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Soil carbon change and CO_2 fluxes under different agricultural land use in the Vea catchment, Upper East Region of Ghana

By

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in

CLIMATE CHANGE AND LAND USE

DECLARATION

I hereby declare that the submission of this thesis is my own work towards the Doctor of Philosophy in Climate Change and Land-use and that, to be the best of my knowledge, it contains no material previously published by another person, nor material which has been accepted for the award of any degree of the University, except where due acknowledgement has been made in the text.

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ABSTRACT

Soil organic carbon is an index for soil fertility and sustainable land management. Monitoring soil respiration and carbon provide quantitative information on soil carbon stocks at a given location. This study assessed soil carbon change across predominant land-uses and soil types in the Vea catchment of Upper East Region, Ghana. The goal was to assess soil carbon change and CO_2 emissions from selected (rice, maize, millet and sorghum) cropping systems in the Vea catchment. To achieve this, farmers were interviewed for information on cropping history; establish the proportion between land use and soil type; determine crop yield components, yield and biomass for selected crops under different tillage (i.e. power tiller, bullock and manual) and amendment; estimate soil carbon stock; and determine the fractions and future trend of soil carbon stock and measure soil CO_2 flux using respiration chamber under different land uses. The majority of the land is occupied by cropland about 41 % with 63 % of Leptosols, 52 % of Fluvisols and 46 % of Lixisols (i.e. the three main soil type) being cultivated. The highest grain yield obtained was 5675 kg/ha, 1375 kg/ha and 970 kg/ha for rice, maize and sorghum, respectively. The mean soil organic carbon stock for the major land-uses obtained in the study area were 10.24 ± 1.2 t/ha for cereals (maize and sorghum), 14.96 ± 2.4 t/ha for paddy irrigated rice 15.88 ± 2.1 t/ha for semi natural area, 16.53 ± 2.3 t/ha for grazing area, 18.5 ± 4.9 t/ha for eucalyptus forest and 23.5 ± 7.1 t/ ha for paddy rain fed rice. Eucalyptus forest had high carbon stock, but this carbon is mainly composed of the light fraction, which is a non-stable fraction. The Introductory Carbon Balance Model (ICBM) simulation revealed a future trend of soil carbon depletion of 8 - 15 % was obtained continuous cereal (i.e. maize and sorghum) production with or without fertilisation with the current management system. However, fertilised maize production in rotation with groundnut will prevent the depletion of soil carbon stock. Soil CO_2 emission had similar trends under the maize - kenaf and sorghum - kenaf cropping systems. However, the cumulative soil CO_2 emission for sorghum - kenaf cropping system was higher (22 %) than that of maize - kenaf cropping system. The study also showed that the trend of soil CO_2 emission was different for the different management practices (power tiller, bullock and manual tillage) of rice. Furthermore, the soil CO_2 emission was sensitive to soil moisture stress but not soil temperature for maize and sorghum cropping systems. For high yield but low CO_2 emission, rice cropping system with bullock tillage and urea in deep placement (UDP) as amendment as well as power tillage with NPK + urea application are the best options for climate change mitigation for rainy and the dry season under irrigation, respectively. Therefore cereal-legume rotation is one of the best ways to sustain SOC in the study area.

RESUME

Le carbone organique du sol est un indice pour la fertilité des sols et la gestion durable des terres. Le monitoring de la respiration du sol et du carbone fournit des données quantitatives sur les stocks de carbone dans le sol à un endroit donné. Cette étude a évalué le changement du carbone du sol dans les prédominantes utilisations des terres et types de sols dans le bassin versant de Vea de la Haute région de l’Est du Ghana. L'objectif était d'évaluer le changement du carbone des sols et les émissions de CO_2 provenant des systèmes de culture sélectionnés (riz, maïs, mil et sorgho) dans le bassin versant de Vea. Pour ce faire, les agriculteurs ont été interrogés sur l'historique culturale; établir la proportion entre l'utilisation des terres et le type de sol; déterminer les composantes du rendement des cultures, le rendement et la biomasse pour les cultures sélectionnées sous différents labour (à savoir motoculteur, charrue et houe) et amendement; estimer le stock de carbone du sol; déterminer les fractions et la tendance future des stocks de carbone et de mesurer le flux de CO_2 du sol en utilisant la chambre de respiration sous différents types d’utilisation des terres. La majorité des terres est occupée par les terres cultivées environ 41% avec 63% de Leptosols, 52% de Fluvisols et 46% de Lixisols (à savoir les trois principaux types de sol). Le rendement du grain le plus élevé obtenu était de 5675 kg / ha, 1375 kg / ha et 970 kg / ha respectivement pour le riz, le maïs et le sorgho. Le stock moyen de carbone organique du sol pour les principales utilisations des terres dans la zone d'étude était de 10,24 ± 1,2 t / ha pour les céréales (maïs et sorgho), 14,96 ± 2,4 t / ha pour le riz irrigué 15,88 ± 2,1 t / ha pour les zones semi naturelles, 16,53 ± 2,3 t / ha pour les zones de pâturage, 18,5 ± 4,9 t / ha pour les forêts d'eucalyptus et de 23,5 ± 7,1 t / ha pour le riz pluvial. La forêt d'eucalyptus avait le stock de carbone le plus élevé mais ce carbone est principalement composé de la fraction non-stable. La simulation avec le modèle Introductory Carbone Balance Model (ICBM) a révélé une tendance future appauvrissement des sols en carbone de 8 - 15% pour la production continue les céréales (à savoir de maïs et de sorgho) avec ou sans apport de fertilisation dans le système actuel système de production. Cependant, la production de maïs avec apport de fertilisation et en rotation avec l'arachide permettra d'éviter l'épuisement du stock de carbone dans le sol. Les émissions de CO_2 du sol ont montrées des tendances similaires dans le cadre des systèmes de culture du maïs - kénaf et sorgho - kénaf. Cependant, les émissions cumulées de CO_2 du sol pour le sorgho - kénaf système de culture était plus élevé (22%) que celles du maïs - kénaf système de culture. L'étude a également montrée que la tendance des émissions de CO_2 du sol était différente pour les différentes pratiques culturales (motoculteur, charrue et labour manuel) de riz. En outre, les émissions de CO_2 du sol étaient sensibles au stress hydrique du sol, mais pas la température du sol pour les systèmes de culture de maïs et sorgho. Pour un rendement élevé avec une faible émission de CO_2, le système de culture de riz avec labour á la charrue et l’utilisation des granules (briquettes) d'urée en placement profond (UDP) comme amendement ainsi que le labour avec motoculteur et NPK + d'urée comme fertilisation sont respectivement les meilleures options pour atténuer les changements climatiques pour

les cultures pluviale et irriguée pendant la saison sèche. Par conséquent, la rotation des céréales avec les légumineuses est l'un des meilleurs moyens de soutenir SