination of animal manure and fertilizers was applied. This was estimated to be equivalent to a sequestration of 1.0-7.5 Tg C $year^{-1}$ on the total permanent cropland area of 20.9 million ha of the SSA region. Naab et al. (2008) in their work in Northern Ghana also recorded similar SOC sequestration rate of 173 kg SOC ha^{-1} yr^{-1} under recommended management practices which included surface application of all plant residues as mulch with full rate inorganic fertilizer application.

Similar trend was also observed under hedgerow intercropping conditions in Malawi by Makumba et al. (2007) who reported a 123 Mg C ha^{-1} under a 10 year old *Gliricidia sepium* and maize alley plot within the top 200 cm soil depth whilst Lal (2005) recorded under a four year old *Leucaena* alley plot in Western Nigeria an amount of 13.6 Mg C ha^{-1} within the top 10 cm soil layer. In Kenya, Impala (2001) reported SOC stock ranging from 2.6-3.7 Mg C ha^{-1} (0-20 cm) on a Ferralsol and 3.1-8.3 Mg C ha^{-1} (0-30 cm) was reported by Onim (1990) under agroforestry. Albrecht and Kandji (2003) reported a SOC stock of 3.4-12.5 Mg C ha^{-1} on a *Ferric Acrisol* in Togo. These values were higher than those recorded in the temperate regions of Canada where Oelbermann et al. (2006) reported 1.25 Mg C ha^{-1} under a 13 year old hybrid poplar + wheat, soybean and maize rotation within the top 40 cm soil layer.

Enhanced sequestration of soil C during the study period could have resulted from combined effect of several factors that operated on the identified hedgerow plots as discussed below. The adoption of no-till could have contributed to reduced soil disturbance that could minimize soil erosion and enhanced soil aggregation that ultimately could have enhanced soil quality and productivity associated with improved SOC (Hutchinson et al., 2007).

Plant residues of differing qualities applied as surface mulch could also have contributed to efficient synchronization of nutrient release and uptake as well as general cropland productivity that greatly could improve soil C sequestration (Tetteh, 2004; Bationo et al., 2007: Fonte et al., 2009).

The application of plant residue as surface mulch has been described as having a better influence on soil C sequestration over buried application of plant residues as a result of fungal dominated decomposition processes of surface mulch with superior C sequestration potential (Holland and Coleman, 1987). They explain the higher C sequestration potential of surface mulch occurs as a result of the retention of a higher proportion of metabolised C of fungi than bacteria decomposition processes of buried biomass. The presence of plant residue mulch under no-till conditions coupled with lower soil temperatures and more limited soil aeration could have led to less soil C decomposition (Hutchinson et al., 2007) and enhanced C sequestration.

The effect of full rate inorganic fertilizer application even though led to a significantly highest grain and biomass yield (Chapter 4), did not lead to highest C sequestration both under hedgerow and non-hedgerow conditions as has been observed by many authors including Vanlauwe et al., (2001); Kramer, (2002); Bationo et al., (2007). In their study conducted in Ghana by Fonte et al., (2009), the application of 120 kg/ha N fertilizer for a three cropping seasons of maize monocropping resulted in lower SOC. They attributed the reduced SOC to enhanced soil C mineralization associated with decreased soil aggregate stability and the capacity of soil to stabilize SOM in soil aggregates upon the application of inorganic fertilizers.

In discussing the contribution of legume hedgerow species with N_2 fixing potential in enhancing C sequestration, it is important to acknowledge the fact that legumes are also able to reduce inorganic N fertilizer requirement of croplands thereby reducing the net fossil fuel requirements and the C cost of manufacturing N fertilizers (Zentner et al., 2001). Dyer and Desjardins (2003) even provide an additional benefit associated with no-till as practiced under the current hedgerow intercropping study. They argue that its adoption is accompanied by a reduction in fossil fuel use that is associated with reduced machinery and tractor use that further has a great effect on CO_2 emission and global C sequestration.

3.5 SUMMARY AND CONCLUSIONS

The effect of cropland management practice, soil depth and season on total SOC, SOC_m, LC, non-LC, MBC, and MBC/SOC ratio could be summarized as follows. (i) Cropland management practice of the various forms of hedgerow intercropping and non-hedgerow plots influenced mean total SOC (within the 0-15 and 15-30 cm soil depth), mean SOC_m, mean LC, mean non-LC, mean MBC (within the 0-15 cm soil depth). (ii) Season (major season and minor season throughout the three years of the study) influenced all the studied SOC and its variants of LC, non-LC and MBC within the levels of measured soil depth. (iii) Cropland management and season interaction significantly influenced SOC_m and LC but did not influence total SOC, non-LC, MBC and MBC/SOC ratio in the study.

The adoption of hedgerow intercropping with no inorganic fertilizer application for continuous maize production in the semi-deciduous zone of Ghana exhibited the highest potential of cropland management practice to sequester C within the 0-15 and 15-30 cm soil depth on a *Ferric acrisol*, than under non-hedgerow conditions. Upon the application of full-rate inorganic fertilizer under hedgerow conditions, the potential of croplands to sequester soil C was greatly reduced as compared to the C sequestration improvement recorded on the full-rate fertilized non-hedgerow plots.

Soil C sequestration rate of 4.02 Mg C ha^{-1} $year^{-1}$ is attainable under hedgerow intercropping adopted for continuous maize production within the semi deciduous forest zone of Ghana using *Gliricidia sepium* as the hedgerow species. Highest soil C sequestration was obtained under hedgerow intercropping when no inorganic fertilizers were applied. Higher doses of inorganic fertilizer application under hedgerows as well as regular removal of high quality *Gliricidia* pruning from the maize plots, reduced soil C sequestration potential whilst inorganic fertilizer application under non-hedgerows conditions improved soil C sequestration. The regular use of bush burning as a land preparation practice as occurred when plant residue were burnt at the beginning of every cropping season reduced the soil ability to sequester C.

CHAPTER 4: DYNAMICS OF MAIZE YIELD AND CROPLAND PRODUCTIVITY UNDER HEDGEROW INTERCROPPING AND CONVENTIONAL SOIL MANAGEMENT PRACTICES

4.1 INTRODUCTION

Improving cropland productivity to feed the ever-increasing world population is a major challenge especially for the resource-limited agricultural system of Ghana. It has been identified by several authors including Young (1997), Madder et al. (2002), Loveland and Webb (2003) and Lal (2004) that enhancing soil organic matter (SOM) is vital to address this challenge in the tropical regions. Young (1997) in his work classified the effect of SOM on soil properties into the following three groups: effects on soil physical properties, nutrient availability and biological activity. He argued that the role of improved SOC in the supply of plant nutrients is even more significant under tropical conditions where soils contain low activity highly weathered clay minerals dominated by Kaolinite as well as iron and aluminium oxide with only about 10 $cmol_c$ kg^{-1} of Cation Exchange Capacity (CEC). Other authors including Theng (1980) and Sanchez and Logan (1992) have supported this assertion and concluded that under such conditions, SOC becomes the major source of plant nutrients for crop growth as decomposition proceeds and also helps improve the ability of the soil to retain nutrient cations against leeching.

Similarly, Lal (2010) confirmed the above role and elaborated the following relationship that exists between agronomic production and improved SOC pool under low input agriculture conditions. He indicated that enhanced SOC positively affects the soil productivity parameters such as: soil structure and aggregation, water retention, nutrient retention, biotic activity including the microbial biomass, erosion control, non-point source pollution abatement, sedimentation reduction and control of hypoxia, C sequestration, increase in use efficiency of inputs, increase in biomass production. Conversely, the continuous adoption of extractive farming practices by the resource poor farmers of SSA lead to the nutrient and C depletion of croplands, resulting in declining agronomic production which further leads to accelerated degradation of agro-ecosystems through accelerated erosion, increased intensity and frequency of drought, decline in rainfall effectiveness and use efficiency of inputs.

The amount and quality of SOC has therefore often been used as an indicator of soil quality and productivity (Bauer and Black, 1994; Davidson, 2000). Consequently in agricultural ecosystems, land use practices aimed at increasing SOC content is often seen as a desirable objective (Madder et al., 2002; Loveland and Webb, 2003; Lal, 2004). Enhancing SOC is therefore considered as a developmental strategy with high potential in SSA where soil degradation has been linked to low crop yield, food crises and overall impoverishment (Vagen et al., 2005).

To be able to evaluate the benefits of soil C sequestration on cropland productivity in Ghana as obtained in chapter 3, it is pertinent to understand and assess the dynamics and potential of cropland productivity as affected by soil C sequestration of the different soil management practices. In practice however, the effectiveness of these soil management practices including hedgerow intercropping, adopted for the continuous maize (*zea mays* L.) production, has largely been assessed for their enhanced agronomic productivity as soil C status improves under tropical conditions (Tiessen et al., 2001; Vagen et al., 2005, Naab et al., 2008). They propose that improving SOM upon the adoption of cropland management practice could improve, reduce, as well as maintain cropland productivity.

The aim of this study was therefore to evaluate changes in cropland productivity and maize yield upon the adoption of hedgerow intercropping and other conventional soil management practices on a *Ferric acrisol* within the semi deciduous zone of Ghana in relation to the associated change in SOM (Chapter 3). This was because detailed evaluation of the relationship between enhanced SOM levels on maize yield under different soil management regimes are scarce in Ghana (Yeboah et al., 2007; Hutchinson et al., 2007; Fonte et al., 2009).

The specific objectives were to assess whether soil management practice of CCBB, CCBM, CCMF, ACPM, ACPf, ACPF and ACPR influence changes in (i) soil chemical properties (pH, total N, available P, exchangeable cations (Ca, Mg, Na, K) and ECEC, (ii) maize grain and stover yield and (iii) fertilizer use efficiency (expressed as the contribution of a unit of applied inorganic fertilizer to average grain yield).

4.2 MATERIALS AND METHODS

In this section, I present a brief description of the laboratory investigations, statistical analyses and calculations used in the study. Detailed description of the study site, experimental treatments and data collection procedures has been presented in Chapter 3.

4.2.1. Study data analyses

4.2.1.1 Laboratory analyses

The study monitored the following soil chemical properties: pH, total N, exchangeable cations, ECEC, over the three years of six maize growing seasons. In addition, maize grain and stover yield dynamics were also assessed.

i. Soil pH

Soil pH was determined in a 1:2.5 suspension of soil and water using a HI 9017 Microprocessor pH meter. A 20 g soil sample was weighed into 100 ml polythene bottle. To this 50 ml distilled water was added from a measuring cylinder and the bottle capped. The solution was shaken on a reciprocating shaker for two hours. After calibrating the pH meter with buffer solution at pH 4.0 and 7.0, the pH was read by immersing the electrode into the upper part of the suspension.

ii. Total Nitrogen

The total soil nitrogen (N) content was determined by the Kjeldahl digestion and distillation procedure as described in the Soil Laboratory Staff (1984). A 0.5 g soil sample was put in a Kjeldahl digestion flask and 5.0 ml distilled water added to it. After 30 minutes, 3.0 ml concentrated sulphuric acid and selenium mixture were added and mixed carefully. The sample was placed on a Kjeldahl digestion apparatus for 3 hours until a clear digest was obtained. The digest was diluted with 50.0 ml distilled water and mixed well until no more sediment dissolved and allowed to cool. The volume of the solution was made to 100 ml with water and mixed well. A 25 ml aliquot of the solution was transferred to the reaction chamber and 10.0 ml of 40 % NaOH solution was added followed by distillation. The distillate was collected in 2 % boric acid. The distillate was titrated with 0.02 N HCl solution with bromocresol green as indicator. A blank distillation and titration were also carried out to take care of traces of nitrogen in the reagents as well as in the water.

Calculation

The % N in the sample was expressed as $= \frac{N*(a-b)*1.4*mcf}{s}$ Eqn. 7

where

N	=	concentration of HCl used in titration
a	=	ml HCl used in sample titration
b	=	ml HCl used in blank titration
s	=	weight of air-dry sample in gram
mcf	=	moisture correction factor (100 + % moisture) / 100
1.4	=	14 x 0.001 x 100 % (14 = atomic weight of nitrogen)

iii. Exchangeable cations

Exchangeable bases (calcium, magnesium, potassium and sodium) in the soil were determined in 1.0 M ammonium acetate (NH_4OAc) extract (Black, 1986) and the exchangeable acidity (hydrogen and aluminium) was determined in 1.0 M KCl extract as described by Page et al. (1982)

Extraction of the exchangeable bases

A 10 g soil sample was transferred into a leaching tube and leached with 250 ml of buffered 1.0 M ammonium acetate (NH_4OAc) solution at pH 7.

Determination of Calcium and Magnesium

A 25 ml portion of the extract was transferred into an Erlenmeyer flask and the volume made to 50 ml with distilled water for the determination of the calcium and magnesium. Also added were a 1.0 ml portion of hydroxylamine hydrochloride, 1.0 ml of 2.0 per cent potassium ferrocyanide, 10.0 ml ethanolamine buffer and 0.2 ml Eriochrome Black T solution. The solution was titrated with 0.01 M ethylene diamine tetraacetic acid (EDTA) to a pure turquoise blue colour. A 20 ml 0.01 M magnesium chloride solution was also titrated with 0.01 M ammonium acetate solution to provide a standard blue colour for the titration.

Determination of Calcium only

A 25 ml of the extract was transferred to a 250 ml Erlenmeyer flask and the volume made to about 50 ml with distilled water. Hydroxylamine hydrochloride (1.0 ml), potassium cyanide (1.0 ml of 2 % solution) and potassium ferrocyanide (1.0 ml of 2 %) were added. After a few minutes, 4 ml of 8 M potassium hydroxide and a spatula of murexide indicator were added. The solution obtained was titrated with 0.01 M EDTA solution to a pure blue colour. Twenty millilitres of 0.01 M calcium chloride solution was titrated with 0.01 M EDTA in the presence of 25 ml l .0 M ammonium acetate solution to provide a standard blue colour

Calculation

Ca + Mg (or Ca) (cmol$^+$ kg soil) = $\frac{0.01*(Va-Vb)*1000}{0.1*W}$ Eqn. 8

Where:

W	=	weight in grams of oven-dry soil extracted
Va	=	ml of 0.01 M EDTA used in the titration
Vb	=	ml of 0.01 M EDTA used in blank titration
0.01	=	concentration of EDTA used

Exchangeable potassium and sodium determination

Potassium and Sodium in the percolate were determined by flame photometry. A standard series of potassium and sodium were prepared by diluting both 1000 mg / l potassium and sodium solution to 100 mg / l. This was done by taking a 25 ml portion of each into one 250 ml volumetric flask and made to volume with water. Portions of 0, 5, 10, 15 and 20 ml of the 100 ml / l standard solution were put into 200 ml volumetric flasks respectively. One hundred millilitres of 1.0 M NH_4OAc solution was added to each flask and made to volume with distilled water. The standard series obtained was 0, 2.5, 5.0, 7.5, 10.0 mg / l for potassium and sodium. Potassium and sodium were measured directly in the percolate by flame photometry at wavelengths of 766.5 and 589.0 nm respectively.

Calculations

Exchangeable K ($cmol^+$ kg soil) = $\frac{(a-b)*250*mcf}{10*39.1*s}$ Eqn. 9

Exchangeable Na ($cmol^+$ kg soil) = $\frac{(a-b)*250*mcf}{10*23*s}$ Eqn. 10

Where:

a = mg/l K or Na in the diluted sample percolate

b = mg/l K or Na in the diluted blank percolate

s = air-dried sample weight of soil in gram

mcf = moisture correction factor

iv. Effective cation exchange capacity (ECEC)

Effective cation exchange capacity was determined as the sum of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and exchangeable acidity (Al^{3+} + H^+)

v. Available Phosphorus (Blay's No 1 Phosphorus)

Available P, which is the readily acid-soluble form, was extracted with a HCl: NH_4F mixture called the Bray's No 1 method as described by Bray and Kurtz (1945) and Olsen and Sommers (1982). Phosphorus in the extract was determined on a spectrophotometer by the blue ammonium molybdate method with ascorbic acid as reducing agent.

A 2.0 g soil sample was weighed into a shaken bottle (50 ml) and 20 ml of extracting solution of Bray-1 (0.03 M NH_4F and 0.025 M HCl) was added. The sample was shaken for one minute and the immediately filtered through a fine filter (Whatman No. 42). One ml of the standard series, the blank and the extract, 2 ml boric acid and 3 ml of the colouring agent (ammonium molybdate and antimony tartarate solution) were pipette into a test tube and homogenized. The solution was allowed to stand for 15 minutes for the blue colour to develop to its maximum. The absorbance was measured on a spectronic 21D spectrophotometer at 660 nm wavelength.

A standard series of 0, 1.2, 2.4, 3.6, 4.8, and 6 mg P/l was prepared from a 12-mg P/l stock solution by diluting 0, 10, 20, 30, 40 and 50 ml of 12 mg P/l in 100 ml volumetric flask and made to volume with distilled water. Aliquots of 0, 1, 2, 3, 4, 5 and 6 ml of the 100 mg P/l standard solution were put in 100 ml volumetric flasks and made to the 100 ml mark with distilled water.

Calculations: $$P\ (\text{mg kg}^{-1}) = \frac{(a-b)*20*6*mcf}{s} \qquad \text{Eqn. 11}$$

where:

a	=	mg/l P in a sample extract
b	=	mg/l P in blank
s	=	sample weight in gram
mcf	=	moisture correcting factor
20	=	ml extracting solution
6	=	ml final sample solution

4.2.1.2 Maize productivity analysis

Maize grain and stover yields were estimated from the harvest plot of size 2 x 10 m. The harvest plot was strategically laid so that the harvested maize crops will include all the maize plant nearest to all the three hedgerows on each plot. The entire plants on the harvest plot were harvested by cutting at the ground level. The plants were separated into ears (cob + grains) and stover (stem, leaves and husk). The plant parts were weighed and their weights recorded as fresh weight. The ears were further separated into cobs and grains by shelling. The various parts were put in brown envelopes and oven dried at 60°C for 48 hours to estimate the dry matter.

Dry matter of the various parts was calculated as follows:

$$\text{TDM (stover) in } 20\ m^2 = \frac{\text{DMs} * \text{TFW}}{\text{FWs}} \qquad \text{Eqn. 12}$$

$$\text{TDM (grain) in } 20\ m^2 = \frac{\text{DMs} * \text{TFW}}{\text{FWs}} \qquad \text{Eqn. 13}$$

Where:

TDM = total dry matter weight

DMs = sub-sample dry matter weight

TFW = total fresh weight

FWs = sub-sample fresh weight

Stover yield (kg ha^{-1}) = TDM (stover) x 500[1]

Grain yield (kg ha^{-1}) = TDM (grain) x 500[1]

([1] refer to the area obtained from 10000 m^2 / 20 m^2)

4.2.1.3 Pruning yield of Hedgerow species

The hedgerow species was pruned twice during the growth cycle of the maize every season, and the pruning spread on the soil surface as mulch. At every stage the dry weight of biomass applied was quantified.

4.2.1.4. Fertilizer use efficiency

The increased maize grain yield obtained on the inorganic fertilized plots (CCMF, ACPF and ACPf, ACPR) over the control (CCBB) plot was assessed for each kg of applied inorganic fertilizer by dividing the extra grain yield (t/ha) by the quantity of inorganic NPK (kg/ha) applied.

4.2.2 Statistical Analyses

This study determined the effect of different cropland management practices, season and soil depth on soil pH, total N, available P, exchangeable cations (Ca, Mg, Na, K) and ECEC for the entire study period. In addition, effect of cropland management and season were assessed on maize grain and stover yields as well as on inorganic fertilizer use efficiency. Analysis of Variance (ANOVA) procedures were employed to test the above factors with test of significance set at probability level of less or equal to 0.05 ($p \leq 0.05$). Means were separated when ANOVA indicated significant differences at $p \leq 0.05$ using Tukey's test for means separation. The SAS software package was used. Described below are the effects tested and the statistical designs used:

Statistical designs

Cropland Management Practices

The effect of cropland management practices of CCBB, CCBM, CCMF, ACPM, ACPf, ACPM and ACPR, were determined on mean soil pH, total N, available P, exchangeable cations (Ca, Mg, Na, K) and ECEC, at 0-15 cm soil depth; as well as on mean maize grain yield in a randomized complete block design.

Cropland management practices, soil depth and seasons

The effect of cropland management practices of CCBB, CCBM, CCMF, ACPM, ACPf, ACPM and ACPR on mean soil pH, total N, available P, exchangeable cations (Ca, Mg, Na, K) and ECEC, was determined at 0-15 and 15-30 cm soil depth, over the seasons, using a completely randomized block split-split plot design. Cropland management practice was the whole plot factor (seven levels) and soil depth (2 levels) as sub plot factor, and seasons as the sub-sub plot factor (seven seasons)

Cropland management practices and seasons (for maize yield)

The effect of the cropland management practices at 0-15 cm soil depth over the seasons of Maj. 2005; Min. 2005; Maj. 2006; Min. 2006; Maj. 2007; and Min. 2007; was determined on maize grain and stover yield as well as fertilizer use efficiency as a split plot in a randomised complete block design. Whole plot factors were the seven cropland management practices. Sub-plot factors were the six seasons.

4.3 RESULTS

4.3.1 Initial soil chemical properties of the study site

Soil chemical properties of the study site varied ($p<0.05$) among the study plots at the start of the current study based on management practices imposed during the nine years of AFNETA study as well as changes that occurred during the six-year fallow period before the start of the current study (Table 4.1).

Soil pH was acidic to moderately acidic ranging from 5.35 on the ACPF plot to 5.85 CCMF plot within the 0-30 cm soil depth. Total N level was low to moderate and ranged from 0.09 % on the ACPR plot to 0.12 % on CCMF, ACPM and ACPf plots within the 0-30 cm soil depth. Least available P of 2.31 mg kg^{-1} soil was recorded on ACPf plot whilst the highest of 3.42 mg kg^{-1} soil was recorded on CCMF. Effective cation exchange capacity at the start of the study ranged from 6.15 $cmol^{+}$ kg^{-1} soil on the CCBM plot to 8.49 $cmol^{+}$ kg^{-1} soil on the ACPM plot within the 0-30 cm soil depth (Table 4.1).

In general, the dominance of *Gliricidia* species on the different hedgerow plots during the nine years of AFNETA study as well as the six-year fallow period did not indicate any superior influence on the levels of soil chemical properties over the non-hedgerow plots (Table 4.1)

Table 4.1. Initial levels of soil pH, Total N, Available P, Exchangeable K, Ca, Mg, Na and ECEC of the study plots

Cropland Management	pH	Total N (%)	Available P (mg kg^{-1})	Exchangeable K (cmol^{+} kg^{-1} soil)	Ca	Mg	Na	ECEC
CCBB	5.73ab	0.11b	2.87bc	0.37ab	5.71ab	1.64b	0.23b	8.11a
CCBM	5.37c	0.10 c	3.07b	0.30d	4.53d	1.29c	0.24b	6.15c
CCMF	5.85a	0.12a	3.42a	0.39a	5.53b	1.95a	0.24b	8.26a
ACPM	5.67b	0.12a	2.65c	0.35bc	6.04a	1.67b	0.24b	8.49a
ACPf	5.39c	0.12a	2.31d	0.31d	5.72ab	1.91a	0.20c	8.34a
ACPF	5.35c	0.10c	2.90bc	0.34cd	5.28bc	1.87a	0.26a	7.93ab
ACPR	5.36c	0.09d	3.35a	0.32cd	4.89d	1.65b	0.26a	7.32b

where CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, and full rate fertilizer; SED = standard error of the difference between means.
Columns means followed by different letters are significantly different at $p < 0.05$

4.3.2. Dynamics of soil chemical properties under different management practices

4.3.2.1. Effect of cropland management

The studied cropland management practices significantly influenced ($p < 0.05$) mean levels of pH, total N, Available P, Exchangeable K, Ca, Mg, and Na as well as ECEC at the end of the three-year period (Table 4.2).

Soil pH

Mean soil pH within the 0-15 cm soil depth over the entire three-year study period, ranged from 5.16 on the ACPF plot to 5.59 on the CCBB plot (Table 4.3). Compared to the pH at the start of this study, all the tested cropland management practices led to the reduction of soil pH over the period. The highest reduction of 6.84% occurred on the fertilized non-hedgerow plot (CCMF) whilst the least reduction of 0.56% occurred on the half-rate fertilized hedgerow plot. The potential of the studied cropland management practices to increase soil acidity was in the following order: CCMF > ACPM > ACPF > ACPR > CCBB > CCBM > ACPf. Full rate inorganic fertilizer application for continuous maize cultivation therefore had a stronger potential to increase cropland acidity under non-hedgerow conditions than under hedgerows.

Total N

Mean soil total N at the end of the study period ranged from 0.09% on both CCBM and ACPR plots to 0.12% on CCMF and ACPM plots (Table 4.3). Whilst CCBB, CCBM and ACPf led to the reduction ($p < 0.05$) of soil total N by 0.01% compared to the levels at the start of this study, CCMF, ACPM, ACPF and ACPR were able to sustain ($p < 0.05$) total N at 0.12, 0.12, 0.10 and 0.09% respectively over the six seasons of continuous maize cropping.

Table 4.2. Summary of p values of ANOVA results for the effects of cropland management, season, depth, cropland management and season; cropland management and depth; season and depth; and cropland management and depth and season on soil pH, total N, available P, Exchangeable K, Ca, Na, Mg, ECEC and Grain yield.

		p-value								
Source	df	pH	N (%)	P (mg kg^{-1})	K	Ca	Na	Mg	ECEC	Grain yield (kg ha^{-1})
					(cmol^{+} kg soil)					
Cropland management	6	0.0001	0.0001	0.0001	0.0001	0.0001	0.11	0.0001	0.0001	0.0001
Season	6	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Depth	1	0.08	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	-
Cropland management *Season	36	0.19	0.25	0.0001	0.008	0.56	0.24	0.18	0.40	0.0024
Cropland management *depth	6	0.98	0.12	0.23	0.52	0.56	0.08	0.66	0.62	-
Season*depth	6	0.32	0.0001	0.0001	0.44	0.15	0.0001	0.33	0.14	-
Cropland management *season*depth	36	0.99	0.83	0.83	0.94	0.99	0.86	0.99	0.99	-

Table 4.3. Means soil pH, total N, Available P, Exchangeable K, Ca, Mg and Na and ECEC at 0-15 cm soil depth.

Cropland Management	pH	Total N (%)	Available P (mg kg^{-1})	Exchangeable K (cmol^{+} kg soil)	Ca	Mg	Na	ECEC
CCBB	5.59a	0.10c	5.57d	0.29b	4.53a	1.68b	0.12b	6.85b
CCBM	5.31c	0.09d	5.65d	0.25d	3.93b	1.32c	0.11c	5.85c
CCMF	5.45b	0.12a	7.57a	0.32a	4.51a	1.64b	0.12b	6.81b
ACPM	5.44b	0.12a	5.65d	0.31a	4.75a	2.06a	0.13a	7.48a
ACPf	5.36bc	0.11b	5.68d	0.27cd	4.43a	2.09a	0.11c	7.30ab
ACPF	5.16d	0.10c	6.94b	0.28bc	3.63bc	1.79b	0.12b	6.11c
ACPR	5.21cd	0.09d	6.35c	0.25d	3.57c	1.41c	0.11c	5.68c

where CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, and full rate fertilizer;
Columns means followed by different letters are significantly different at $p < 0.05$

Available P

The studied cropland management practices maintained varied levels ($p < 0.05$) of mean soil available P ranging from 5.57 mg kg^{-1} soil on the CCBB plot to 7.57 mg kg^{-1} soil on the CCMF plot (Table 4.3). Compared to the initial status, all the studied cropland management practices led to increases in soil available P. The highest improvement of almost 146% occurred on the ACPf plot whilst the least improvement of 84% occurred on the CCBM plot.

Exchangeable K

Mean exchangeable K ranged from 0.25 $cmol^{+}$ kg^{-1} soil on the CCBB and ACPR plots to 0.32 $cmol^{+}$ kg^{-1} soil on the CCMF plot (Table 4.3). There was a general reduction in the status of exchangeable K compared to the initial levels. The highest reduction of 21.9% occurred on the ACPR plot whilst the least reduction of 11.4% occurred on the ACPM plot.

Exchangeable Ca

Mean cropland exchangeable Ca ranged from 3.57 $cmol^{+}$ kg^{-1} soil on the ACPR plots to 4.75 $cmol^{+}$ kg^{-1} soil on the ACPM plot (Table 4.3). In general, the studied cropland management practices caused exchangeable Ca depletion compared to their initial levels over the study period. The highest depletion of almost 31.3% occurred on the ACPF plot whilst the least depletion of 13.3% occurred on the CCBM plot.

Exchangeable Mg

The mean level of cropland exchangeable Mg ranged from 1.32 $cmol^{+}$ kg^{-1} soil on the CCBM plot to 2.09 $cmol^{+}$ kg^{-1} soil on the ACPf plot (Table 4.3). Whereas CCBB, CCBM, ACPM and ACPf recorded mean exchangeable Mg improvement over the initial levels, CCMF, ACPf and ACPR recorded a reduction over the six seasons of continuous maize cropping.

The highest improvement 23.4% exchangeable Mg occurred on the ACPM plot whilst the severest reduction of 15.9% occurred on the CCMF plot.

Exchangeable Na

Mean cropland exchangeable Na ranged from 0.11 $cmol^{+}$ kg^{-1} soil on the CCBM, ACPf and ACPR plots to 0.13 $cmol^{+}$ kg^{-1} soil on the ACPM plot (Table 4.3). In general, the studied cropland management practices caused mean exchangeable Na depletion compared to their initial levels over the study period, ranging from 45% on the ACPf plot to 58% on the ACPR plot.

ECEC

The studied cropland management practices maintained varied levels ($p < 0.05$) of mean ECEC ranging from 5.68 $cmol^{+}$ kg soil on the ACPR plot to 7.48 $cmol^{+}$ kg soil on the ACPM plot (Table 4.3). Compared to the initial status, all the studied cropland management practices led to the reduction of ECEC levels. The highest reduction of 23% occurred on the ACPF plot whilst the least reduction of 5% occurred on the CCBM plot in the following order:

ACPF > ACPR > CCMF > CCBB > ACPf > ACPM > CCBM.

4.3.2.2. Effect of cropland management practices and seasons interaction

Cropland management practices and season interaction influenced soil available P and exchangeable K ($p < 0.05$) but did not influence pH, total N, Exchangeable Ca, Mg and Na as well as ECEC ($p > 0.05$) dynamics over the six seasons of continuous maize cultivation (Table 4.2).

Dynamics of soil available P over the seasons

Six seasons of continuous maize cropping on the different plots resulted in the general improvement in the soil available P levels. Under non-hedgerow conditions, significant improvement of 4.18 mg kg^{-1} soil ($p < 0.05$) was recorded on only the mulched and fertilized plot (CCMF) whilst under hedgerow condition, significant improvement was recorded on all hedgerow plots with the highest improvement of 2.39 mg kg^{-1} soil recorded on the ACPF plot. (Figure 4.1a).

Dynamics of soil exchangeable K over the seasons

Significant depletion ($p < 0.05$) of soil exchangeable K was recorded on all the studied cropland management practices over the six years of continuous maize cropping. Absolute levels of soil available K depletion ranged from 0.08 $cmol^{+}$ kg^{-1} soil on the CCMF and ACPM plots to 0.17 $cmol^{+}$ kg^{-1} soil on the ACPR plot over the study period. The potential of the studied cropland management practices to cause depletion in soil exchangeable K was in the following order: ACPR > ACPF > CCBM > CCBB > ACPf > ACPM > CCMF (Figure 4.1b).

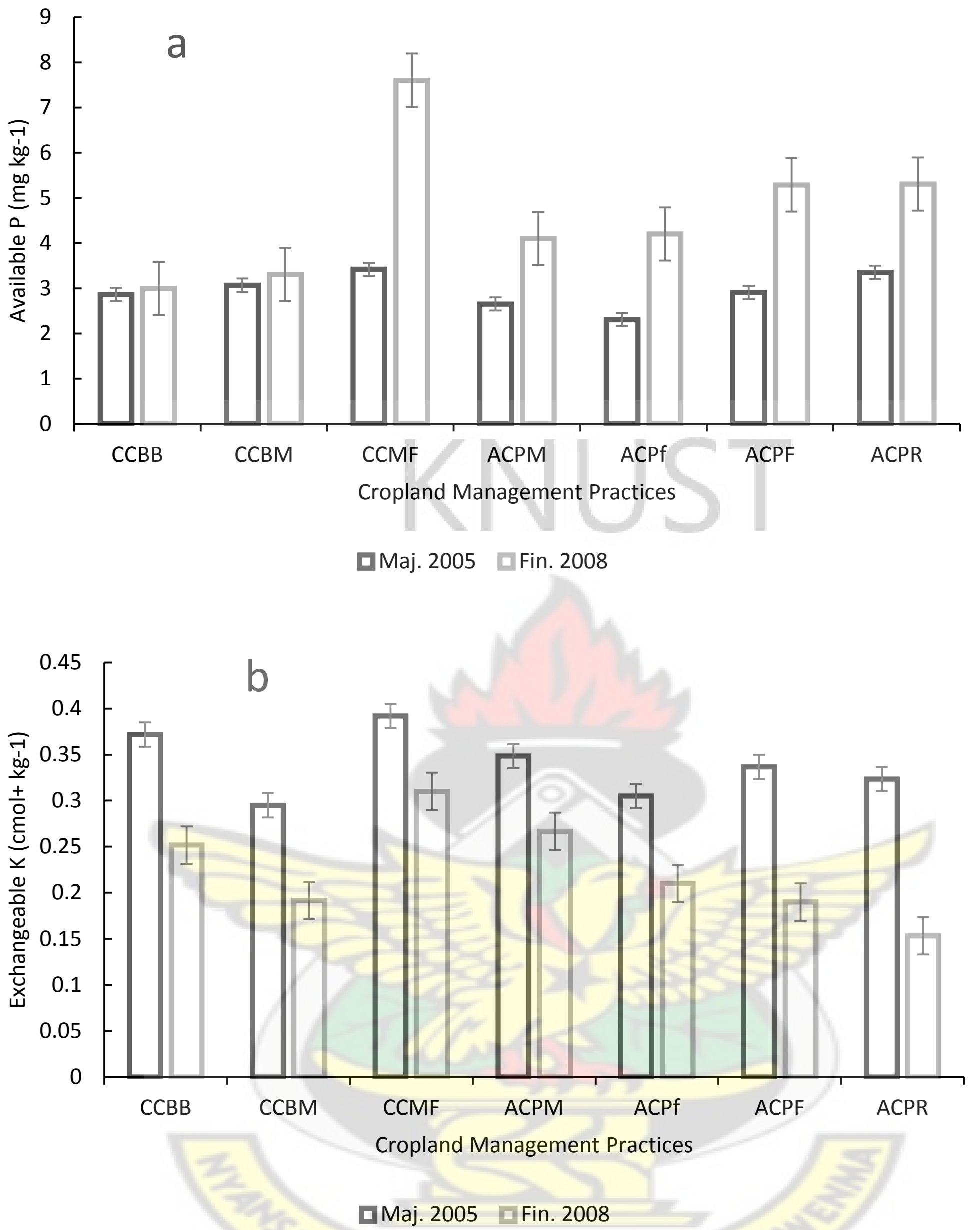


Figure 4.1. Comparison of initial (Maj. 2005) and final (Fin. 2008) levels of soil Available P (a) and soil Exchangeable K (b); CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, and full rate fertilizer.

4.3.3. Maize yield and productivity dynamics

4.3.3.1. Mean maize grain yield

Mean maize grain yield over the three-year study period ranged from 3.20 Mg ha^{-1} on the CCBB plot to 5.32 Mg ha^{-1}on the CCMF plot. The highest ($p<0.05$) mean maize grain yield was recorded on both hedgerow and non-hedgerow plots that received inorganic fertilizer application every cropping season (CCMF, ACPf, ACPF and ACPR). Grain yield improvement over the CCBB plot among the fertilized plots was in the following order: CCMF > ACPF > ACPf > ACPR; ranging from 66.4% on the CCMF plot to 50.75% on the ACPR plot (Table 4.4).

Among the non-fertilized plots, the hedgerow plot (ACPM) maintained significantly higher ($p<0.05$) mean grain yield levels than the CCBB and CCBM plots. However, the non-hedgerow plot with all plant residue burnt at the beginning of every cropping season recorded the least ($p < 0.05$) mean maize grain yield (Table 4.4).

4.3.3.2. Fertilizer use efficiency (Maize yield per unit fertilizer)

The fully-fertilized non-hedgerow (CCMF) and hedgerow (ACPF) plots produced a similar ($p < 0.05$) three-year mean fertilizer yield response of almost 2.1 and 2.0 Mg ha^{-1} grain yield improvement respectively over the control plot (CCBB) whilst the half rate fertilized hedgerow plot (ACPf) also maintained fertilizer yield response of 1.8 Mg ha^{-1} (Table 4.2). Considering that the CCMF and ACPF plots received full rate inorganic fertilizer application of N-P_2O_5-K_2O kg ha^{-1} -70-40-40 and the ACPf received N-P_2O_5-K_2O kg ha^{-1} -35-20-20, the resultant maize yield per kg of applied inorganic fertilizer were 30-52.5-52.5 kg grain ha^{-1} for CCMF and 28.6-50-50 kg grains ha^{-1} for ACPF. The ACPf plot however yielded almost two fold of 51.4-90-90 kg grain ha^{-1} for every kg of applied inorganic fertilizer. Thus half-rate fertilized hedgerow plot was able to reduce up to 50% the inorganic fertilizer requirement for comparable and sustainable maize production on tropical soils.

4.3.3.3. Effect of cropland management practices and season on maize grain yield

Cropland management practice and season significantly influenced ($p < 0.05$) maize grain yield on the various plots over the study period (Table 4.2).

Among the non-hedgerow plots of CCBB, CCBM and CCMF, there was a general significant reduction ($p < 0.05$) in maize grain yield compared to their respective initial levels by the end of the sixth season of continuous maize cropping. Maize grain yield reduction even occurred upon the application of full rate inorganic fertilizer every cropping season (Figure 4.2). Sustained and significant reduction ($p < 0.05$) in maize grain yield on CCBB and CCBM plot, started from the third season whilst on the CCMF plot yield reduction started from the fifth seasons (Table 4.4). On the hedgerow plots however, there was a general maize grain yield improvement (not always significant) over the initial levels by the end of the sixth season, except on the hedgerow plot with pruning removed (ACPR) which recorded significant ($p < 0.05$) maize grain yield reduction (Figure 4.2).

Table 4.4 Seasonal and mean maize grain yield

Management Practice	Maj. 2005	Min. 2005	Maj. 2006	Min. 2006	Maj. 2007	Min. 2007	Mean
	(Mg ha^{-1})						
CCBB	3.81c	2.82b	3.83bc	2.78d	2.89c	3.06cd	3.20c
CCBM	3.92c	2.96b	4.85bc	3.59c	3.23c	3.30bc	3.64bc
CCMF	4.84a	4.59a	7.50a	5.74a	5.16ab	4.10ab	5.32a
ACPM	4.09c	3.18b	2.96c	4.65b	5.33a	4.33a	4.10b
ACPf	4.50b	4.08a	6.71a	4.80b	5.19ab	4.64a	5.00a
ACPF	4.06c	4.29a	6.60a	6.01a	5.51a	4.70a	5.21a
ACPR	4.38b	4.50a	7.21a	4.60b	4.45ab	3.78ab	4.82a

where CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, full rate fertilizer;
Maj. 2005 represents maize yield during major season of 2005; Min. 2005 represents maize yield during minor season of 2005; Maj. 2006 represents maize yield during major season of 2006; Min. 2006, represents maize yield during minor season of 2006; Maj. 2007 represents maize yield during major season of 2007; Min. 2007 represents maize yield during minor season of 2007;
Columns means followed by different letters are significantly different at $p < 0.05$

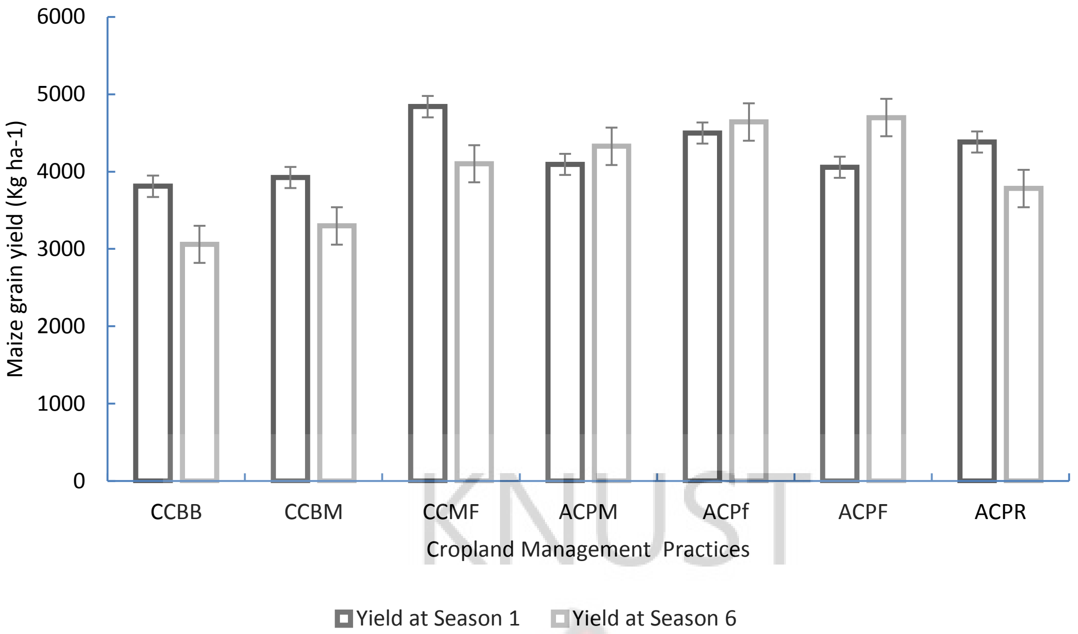


Figure 4.2 Comparison of season 1 and season 6 maize grain yield; CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, and full rate fertilizer.

4.3.3.4. Contribution of plant nutrients from maize stover and hedgerow pruning for improving soil productivity

Mean maize stover yield at every growing season over the study period ranged from 3.3 to 4.4 Mg ha^{-1} with the highest occurring on the mulched and fertilized plots under both hedgerow (CCMF) and non-hedgerow (ACPf and ACPF) conditions. On the hedgerow plots, mean hedgerow pruning yield every cropping season on ACPM, ACPf, ACPF and ACPR plots were 6.61, 7.48, 9.21 and 5.10 Mg ha^{-1} respectively.

The contribution of plant nutrients from the maize stover and hedgerow pruning sources applied to the soil under the various management practices (Tables 4.5 and 4.6) indicated that whereas maize stover contributed a maximum of about 37.0 kg N ha^{-1} to soil fertility every season, *Gliricidia* biomass applied as surface mulch contributed over 300 kg N $ha^{-1}$from plant sources on the fully fertilized hedgerow plots. This supply of over 300 kg N through pruning application into the agro-ecosystem did not include the potential amount of N fixed by the root system of the hedgerow species. The evaluation of the contribution of biologically fixed N to cropland productivity is beyond the scope of this thesis.

With the average nutrient concentration of *Gliricidia* pruning estimated at N:P:K of N=8.50 g kg^{-1}; P=1.0 g kg^{-1}; K=11.0 g kg^{-1} respectively (Tetteh, 2004), nutrient yield from pruning sources ranged from 178.4 – 322.2 kg ha^{-1} for N, 12.7 – 23.0 kg ha^{-1} for P and 114.7 – 207.1 kg ha^{-1} for K. Considering 30-70% mineralization and release of nutrients from *Gliricidia* pruning and 10% recovery of the nutrients by the companion crops from recently applied pruning (Kang, 1993), almost between 10-20 kg N ha^{-1}, 0.8-1.4 kg P ha^{-1}, 6.8-12.4 kg K ha^{-1} 8.1-14.6 kg Ca ha^{-1} and 3.8-6.9 kg Mg ha^{-1} were recovered by maize from the applied biomass every season. The highest contribution of plant nutrient from pruning was obtained from the fertilized and mulched hedgerow plots (ACPf and ACPF) whilst the least was obtained from the hedgerow plots with pruning removed (ACPR).

Table 4.5 Mean maize stover yield and total nutrient content

Treatment	Mean seasonal stover yield (Mg ha^{-1})	Nutrient content (kg ha^{-1})[a]				
		N	P_2O_5	K_2O	CaO	MgO
CCBB	3.58c	30.39	3.58	39.33	22.89	6.79
CCBM	3.31d	28.14	3.31	36.41	21.19	6.29
CCMF	4.39a	37.28	4.39	48.25	28.08	8.33
ACPM	3.94b	33.50	3.94	43.36	25.23	7.49
ACPf	4.36a	37.03	4.36	47.92	27.88	8.28
ACPF	4.31a	36.61	4.31	47.38	27.57	8.18
ACPR	3.65c	31.02	3.65	40.14	23.35	6.93
SED	0.44					

[a]Average nutrient concentration of maize stover of N=8.50 g kg^{-1}; P=1.0 g kg^{-1}; K=11.0 g kg^{-1}; Ca=6.4 g kg^{-1}; Mg=1.9 g kg^{-1} (Tetteh, 2004)

Table 4.6. Mean *Gliricidia* pruning yield and total nutrient content

Treatment	Mean seasonal pruning yield (Mg ha^{-1})	Nutrient content (kg ha^{-1})[b]				
		N	P_2O_5	K_2O	CaO	MgO
CCBB	-	-	-	-	-	-
CCBM	-	-	-	-	-	-
CCMF	-	-	-	-	-	-
ACPM	6.61	231.26	16.52	148.67	175.10	83.25
ACPf	7.48	261.70	18.69	168.23	198.14	94.21
ACPF	9.21	322.22	23.02	207.14	243.97	116.00
ACPR	5.10	178.42	12.74	114.70	135.10	64.23

[b]Average nutrient concentration of N=35.0 g kg^{-1}; P=2.5 g kg^{-1}; K=22.5 g kg^{-1}; Ca=26.5 g kg^{-1}; Mg=12.6 g kg^{-1} (Tetteh, 2004); CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, and full rate fertilizer.

4.4 DISCUSSIONS

Hedgerow intercropping has been promoted as an alternative to bush fallow system to improve cropland productivity for producing enough food to feed the ever increasing population in tropical Africa. A major drawback to its widespread adoption however, is the inability to understand and effectively exploit the dynamics of nutrient supply into the system; either from the organic or inorganic sources. Also important is the need to understand the influence of SOM dynamics under hedgerow intercropping on plant nutrients supply and yield improvement for the companion crops as well as general cropland productivity (Batish et al., 2007; Nair et al., 2008).

In this study, the combination of inorganic fertilizer application as well as plant nutrients supplied from maize stover and hedgerow pruning sources, applied as surface mulch had variable effect on soil chemical properties over the study period. Maize grain yield and cropland productivity was also variably influenced by the presence of hedgerows as well as organic and inorganic fertilizer application. Details of the study results are discussed below.

4.4.1 Soil chemical properties dynamics

Levels of soil chemical properties at the start of the study (Table 4.1) were comparable to levels observed by many authors who have worked on similar soils in the semi-deciduous forest zone in tropical Africa including Abunyewa et al. (2004) and Yeboah et al. (2005). Soils of such fertility status within the agro ecological zone have been rated as fairly good for sustainable maize production (Quansah, 2010).

Soil pH

Mean soil pH reduction of 0.03 – 0.23 under the various cropland management practices compared to the pH at the start of the study was anticipated. Similar soil pH reduction associated with maize cultivation and inorganic fertilization under tropical conditions have been reported by several authors including Brown (2002), Yeboah et al. (2005) and Vagen et al. (2005). They reported pH reduction potential of up to 10% over a 5 year period with severe consequences to cropland productivity. The soil pH reduction could have resulted partly from acidification potential of inorganic NPK fertilization on tropical soils and also greater litter (biomass) production associated with increased cation uptake by the tree components of agroforestry systems (Young, 1997 and Brown, 2002).

Comparably lower reduction of soil pH recorded on the plot on which all plant residues were burnt (CCBB) at the beginning of every cropping season, could have resulted from the seasonal production of ash from biomass burning that could have contributed significant amount of P, Mg, Ca and K ions into the soil medium needed to buffer extreme pH reduction. In addition, full rate inorganic fertilizer use for continuous maize cultivation exhibited a stronger potential to cause cropland pH reduction under non-hedgerow conditions than under hedgerows. This observation suggests the superior potential of hedgerow intercropping to buffer cropland pH change compared to non-hedgerow conditions (Young, 1997; Nair et al., 2009).

The study results were however contrary to the observation of Abunyewa et al., (2004) who rather reported almost 6% reduced acidity over a two year period under similar agroforestry conditions in northern Ghana. They attributed the pH increase to the release of cations from the added *Gliricidia* biomass. The above results therefore suggest that there is no clear effect of cropland management on soil pH and the results may increase of reduce depending on soil type, management practice and climatic conditions.

Total N

The reported lowering of soil total N under CCBB and CCBM of about 9-10% during the study could have resulted from the exploitation of conserved soil N accumulated before the start of current study. The accumulated soil N may have been spent for maize grain and biomass production without adequate and corresponding replacement either from organic or inorganic sources. Regular plant residue burning as a cropland management practice has been reported by several authors as detrimental for the sustenance of cropland productivity under tropical conditions (Nye and Greenland, 1960; Vanlauwe et al., 2001; Lal, 2006). It is cited as leading to loss of soil organic matter that has severe consequences to the sustenance of plant nutrients within the soil medium. Similarly, the loss of soil total N under CCBM over the study period could also have resulted from the inadequate nutrient supply provided from low quality maize stover and other plant residue mulch sources. The inadequacy of sole plant residue mulch without inorganic fertilizer application under non-hedgerow conditions for sustainable and continuous maize production has also been reported by Yeboah (2007).

Highest mean soil total N maintained on CCMF and ACPM (Table 4.3) suggests that inorganic NPK fertilizer application under non-hedgerow conditions could sustain similar higher level of soil total N comparable to hedgerow intercropping with no inorganic fertilizer application. This shows the capacity of the presence of hedgerows species and pruning application as surface mulch in contributing to the supply of similar quantity of N from organic sources to the maize plants. Observed sustenance in total N could have resulted from the production and application of high pruning biomass of 6.6-7.5 Mg ha^{-1} that released about

138.7 – 158.0 kg N ha^{-1} into the soil medium every season (Table 4.6). This could have been made possible by capacity of trees being able to exploit plant nutrients from deeper layers of soil depth and transferring these nutrients to the surface soil layer through litter fall, pruning application as well as from biological N fixation of *Gliricidia* (Young, 1997; Nair et al., 2009). Similar increased levels of soil total N of up to 32%, over a two year period, have been achieved on non-fertilized hedgerow plot by Vanlauwe et al. (1999) and Abunyewa et al. (2004). Under the hedgerow conditions, the maintenance of higher levels of soil total N on the non-fertilized plot (ACPM) over the fertilized plots (ACPf and ACPF) confirmed the proposition by Fisher (1995) and Young (1997) that suggests that higher doses of inorganic N fertilizer application could inhibit the N fixation potential of leguminous plants.

Available P

Highest mean soil available P under the fully-fertilized non-hedgerow intercropped plots (CCMF) confirmed the need for inorganic fertilizer application in sustaining cropland nutrient status for sustainable maize production in the tropics (Fisher, 1995; Tetteh, 2004; Yeboah et al., 2005). Soils of this region have been described as low P soils by Adu (1992) and therefore require supplemental application of inorganic P fertilizers to sustain cropland productivity. Highest available P improvement on the CCMF could have resulted from the application inorganic fertilizer sources. Improvement of soil P on the hedgerow plots could have been due to improved P exploitation from a greater soil volume by the tree components and returning these to the soil surface through litter fall and pruning application. Similar available P improvement levels have been observed under agroforestry conditions by Harcombe (1980) and Fisher (1995).

Exchangeable K

The general depletion ($p < 0.05$) of cropland exchangeable K over the six seasons of continuous maize cropping was anticipated (Figure 4.1b). The depletion of soil exchangeable K ranging from 0.4 – 0.8 $cmol^{+}kg^{-1}$ soil could have resulted partly from the efficient exploitation of cations by the tree components for tree biomass production without adequate replacement even from the inorganic fertilizer sources as well as its limited return to the soil medium through pruning application (Lal, 2004). Higher tree root density could have enhanced the reduction in soil exchangeable K as was observed by Bowden (1985). Similar reduction of exchangeable K of 0.1 – 0.7 under agroforestry systems compared to pastures was also observed by Tornquist (1999).

In general, the reduction in soil exchangeable bases under the different soil management practices studied confirms the importance of inorganic fertilization in integrated soil fertility management (ISFM) protocols to provide more plant nutrient into such agro-ecosystems to ensure continuous land-use for sustainable maize production. This also calls for the need to formulate and promote improved blends of NPK inorganic fertilizers that contain other nutrient elements such as Ca and Mg for sustaining cropland maize production on tropical croplands (Tetteh, 2004; Yeboah et al., 2007; SRI, 2008).

4.4.2 Maize grain yield and cropland productivity

The significantly higher ($p < 0.05$) mean maize grain yield obtained on all the hedgerow and non-hedgerow plots that received inorganic fertilizer application (CCMF, ACPf, ACPF and ACPR) (Table 4.4), confirms the contribution of inorganic fertilization in ISFM practices for sustainable crops production under tropical conditions (Abunyewa et al., 2004; Yeboah et al., 2005; Naab et al., 2008). Similar higher maize grain yield with inorganic fertilizer but crop residue removed was observed by Naab et al. (2008) who reported over 178% more grain yield than the recorded 1.3 Mg ha^{-1} on control plot. The grain yield increase could be attributed to the improvement in soil physical, chemical and microbiological properties as a result of the applied organic and inorganic fertilizer sources into the agro-ecosystem as suggested by Lal (2010). Relative improvement in soil Total N and available P levels, coupled with relative improvement in SOC (Chapter 3) on the hedgerow pots could have contributed to increased maize grain yield.

The general reduction of maize grain yield on all the non-hedgerow plots (Fig 4.2), even upon full rate inorganic fertilizer application, by the end of the sixth season, confirms the inadequacy of inorganic fertilizer use alone for continuous and sustainable maize production on tropical soils (Young, 1997; Vagen et al., 2005). They argued that yield response to inorganic fertilizer use continue to decline under tropical conditions where soils have low SOM with soil physical degradation or micronutrient deficiency. They concluded that such situations call for the subsequent requirement of higher rates of inorganic fertilizer use on tropical soils that also lead to environmental problems as well as economic challenges to the resource poor farmers of the tropical regions, to sustain adequate levels of cropland productivity.

Similarly, the higher mean grain yield obtained on the non-fertilizer hedgerow plot (ACPM) over the non fertilized non-hedgerow plots (CCBM) supports the general view that the presence of hedgerow species and pruning application can reduce the inorganic fertilizer requirement for sustainable maize production within the semi deciduous forest zone of Ghana (Karim and Savil, 1991; Young, 1997; Abunyewa et al., 2004). Karim and Savil (1991) have reported that the application of 20 Mg ha^{-1} of *Gliricidia* biomass improved maize grain yield by 54% over the plot that received 120 kg N ha^{-1}.

The application of over 6.6 Mg ha^{-1} (Table 4.6) of high quality *Gliricidia* pruning onto the hedgerow plots as surface mulch every cropping season, coupled with the presence of N fixing *Gliricidia* hedgerows could have contributed significant amount of plant nutrients into the soil medium to enhance the productivity of the accompanying maize crop. Almost 20 kg N ha^{-1} could have been made available to the maize crop every cropping season from the seasonal N yield of 178.4 – 322.2 kg ha^{-1} (Table 4.6) from the *Gliricidia* pruning. This is based on the estimation that 30-70% of recently applied pruning were mineralized and released with 10% recovery of the nutrients by the companion crops (Kang, 1993; Hagger et al., 1993). Similarly, nutrient supply from the maize stover, even though less than from the *Gliricidia* pruning, could also have contributed to enhanced productivity of the mulched plots over the CCBB plot through improved synchronization of nutrient release and uptake by companion plants (Tetteh, 2004). In this study, maize stover yield values were comparable to 4.0-7.7Mg ha^{-1} observed by Naab et al. (2008) but slightly higher than observation of Abunyewa et al. (2004) of between 1.84 – 2.21 Mg ha^{-1} on an alley cropping plot in Northern Ghana.

The least maize grain yield on the non-hedgerow plot with plant biomass burnt every season (CCBB) which was below the levels obtained on the mulched non-hedgerow CCBM plot also confirmed the detrimental effect of biomass burning in sustaining cropland productivity as well as the superiority of plant residue mulch farming (Lal, 2010).

This study also revealed that under continuous low input maize production on a *Ferric acrisol* within the semi deciduous forest zone of Ghana, significant reduction in maize grain yield starts from the fourth season under CCBB and from the fifth season under CCBM.

Fertilizer use efficiency

The highest mean grain yield response per kg of applied NPK of 51.4-90-90 kg obtained on the half rate fertilized hedgerow plot (ACPf) demonstrate the ability of hedgerow intercropping in reducing up to 50% the inorganic fertilizer requirement for sustainable maize production on tropical soils (Table 4.4). This could be attributed to the improvement in SOM status associated with the adoption of hedgerow intercropping (Chapter 3) which could have enhanced the productivity of the cropland for sustainable maize production (Lal, 2006; 2010).

With most farmers being resource poor and operating under low input conditions for crops production, the potential of reducing the inorganic fertilizer requirement by 50% for the sustainable production of maize becomes a developmental strategy. This means that farmers in Ghana, and in other parts of tropics operating on similar soils under similar environmental conditions, could improve their crop yields, ensure food security, reduce malnutrition, reduce poverty as well as reduce land and environmental degradation upon the adoption of hedgerow intercropping. It is important to emphasize that these significant improvements could be achieved under reduced cost of input for crops production as well as reduced energy requirement for the less fertilizers use which has important environmental consequence (Haile et al., 2008; Nair et al., 2009; Lal, 2010).

4.5 SUMMARY AND CONCLUSIONS

The main rationale for the promotion of hedgerow intercropping into cropping systems is to improve cropland productivity through improved soil fertility resulting from the enhanced SOM as a result of the positive effect of the tree components on the agro-ecosystem. The effect of cropland management practice and season on soil nutrients dynamics and maize grain yield could be summarized as follows. (i) Cropland management practice and season influenced soil P and K levels as well as maize grain yield but did not influence soil pH, total N, Ca, Mg and ECEC. (ii) Cropland management and soil depth as well as cropland management and soil depth and season interactions did not influence any of the monitored soil nutrient levels during the study.

The adoption of hedgerow intercropping system for the continuous production of maize had variable effect of soil fertility indices that cumulatively resulted in marked improvement in maize grain productivity over the three year study period. Maize grain yield generally improved under the various forms of hedgerow intercropping plots with pruning applied as mulch whilst on the conventional plots, maize grain yield decline over the seasons. Mean maize grain yield was maintained higher under hedgerow intercropping (4.10 Mg ha^{-1}) over the non-hedgerows (3.64 Mg ha^{-1}) when no inorganic fertilizer was applied. The adoption of hedgerow intercropping and inorganic fertilizer application either alone or in their combination with the plant residues applied as surface mulch also improved maize grain yield.

Hedgerow intercropping improved fertilizer use efficiency by reducing the inorganic fertilizer requirement by half for comparable and sustainable higher maize production in the semi deciduous zone of Ghana. Thus the study confirmed that hedgerow intercropping can improve long term maize yield even under little application of inorganic fertilizers thereby conserving the environmental impact of agricultural production. The burning of plant residues at the beginning of every cropping season as a means of land preparation practice employed by most farmers led to cropland productivity decline with severe decline starting from the third season of continuous cropping.

CHAPTER 5: CHANGE IN CARBON MANAGEMENT INDEX UNDER HEDGEROW INTERCROPPING AND CONVENTIONAL SOIL MANAGEMENT PRACTICES

5.1 INTRODUCTION

Ghana's agricultural land management system is in transition. It is gradually changing from the traditional low-input slash and burn with intermittent long fallow periods for soil fertility regeneration, to a more sedentary land management practice with shorter fallow periods due to high population growth especially around urban areas and large communities (Tutu, 1996; Drechsel, 2002; IFPRI, 2004). As a result, farmers have fewer options of fertile natural lands to convert into croplands and are therefore compelled to continuously operate on parcels of low productive croplands under low input conditions. Cropland productivity therefore continues to rapidly decline leading to food insecurity, malnutrition, land degradation and rural poverty (Bonsu et al., 1999; World Bank, 2007; Diao et al., 2007; Naab et al., 2008). A major effect of this transformation is the continuous loss of soil organic matter (SOM) reaching as high as 50-75 % of the original C content in most tropical soils within 20 years of cropping (Dumanski and Lal, 2004). Consequently, there is the need to promote for adoption, land use practices such as agroforestry and other recommended management practices (RMP) that can improve soil quality and its resilience for sustainable food production and environmental sanity (Blair et al., 1995; Young, 1997).

Based on the above premise, several indices of cropland quality and its resilience to continuously support crop production have been proposed to assess the effect of different soil management practices. These have included the adoption of the minimum dataset (MDS) for soil quality assessment that uses soil properties such as bulk density, infiltration rate, total C and N content, pH and electric conductivity (Doran and Parkin, 1994). Later, Gregorich et al. (1994) proposed the inclusion of SOM in the MDS not only as a single factor but as an integrative attribute related to several other soil properties included in the MDS. It is in agreement with the above principle and the need for early prediction of likely future changes in soil quality as a result of land use or management change that Blair et al. (1995) proposed the adoption of Carbon Management Index (CMI) for soil quality assessment. Other authors however proposed the use of other conceptual SOC turnover models such as RothC (Jenkinson, 1990) and Century (Parton et al., 1987). These proposals have resulted from the fact that SOM has been identified as a very important component of cropland productivity, contributing a number of soil physical, chemical and biological properties, including acting as an important store and source of plant nutrients (Lal, 2010) especially under low input conditions.

The above observation also agrees with the new approach of improving cropland quality and productivity, especially for tropical soils. This approach encourages the reliance on enhancing SOM and biological activity as well as optimising nutrient cycling to reduce external inputs and maximize the efficiency of their use. It also focuses on exploring the use of the positive attributes of trees and plant residues on croplands as occurs under hedgerow intercropping used for maize production (Sanchez, 1994; 1995, Vanlauwe et al., 2001; Bationo et al., 2007). This approach is based on the assumption that tree litter and pruning application substantially help to maintain SOM, improve soil physical properties and enhance water-use efficiency as well as nutrient supply into croplands (Young, 1997; Sanchez, 2000; Nair et al., 2008).

Under hedgerow intercropping, hedges are regularly pruned with pruning retained on the soil as surface mulch contributing significantly in maintaining SOM levels through the supply of litter and root residues (ICRAF, 1993; Young, 1997; Vanlauwe et al., 1999). In addition, improved SOM helps in the supply of plant nutrient which is more significant under tropical conditions where soils contain highly weathered clay minerals dominated by Kaolinite as well as iron and aluminium oxide with about 10 $cmol_c$ kg^{-1} of Cation Exchange Capacity (CEC) (Theng, 1980; Vagen et al., 2005).

Even though several studies have been undertaken to assess the potential of hedgerow intercropping in improving croplands productivity, the effect of hedgerow intercropping on soil quality and its resilience to withstand the effects of continuous long term cropping regimes has not been fully explored in literature.

The objective of this study was therefore to evaluate the different variants of *Gliricidia* hedgerow intercropping and conventional cropland management practices used for continuous maize production over six cropping seasons for their capacity to promote soil quality on a *Ferric acrisol* in the semi deciduous forest zone of Ghana. The Carbon Management Index (CMI) originally proposed by Blair et al. (1995) is used as the soil quality indicator.

5.2 MATERIALS AND METHODS

The study location as well as the soil and environmental conditions of the study plots are described in chapter 3 of this thesis. Field experimental procedures and laboratory analytical protocols used for determining the different soil C fractions are also described in chapter 3.

5.2.1Carbon Management Index determination

The CMI was calculated for the top 0-15 cm soil depth using the weighed average content (expressed in Mg C ha^{-1}) of the total SOC (Mg C ha^{-1}), Labile C (Mg C ha^{-1}) and non-labile C (Mg C ha^{-1}) as described in chapter 3 by Blair et al., (1995) in the following mathematical procedures:

$$CMI = CPI \times LI \times 100 \qquad \text{Eqn. 14}$$

Where:

CPI is the Carbon Pool Index and LI is the Lability Index.

The CPI was determined as the ratio between the total C content (Mg C ha^{-1}) of the treatment (C pool in treatment) and the total C content (Mg C ha^{-1}) of the reference soil (C pool in reference).

The CPI was determined as:

$$CPI = \frac{\text{C pool in treatment}}{\text{C pool in reference}} \qquad \text{Eqn. 15}$$

The LI was determined as the ratio between the C lability of the treatment soil (L in treatment) and the C lability in the reference soil (L in reference) as shown in the equation below:

$$LI = \frac{\text{L in treatment}}{\text{L in reference}} \qquad \text{Eqn. 16}$$

The C lability is given as the ratio between the content of C (Mg C ha^{-1}) oxidized by the 60 mM $KMnO_4$ solution, designated as labile (content of labile C), and the content of C (Mg C ha^{-1}) not oxidized by the above solution, designated as non-labile (content of non-labile C):

$$L = \frac{\text{content of labile C}}{\text{content of non-labile C}} \qquad \text{Eqn. 17}$$

The Reference Soil:

For the use of CMI in assessing the effect of land management practice on soil quality, an adjacent native land under a secondary forest dominated by different tropical tree and volunteer *Leuceana* species, was selected as the reference soil with CMI of 100 as suggested by Blair (1995). Soil sampling of the reference soil was undertaken at the beginning of every cropping season, as well as at the end of the study, and the mean soil C properties used in computing the CMI of the study plots.

5.2.2 Statistical Analyses

The effect of cropland management practices and seasons was determined on CPI, LI, and CMI for the entire study period. Separate analysis of variance tests were done and significance of hypothesis for both main and interaction effects was set at probability level of less or equal to 0.05 ($p \leq 0.05$). Means were separated when ANOVA indicated significant differences at $p \leq 0.05$ using Tukey's test for means separation. The SAS software package was used. Described below are the effects tested and the statistical designs used:

Statistical designs

Cropland Management Practices

The effect of cropland management practices of CCBB, CCBM, CCMF, ACPM, ACPf, ACPM and ACPR, were determined on CPI, LI, and CMI at 0-15 cm soil depth in a randomized complete block design.

Cropland management practice and seasons

The effect of cropland management practices of CCBB, CCBM, CCMF, ACPM, ACPf, ACPM and ACPR at 0-15 cm soil depth over the seasons of Maj. 2005; Min. 2005; Maj. 2006; Min. 2006; Maj. 2007; Min. 2007; and Fin. 2008 was determined on CPI, LI, and CMI as a split plot in a randomised complete block design. Whole plot factors were the seven cropland management practices and sub-plot factors were the seven seasons.

5.3 RESULTS

5.3.1 Dynamics of soil quality under different cropland management practices

5.3.1.1. Effect of cropland management and seasons

The studied cropland management practices, seasons and interaction interactions significantly influenced ($p < 0.05$) mean levels of CPI, L, LI and CMI on the various plots during the three-year period, made up of six maize growing seasons on a *Ferric acrisol* within the semi-deciduous forest zone of Ghana (Table 5.1).

Mean CPI

Mean cropland CPI within the 0-15 cm soil depth over the entire three-year study period, ranged from 0.67 on the ACPR plot to 0.81 on the ACPM plot (Table 5.2). The highest CPI recorded on the mulched hedgerow intercropping plot (ACPM) was similar to the 0.8 recorded on the fertilized and mulched conventional plot (CCMF) and 0.73 recorded on the fertilized and mulched hedgerow intercropping plot (ACPF). Compared to the CPI at the start of this study, all the various forms of hedgerow intercropping plots improved their CPI status by the end of the study whilst under conventional conditions only the fully fertilized and mulched plot recorded improved CPI (Figure 5.1a). The highest CPI improvement of 44% however occurred on the ACPF plot. This study results indicate that with respect to the total C pool as expressed in CPI, absolute soil quality improvement over the six season of study was in the following order: ACPM = ACPF >ACPf > CCMF > ACPR > CCMB > CCBB (Figure 5.1a)

Table 5.1. Summary of p values of ANOVA results for the effects of cropland management practice, season, as well as cropland management practice and season interaction on total CPI, L, LI and CMI.

Source	Df	p-value			
		CPI	L	LI	CMI
Cropland Management	6	0.04	0.02	0.02	0.04
Season	6	0.0001	0.0001	0.0001	0.0001
Cropland Management * Season	36	0.01	0.001	0.001	0.02

Table 5.2. Overall means of CPI, L, LI and CMI within 0-15 cm soil depth under the different cropland management practices.

Cropland Management	CPI	L	LI	CMI
Reference soil	*1.00*	*0.11*	*1.00*	*100*
CCBB	0.68b	0.10a	0.89ab	61.3ab
CCBM	0.69b	0.11a	0.95a	64.2a
CCMF	0.80a	0.09ab	0.82b	66.7a
ACPM	0.81a	0.07c	0.60c	49.5bc
ACPf	0.68b	0.09a	0.84b	55.0bc
ACPF	0.73ab	0.10a	0.89ab	64.7a
ACPR	0.67b	0.07bc	0.64c	42.9c
SED	0.11	0.02	0.22	15

where CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, and full rate fertilizer; SED = standard error of the difference between means.
Columns means followed by different letters are significantly different at $p < 0.05$

Mean lability dynamics of the studied cropland management practices

Mean cropland L (which is the ratio between the concentration of labile C and the concentration of non-Labile C of a studied soil management practice) within the 0-15 cm soil depth, over the entire three-year study period, ranged from 0.07 on the ACPM plot to 0.11 on the CCBM plot. Similar highest mean cropland L levels were also recorded on CCBB, ACPF and ACPf plots (Table 5.2).

All the studied non-hedgerow plots recorded improved cropland L compared to the L levels at the start of this study. Under hedgerow plots however, only the ACPf recorded L improvement. The other hedgerow intercropping plots however, recorded reduced cropland L by the end of the study. The study revealed that full rate inorganic fertilizer application under non-hedgerow conditions improved cropland L from 0.05 to 0.1, which contrasted the L reduction from 0.14 to 0.07 under fully fertilized hedgerow conditions by the end of the study (Figure 5.1b).

Mean cropland lability index dynamics

Mean cropland LI (which is the ratio between C lability of a studied soil management practice and C lability of the reference soil) within the 0-15 cm soil depth, over the study period, ranged from 0.60 on the ACPM plot to 0.95 on the CCBM plot. Similar highest cropland LI was recorded on both CCBB and ACPF plots (Table 5.2).

All the studied non-hedgerow plots recorded improved cropland LI compared to the index at the start of this study whilst under hedgerow conditions only the ACPf recorded mean LI improvement. The other hedgerow intercropping plots however recorded reduced cropland LI by the end of the study ranging from 0.29 on the ACPM to 0.63 on the ACPF plots. Similar to the mean cropland L dynamics above, full rate inorganic fertilizer application under non-hedgerow conditions led to improved mean cropland LI of 92%, whilst under hedgerow conditions, it resulted in reducing cropland LI by -49% (Figure 5.1c).

Mean cropland carbon management index dynamics

Mean cropland CMI within the 0-15 cm soil depth, over the entire three-year study period, ranged from 42.9 on the ACPR plot to 66.7 on the CCMF plot. The highest mean CMI of 66.7 was similar to the levels recorded on CCBB, CCBM, ACPf and ACPF plots (Table 5.2). By the end of this study, all the non-hedgerow plots recorded improved CMI ($p < 0.05$) compared to the levels at the start of this study, ranging from 50% on the CCBM plot to 112% on the CCMF plot whilst under hedgerow plots only the ACPf recorded CMI improvement of over 133%. On the other hedgerow intercropping plots, the ACPM plot maintained similar CMI level by the end of the study period, whilst ACPR and ACPF recorded reduced CMI of -29% and -26% respectively (Figure 5.1d).

The study recorded variable effect of full rate inorganic fertilization under hedgerow and non-hedgerows on CMI. Whilst CMI improved by 112% under non-hedgerow conditions upon full rate full rate inorganic fertilizer application, under hedgerow conditions, full rate inorganic fertilizer use resulted in reducing cropland CMI by -26% with hedgerow pruning applied as surface mulch and -29% with hedgerow pruning removed. On the contrary, half rate inorganic fertilizer use for continuous maize cultivation led to the highest improved cropland CMI of 133% under hedgerow conditions (Figure 5.2). Similarly, the use of all plant residues as surface mulch every cropping season also resulted in 50% improved cropland CMI under non-hedgerow conditions, whilst under hedgerow conditions, it resulted in -26%

reduction in CMI by the end of six seasons of continuous maize cultivation on a *Ferric acrisol* within the semi-deciduous forest zone of Ghana.

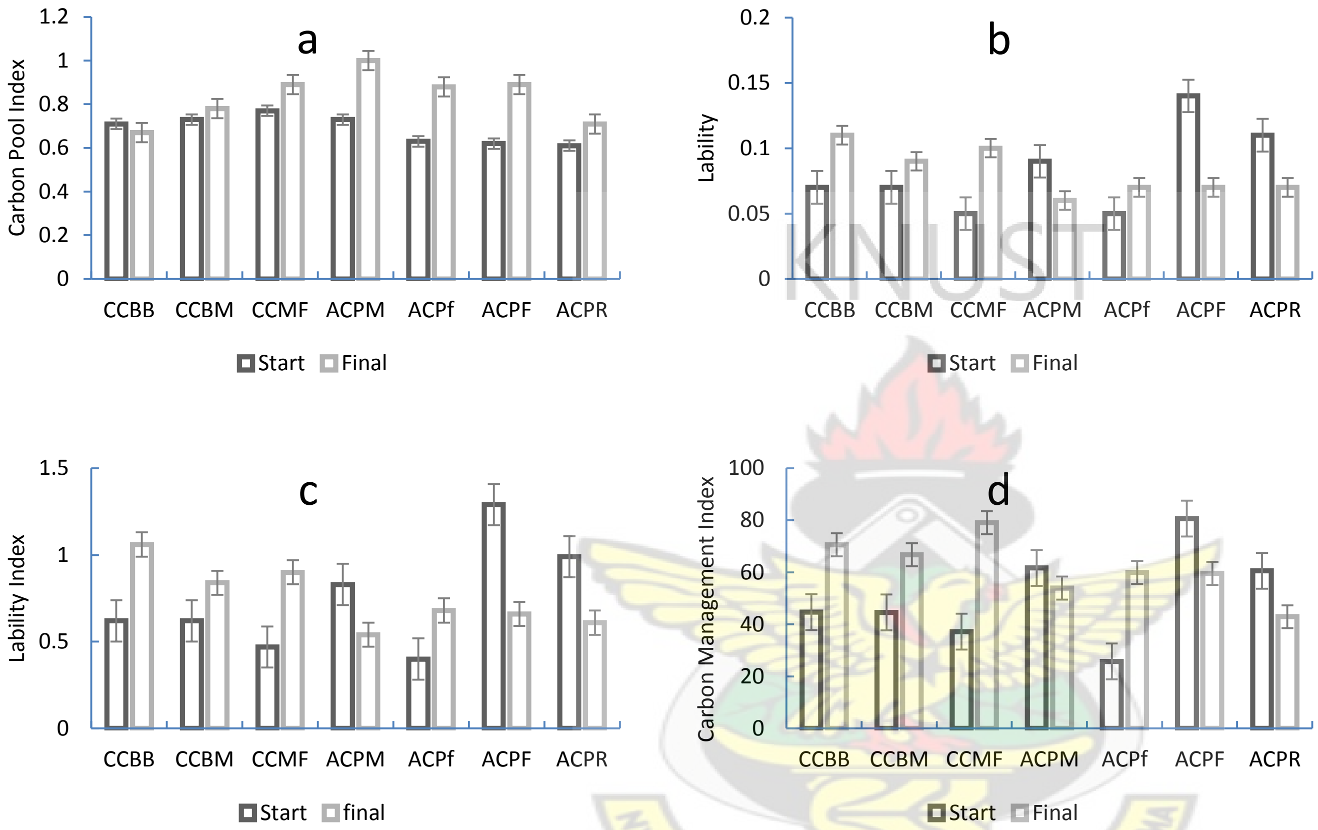


Figure 5.1. Comparison of the starting and final values of CPI (chart a), L (chart b), LI (chart c) and CMI (chart d) over the study period; where CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, full rate fertilizer

The overall potential of the studied cropland management practice to improve soil quality as expressed using CMI was in the following order: ACPf > CCMF > CCBB > CCBM > ACPM > ACPF > ACPR.

5.3.4 Relationship between carbon management index and other soil C fractions

There were variable relationships between CMI and some SOC fractions such as MBC/SOC and LC. There was a significant negative relationship between CMI and MBC/SOC (R^2 = 0.92, $p < 0.0005$) whilst CMI and LC recorded a significant positive relationship (R^2 = 0.89, $p < 0.0014$) by the end of this study (Fig. 5.2).

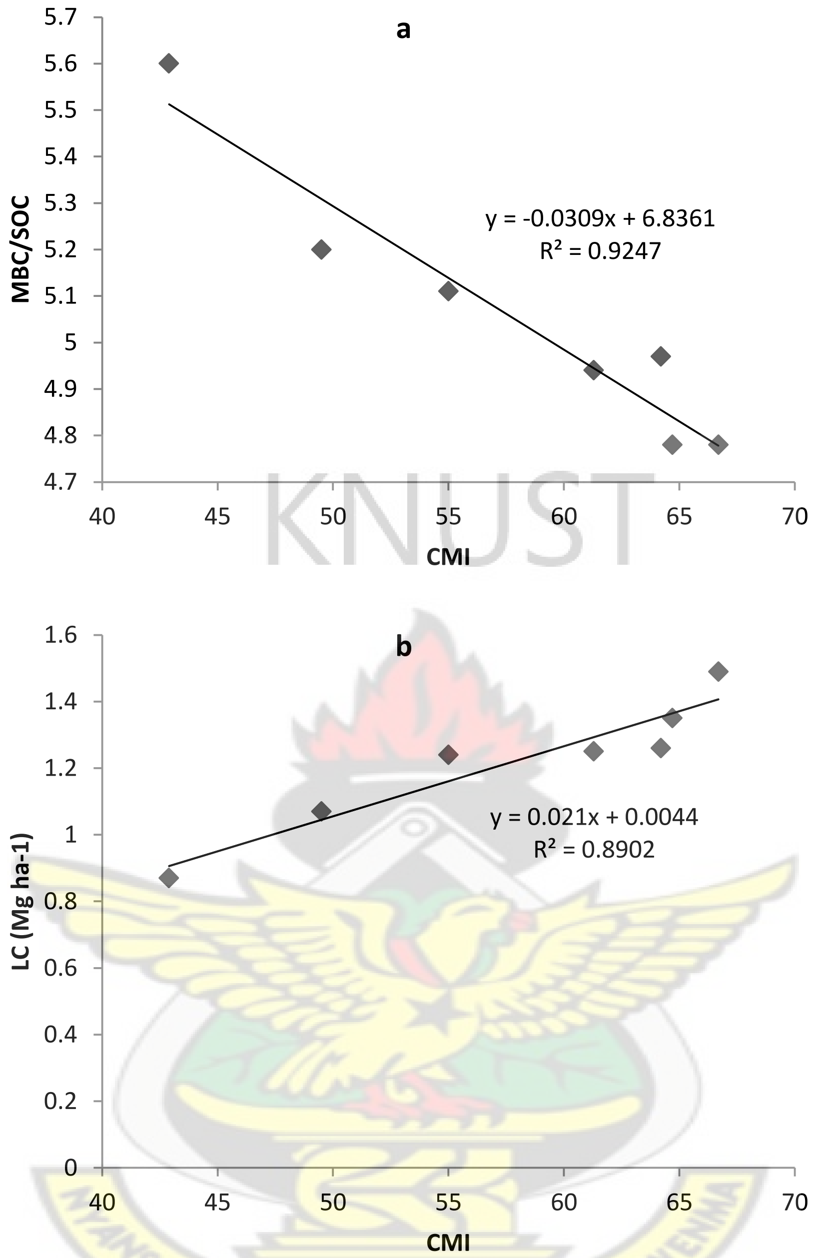


Figure 5.2. Relationship between CMI and MBC/SOC (a) and CMI and LC (b).

5.4 DISCUSSIONS

5.4.1 Mean Carbon Pool Index

Improvement in CPI recorded on all the mulched hedgerow plots of ACPM, ACPf, ACPF and ACPR could be attributed to the addition of large volumes of high quality pruning biomass of over 6.0 – 9.2 Mg ha^{-1} (chapter 4) every cropping season and also high hedgerow root turnover associated with *Gliricidia* hedgerow intercropping (Vagen et al., 2005; Haile, 2007; Makumba et al., 2007). Another reason for improved CPI on the hedgerow plots could have been due to N fixation capabilities of the hedgerow species that could have enhanced higher phytomass production of the intercropped maize. This could have resulted in the return of greater amounts of maize stover ranging from 3.65 to 4.36 Mg ha^{-1} (Chapter 4) as surface mulch to improve soil C status as observed by Bayer et al. (2000); Lal (2002) and Vieira et al. (2007). Total SOC improvement of up to 25% associated with surface mulch application of hedgerow pruning alone have also been reported by other authors including Tetteh (2004) and Yeboah et al. (2005) on similar soils under similar climatic conditions.

Similar CPI improvement on the fertilized non-hedgerow plot (CCMF), comparable to the hedgerow plots could be due to the increased and sustained maize productivity associated with increased inorganic fertilizer use (Chapter 4) that could also have returned higher amount of plant biomass into the soil thereby improving SOC stocks (Vanlauwe et al., 2001; Kramer, 2002; Naab et al., 2008). They reported over 65% improvement in maize grain and stover yield associated with the adoption of inorganic fertilization under similar tropical conditions. In addition, continuous cropping with biomass burning as a soil management practice reduced soil quality. Furthermore, hedgerow pruning removal from the cropland for other purposes rather than being used as mulch could be detrimental to the maintenance of CPI and soil quality (Table 5.2).

5.4.2 Carbon Lability (L) and Lability Index (LI)

Soil quality of the studied cropland management practices assessed using L and LI were contrary to the observation when soil quality was assessed using CPI. Under non-hedgerow conditions, all the studied management practices maintained improved soil quality (L and LI) compared to the levels at the start of the study (Fig. 5.1). Improvement in L and LI under non-hedgerow conditions could be attributed to the enhanced decomposition of the accumulated plant nutrients and SOM on the study plots before this experiment was established. In addition, the levels of SOM and plant nutrient before the start of the study could have helped to sustain the production and return of adequate amounts of plant residue into the soil medium to sustain higher levels of L and LI in the croplands over the three years.

Regular plant residue burning could also have contributed readily available plant nutrients such as P and K to support cropland productivity and hence sustain cropland labile C levels over the three year period. It is however believed that the three year study period was not long enough to observe severe cropland soil quality degradation as measured using L and LI associated with conventional soil management practices as suggested by Blair et al. (1997) and Vieira et al. (2007). The maintenance of even higher levels of L and LI under fertilized non-hedgerow conditions could have been due to the sustenance of higher cropland productivity of over 5.3 Mg ha^{-1} and 4.4 Mg ha^{-1} mean maize grain and stover yield respectively, that could have returned higher crop residue biomass into the soil to sustain higher LC level throughout the study period as was also observed by De Bona et al. (2008) on a subtropical *Acrisol*.

Under hedgerow conditions, soil quality assessed using LI, was improved only upon the application of half rate inorganic fertilizer (Figure 5.1c). This could be attributed to the supporting role of lower doses of inorganic fertilizer in sustaining higher cropland productivity under hedgerow intercropping (Chapter 4). Higher phytomass productivity on the ACPf plot could have helped return greater amounts of plant biomass of 4.4 and 7.5 Mg ha^{-1} mean maize stover and pruning yield respectively every cropping season, needed to sustain higher L and LI. This observation has been the underlying principle of integrated soil fertility management (ISFM) that has been developed and promoted to help sustain the productivity of tropical cropland for maize production (Vanlauwe, et al., 2001; Kramer, 2002; Tetteh, 2004, Bationo et al., 2007). In addition, Tetteh (2004) argued that the regular addition of plant residue of varying quality also ensures better synchronization of plant nutrient releases into the soil medium and uptake by the associated maize crop that could promote cropland productivity and subsequent SOM increase.

The other forms of hedgerow intercropping studied (ACPM, ACPF and ACPF) however suffered reduction in L and LI during the period. This reduction could be attributed to the fact that the introduction of high quality *Gliricidia* hedgerow pruning mulch alongside possible N fixation, could have created favourable condition for higher microbial SOM mineralization leading to reduced L and LI. Under non-fertilized and mulched hedgerow condition (ACPM), the reduction of L and LI could have been exacerbated by the effect of competition of the hedgerow species for plant nutrient and water resource that could have adversely affected soil SOM dynamics at the expense of cropland productivity (chapter 4). Similarly, the reduction of L and LI could have resulted from the production of more stable form of soil C from the tree component (C3 plants) that could enhance total SOC rather than labile fractions of soil C as reported by Haile (2007). He observed that most of SOC in deeper soil profiles and the relatively stable forms of SOC were derived from C3 plants rather than the C4 components in a tree-based mixed cropping system.

Upon the application of full rate of inorganic fertilizer (ACPF), L and LI reduction could have been exacerbated by the potential of higher doses of inorganic fertilizers to enhance SOM mineralization as a result of possible reduction in soil aggregates stabilization that has negative effect on the accumulation of aggregate associated SOM (Six et al., 2000; Sarkar et al., 2003; Fonte et al., 2009). Six et al. (2000) argued that the effect of higher doses of inorganic fertilizer application on soil aggregation degradation and hence SOM mineralization, was equivalent to the effect of tillage on soil aggregation. The above observation however contrasted the results of other studies where soil aggregation increased upon inorganic fertilizer application as observed by Hati et al. (2006).

The lowering of L and LI under ACPR was not unexpected since the regular removal of over 5 Mg ha^{-1} high quality *Gliricidia* biomass from the cropland every cropping season (chapter 4) could have led to the reduction of cropland productivity as well as SOM and its associated L and LI. In addition, the adverse effect of tree species competition for nutrient and other resources could have also reduced cropland productivity and associated L and LI. Moreover the adverse effect of inorganic fertilizers on soil aggregation under hedgerow conditions, as observed by Six et al. (2000), could have enhanced the SOM depletion which could have reflected in reduced L and LI.

In principle, increasing levels of L and LI indicates the capacity of the various management practices to maintain higher level of labile C and sustain soil quality (Blair et al., 1995; De Bona et al., 2008). In this study however, the monitoring of cropland L and LI within the 0-15 cm soil depth could not have accounted for the labile fractions of soil C in lower soil layers that are closely linked with the C3 tree components as suggested by Haile (2007). It is however important to consider that lower L or LI does not necessarily mean lower total C stock of the cropland but rather an indication of its future dynamics (Blair et al., 1995).

5.4.3 Carbon management index

Highest CMI improvement of 133% under the half-rate fertilized and mulched hedgerow intercropping management systems (ACPf) is a reflection of the improved LI that resulted from the gradual build up of LC, CPI as well as cropland productivity (Chapter 4). This improvement could have resulted from the regular addition of large quantities of over 7.5 Mg ha^{-1} high quality *Gliricidia* pruning every cropping season, possible higher root biomass turnover from the hedgerows and also the higher return into the soil from the intercropped maize stover of 4.4 Mg ha^{-1} (Chapter 4). This result is similar to the observation reported by several authors including Vanlauwe et al. (2001); Lal (2002); Bationo et al. (2007) and Makumba et al. (2007). In addition, the application of lower doses on inorganic fertilizers under hedgerow conditions could have contributed in creating a very favourable condition for improved and sustainable cropland productivity and resulted in highest cropland quality improvement measured using CMI.

Cropland productivity improvement under ACPf could have been higher enough to counterbalance the possible effect of competition for nutrients and soil moisture from the hedgerow species that could have helped to reduce soil quality on the hedgerow plot where no inorganic fertilizer was applied (ACPM). The above results therefore supports the principles of integrated soil fertility management that encourages the judicious use crop residues in combination with lower doses of inorganic fertilizers in enhancing the productivity of tropical cropland for sustainable crops production (Tetteh, 2004; Yeboah, 2007).

The 26% reduction in CMI upon full-rate inorganic fertilizer use under hedgerows with pruning applied as surface mulch (ACPF) was not expected. The reduced soil quality was not a reflection of cropland total SOM dynamics expressed in CPI and also cropland productivity since maize grain and stover yield were maintained highest throughout the study period (Chapter 4). Several authors including Blair et al. (1995), Vieira et al. (2007) and De Bona et al. (2008) have reported higher correlation between improved cropland quality and improved productivity as well as SOM. It is however believed that the reported CMI reduction in this study could have been due to enhanced SOM mineralization as a result of the soil aggregate degradation effect of higher doses of inorganic fertilizer use on tropical croplands as reported by Six et al. (2000); Sarkar et al. (2003) and Fonte et al. (2009). In addition, the return of higher amount of *Gliricidia* pruning could have helped to create favourable conditions for enhanced soil microbial mineralization of SOM.

Soil quality improvement on the fertilized non-hedgerow plot (CCMF) was also consistent with the improved cropland productivity (chapter 4) as well as improved SOM expressed in CPI. Soil quality improvement on the CCBB and CCBM was contrary to the cropland productivity as well as SOM dynamics and is expected to have experienced CMI reduction if the study had lasted longer than the three years as suggested by Blair et al. (1997) and Vieira et al. (2007).

The monitoring of CMI within the 0-15 cm soil depth under both hedgerow and non-hedgerow conditions in this study did not allow for the complete accounting of SOM and soil quality dynamics within the agro-ecosystems since hedgerow species (C3 plants) had the potential of enhancing SOM in deeper soil profiles than the C4 components in a tree-based mixed cropping system (Haile, 2007).

This study demonstrated a strong relationship of CMI with other soil quality indicators as MBC/SOC and LC but not with soil chemical and physical properties as well as cropland productivity (Figure 5.2). The result therefore supports the proposition of CMI to be used as a credible indicator of cropland quality under tropical conditions (De Bona et al., 2008; Vieira et al., 2007).

5.5 SUMMARY AND CONCLUSIONS

The study assessed the effect of the various cropland management practices on improving soil quality and its resilience for sustainable and continuous maize production using CMI as the soil quality indicator. The study revealed that cropland management practices and seasons variably influenced soil quality as measured by CPI, L, LI and CMI.

Soil quality was best improved upon the adoption of hedgerow intercropping for continuous maize cropping at reduced level of inorganic fertilizer application on a *Ferric acrisol* within the semi-deciduous forest zone of Ghana. Soil quality was however reduced upon the application of full rate inorganic fertilizers under hedgerow conditions with hedgerow pruning applied as surface mulch or removed. Soil quality was also lowered under hedgerow conditions when no inorganic fertilizer was applied to support continuous maize production. Under non-hedgerow conditions, soil quality improved over the three years of continuous maize cultivation upon the adoption biomass burning, application of all plant residues as surface mulch as well as upon the adoption of inorganic fertilizer use.

The overall potential of the studied cropland management practice to improve soil quality was in the following order: ACPf > CCMF > CCBB > CCBM > ACPM > ACPF > ACPR.

Soil quality assessed using CMI was closely related to other soil quality indicators as MBC/SOC and LC.

CHAPTER 6: GENERAL DISCUSSION

6.0 INTRODUCTION

This chapter discusses the conclusions with respect to the initial research objectives and hypothesis as well as summarises the salient results of the study and also include some suggestions for directing future research in soil carbon sequestration studies.

6.1 STUDY CONCLUSIONS

Soil C stocks build up potential

Highest soil C stocks build-up of 4.02 Mg C ha^{-1} $year^{-1}$ is attainable under hedgerow intercropping adopted for continuous maize production within the semi deciduous forest zone of Ghana (Chapter 3). This was obtained under hedgerow conditions when no inorganic fertilizers were applied (ACPM). The sequestration rate obtained in this study was very significant, considering the fact that the study was established on a plot that had undergone a six-year *Gliricidia sepium* fallow but not on a degraded land that could have resulted in a higher C sequestration rate with higher environmental and socio-economic returns

Cropland productivity improvement and net returns on inputs

Inorganic fertilizer application under both hedgerow (ACPf, ACPF, ACPR) and non-hedgerow (CCMF) conditions produced similar highest mean maize grain yield over the six seasons study period. However maize grain yield levels on all the non-hedgerow plots had started to decline by the end of the sixth season, whilst under hedgerow conditions maize grain yield were sustained but declined only upon hedgerow pruning removal (ACPR).

The mean maize grain yield of 5.0 Mg ha^{-1} obtained under half rate fertilized hedgerow (ACPf) conditions, makes hedgerow intercropping potentially very attractive to the resource poor farmers who form the majority of farmers and are operating low-input subsistence production systems within the ecological zone. In terms of net returns on input, the adoption of hedgerow intercropping with half rate (ACPf) and full rate inorganic fertilizer application (ACPF) produced additional 1.8 and 2.0 Mg ha^{-1} maize grain yield respectively, over the traditional farmer practice of regular plant residue burning (CCBB) at the beginning of every cropping season. The productivity improvement could have been higher if the study had continued beyond the three-year study period because the traditional farmer practice had started experiencing severe yield decline by the third year of continuous cropping as discussed in Chapter 4. In this study, hedgerow intercropping was able to reduce the inorganic fertilizer requirement by almost 50 % for sustainable maize production in the semi deciduous zone of Ghana.

Soil quality improvement associated with hedgerow intercropping

Soil quality improvement, which describes the resilience of the cropping system in reducing the risk of crops failure under unfavourable climatic conditions, the adoption of hedgerow intercropping, with lower doses on inorganic fertilizer use (ACPf), for continuous maize cropping was able to promote highest soil quality and its resilience as measured using CMI. Regular hedgerow pruning removal (ACPR) and biomass burning (CCBB) however reduced cropland quality (Chapter 5). Observed high CMI improvement under hedgerow condition was also attained on the plot that recorded similar highest maize grain yield improvement. Soil quality improvement therefore, could have resulted from improved cropland productivity and associated higher soil LC content that provided readily available plant nutrients, stabilized soil aggregates, controlled soil erosion, improved soil nutrient and moisture retention as well as enhanced soil biodiversity. These attributes could have effectively counterbalanced the effects of hedgerow species competition for nutrients and soil moisture, fertilizer related soil aggregate degradation, harsh environmental conditions as drought during the growing season, high temperatures and increased soil erosion that are prevalent in the semi deciduous forest zone of Ghana.

Overall conclusions

This study concludes that hedgerow intercropping of *Gliricidia sepium* for continuous maize production on a *Ferric acrisol* in the semi deciduous forest zone of Ghana is able to build up SOC, improve cropland productivity and also enhance soil quality compared to continuous maize cropping under non-hedgerow conditions. It therefore demonstrates the potential of hedgerow intercropping in soil C accumulation on tropical croplands whilst ensuring sustainable cropland productivity and food security. In addition, hedgerow intercropping also enhanced efficiency of inorganic fertilizer use under tropical condition as was reflected in higher maize yield gains per unit of applied inorganic fertilizer.

The study confirmed that improving soil C stocks is indeed a development strategy with greater potential within the tropics in sustaining environmental quality by reducing CO_2 concentration in the atmosphere whilst sustaining cropland productivity and ensuring food security for the growing population. On croplands productivity and socio-economic development, the adoption of hedgerow intercropping for sustainable maize production offers hope in addressing food insecurity, malnutrition, poverty and environmental degradation challenges within the low input crops production systems of the semi deciduous zone. It also addresses the global climate change issues associated with food production including increasing temperatures, decreasing rainfall effectiveness, increasing frequency of extreme weather events and increasing soil degradation as described by Lal (2010).

In terms of energy use efficiency, this study demonstrates that non-application as well as lower doses of inorganic fertilizer use under hedgerows improved Soil C as well as increased maize grain yields whilst improving soil quality. This implies that the adoption of hedgerow intercropping for continuous maize production in the semi deciduous forest zone of Ghana is capable of reducing the inorganic fertilizer requirement for sustainable agriculture. Considering the fact that many agricultural ecosystems in the tropics are nitrogen-limited and also inorganic fertilizer production is an energy intensive activity emitting about 1 kg C for the manufacture and transportation 1 kg N fertilizer (Janzen et al., 1999), hedgerow intercropping offers a more environmentally friendly land management option that reduces fossil fuel energy requirement in agriculture whilst reducing the release of CO_2 into the atmosphere and its associated global warming.

6.2 RECOMMENDATIONS

Addressing constrains to soil organic carbon measurements: Research focus

Soil carbon accounting research is still in its infancy on African croplands. Thus there is almost an endless list of future research topics that are of interest in providing answers to current information gaps. Even though many lessons and best practices can be learned from other parts of the world, it is relevant that best-fit options are identified and evaluated under the low input agriculture conditions using participatory approach. In practice however, there exist significant differences in the methods and procedures adopted for soil C sequestration dynamics studies by researchers. This has resulted in lack of uniformity and rigor in the generated research datasets (Nair et al., 2009). However, current global interest in ecosystem C dynamics demands that effective and objective C accounting methodologies and standards are developed and adhered to in addressing some of the following deficiencies in SOC measurement. This would enable farmers, environmentalists and other C trading practitioners to fully explore the potential and benefits of croplands C sequestration of agroforestry for productivity enhancement and C trading purposes.

i. Soil related constraints

An important constraint to current assessment of Soil C stock in SSA is that soil organic C study results are usually estimated at different soil depth by different authors thereby creating some difficulty in comparing such results. Available data ranges from 0-5 cm to as deep as 0-200 cm soil layer which has resulted in such variability in Soil C values ranging from as low as 1.25 Mg C ha^{-1} to as high as 173 Mg C ha^{-1} reported in literature (Vagen et al., 2005; Nair et al., 2009). However, most studies showing significant improvement in soil C have been limited to the topsoil layer of 0-20 cm (Nair et al., 2009). Comparison of different results from different soil depth therefore requires the use of soil depth adjustment factors which could introduce so much variability into such comparative studies.

Time of soil sampling which is influenced by the weather as well as the above and below ground biomass dynamic has also been shown to influence SOC content. This makes the time and season of soil sampling very crucial to accurately quantify SOC content. Vagen et al. (2005) therefore recommends that organic C measurements are carried out at different periods and seasons of the year instead of the one-time measurement often reported in literature.

In addition, differences in soil sampling techniques and soil analytical procedures also confound the limitations associated with current research results by different authors. The use of different equipment and reagents that have variable effect and sensitivity in determining components and fractions of soil C status, add to the uncertainty of current estimates (Lal., 2004).

Similarly, different soil series have variable potential to accumulate soil C under agroforestry conditions. This is because in practice, the different crop and tree species have different productivity levels on the different soils series based on weather (moisture and temperature), physical properties, fertility levels or the level of soil degradation at the establishment of the agroforestry programme (Watson et al., 2000; Albrecht and Kandji, 2003; Hutchinson et al., 2007). The different tree species have also been shown to integrate differently with different associated crops for crops productivity improvement and C sequestration purposes (Albrecht and Kandji, 2003; Nair et al., 2009).

There is also a great uncertainty regarding the size of the potential C stock a particular soil series could sequester. In principle, soils are not able to indefinitely accrue C stock but rather achieve a dynamic equilibrium point which they are not able to exceed (Young, 1997; Lal, 2004). This potential has also been shown to depend greatly on climate, soil physical and chemical properties as well as selected tree species and associated crops (Hutchinson et al., 2007).

Another important limitation is the uncertain estimate of soil bulk density due to methodological problems. The different methods used by different authors (i.e., core method, clod method etc.), contribute to uncertainty in soil C estimates (Vagen et al., 2005) which presents an important constraint in interpreting such study results. They also argue that the current interest in the use of modelling techniques in estimating SOC dynamics for longer period of time, even though addresses some methodological challenges associated with the establishment of long term C monitoring study trials, also introduce other form of statistical inaccuracies associated with the required data input into the models.

I propose that future research effort should therefore explore the establishment of certain standard sets of procedures and protocols that could be adopted and adhered to by all research workers to regulate the conduct of soil C stock determination activities on hedgerow intercropping plots and other agroforestry systems. In situation where different methods are used, standard conversion factors could be adopted. Consistent with this, future research efforts need to take into consideration strategies to address the above challenges including acceptable method of soil bulk density determination, depth of soil sampling, time and periods of soil sampling as well as standard analytical methods effective under tropical conditions. Such studies must be undertaken on the major benchmark soils of Ghana as well as in Africa for optimum SOC sequestration and cropland productivity improvement for ease of extrapolation and technology transfer.

ii. Root and below ground biomass carbon accounting constraints

In practice, most soil C accounting procedures do not report on the below ground biomass components (Schroth et al., 2007; Nair, 2009). Estimates of soil C stock in deeper layers where most of the roots occur are generally lacking in literature. This is partly because the dynamics of growth, decay and turnover of roots has been described as one of the least understood aspects of below ground interactions in agroforestry (Schroth et al., 2007). As a result soil C status under agroforestry and other land use systems that have tree components becomes significantly underestimated.

The severity of soil C underestimation is based on the fact that trees roots form a significant part of soil C and could store a considerable amount of C in deeper soil layer which also confer a longer residence time of C (Akinifesi et al., 2004). They estimate that more than half of the C assimilated by plants is eventually transported below ground via root growth and turnover. Moreover, whilst the fine roots of both tree and crops have a relatively fast turnover under hedgerow intercropping and other tree-crop ecosystems, the lignified coarse roots are found to decompose slowly and contribute substantially to below ground C stock (Vanlauwe et al. 1996). Future research effort should adopt standard procedures for accurate quantification of the contribution of root systems in soil C accounting procedures. It is recommended that a standard soil depth for measuring SOC is adopted for hedgerow intercropping and other agroforestry systems because of the peculiar tree and crop integration.

iii. Tree species selection and integration

In agroforestry, tree species selection for C sequestration purposes is still yet to be clarified due to the physiological differences among tree species as well as the environmental variability of croplands. The choice of a "native" species with supposedly better adaptability to local conditions over the "exotic" species will continue to remain a controversy in science (Kumar et al., 1998; Nair, 2007). This controversy has resulted from the over three decades of promoting exotic species in tree crop plantations and agroforestry programmes over the use of the "native" species in the tropics (FAO, 2007). Another aspect of uncertainty is the differences in wood quality of species in relation to their C sequestration rates.

In practice, wood of slower growing species is usually of higher specific gravity than the fast growing species such that the slow growing species accumulate more C in the long term (Baker et al., 2004; Bunker et al., 2005). Moreover these high specific gravity woods are used as construction timber, furniture and wood craft that also constitute a longer term sink for fixed C than the low-specific gravity wood which are used for short lived purposes as packing cases and poles (Nair et al., 2009). However, under hedgerow intercropping conditions where more pruning are required as mulch from tree species with higher biomass turnover and also for rapid mineralization to supply plant nutrients for the associated arable crops, the choice of tree species become very critical for C sequestration and cropland productivity purposes.

Also critical is the choice of N_2 fixing species over the non-N_2 fixing species in agroforestry. Research has shown that mixed planting of N_2 fixing tropical species with other non N_2 fixing species lead to more biomass production as well as greater resistance to disease and insect outbreak compared to their monocultures and therefore offer a better option for ecosystem sustainability (Bauhus et al., 2004; Jactel et al., 2005; Forrester et al., 2006). Other tree management regimes as stand density, design of planting schemes and orientation, pruning regimes and its management are critical in promoting soil C sequestration (Kumar et al., 1995).

Future research efforts must therefore focus on developing optimum tree species selection and management protocols for enhanced soil C sequestration for the various ecological zones since tree productivity is closely related to its climatic conditions. Tree species research must also lead to improved soil C sequestration alongside associated crop productivity improvement.

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APPENDIX

Appendix 1

Seasonal soil bulk density dynamics within 0-15 cm soil depth monitored over the study period

Management Practice	Maj. 2005[2]	Min. 2005	Maj. 2006	Min. 2006	Maj. 2007	Min. 2007	Fin. 2008
				($g\ m^2$)			
CCBB[1]	1.25a	1.25ab	1.31b	1.39a	1.39a	1.35ab	1.36a
CCBM	1.27a	1.29a	1.43a	1.33b	1.39a	1.37a	1.36a
CCMF	1.18b	1.24ab	1.37ab	1.28b	1.31bc	1.27c	1.27c
ACPM	1.14b	1.17c	1.18c	1.27b	1.26bc	1.28c	1.35ab
ACPf	1.04c	1.09d	1.17c	1.15c	1.17d	1.19a	1.25c
ACPF	1.16b	1.23b	1.33b	1.29b	1.28bc	1.28c	1.32b
ACPR	1.27a	1.28a	1.36b	1.35ab	1.36ab	1.32bc	1.34ab

[1] CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, full rate fertilizer;

[2] Maj. 2005 represents results obtained during major season of 2005; Min. 2005 represents results obtained during minor season of 2005; Maj. 2006 represents results obtained during major season of 2006; Min. 2006, represents results obtained during minor season of 2006; Maj. 2007 represents results obtained during major season of 2007; Min. 2007 represents results obtained during minor season of 2007 and Fin. 2008 represents final level at the end study in 2008.

Columns means followed by different letters are significantly different at $p < 0.05$

Appendix 2

Seasonal soil organic carbon mass dynamics within 0-15 cm soil depth monitored during the study period.

Management Practice	Maj. 2005[2]	Min. 2005	Maj. 2006	Min. 2006	Maj. 2007	Min. 2007	Fin. 2008
				(Mg ha^{-1})			
CCBB[1]	18.75b	20.12ab	16.70d	15.99c	16.11c	17.54bc	19.42d
CCBM	19.42ab	18.74b	18.04c	19.11bc	16.01c	15.98c	20.77cd
CCMF	20.44a	18.59b	20.74a	24.77a	21.57a	19.34b	24.93bc
ACPM	19.23ab	18.19c	19.26bc	23.34a	20.94a	22.82a	31.29a
ACPf	16.64c	14.91c	18.58c	18.38c	20.27a	13.67cd	27.32b
ACPF	16.42c	17.97d	19.67b	21.01b	18.32b	18.29b	23.64c
ACPR	16.20c	20.78a	17.24d	17.35c	17.02bc	15.87c	18.87d

[1] CCBB represents continuous cropping with no fertilizer application and plant biomass burnt; CCBM - continuous cropping with no fertilizer application and plant residue mulch; CCMF - continuous cropping with full rate fertilizer application and residue mulch; ACPM - alley cropping with pruning and plant residue mulch, and no fertilizer; ACPf - alley cropping with pruning and plant residue mulch, and half rate fertilizer; ACPF - alley cropping with pruning and plant residue mulch, and full rate fertilizer; ACPR - alley cropping with pruning removed, full rate fertilizer;

[2] Maj. 2005 represents results obtained during major season of 2005; Min. 2005 represents results obtained during minor season of 2005; Maj. 2006 represents results obtained during major season of 2006; Min. 2006, represents results obtained during minor season of 2006; Maj. 2007 represents results obtained during major season of 2007; Min. 2007 represents results obtained during minor season of 2007 and Fin. 2008 represents final level at the end study in 2008.

Columns means followed by different letters are significantly different at $p < 0.05$.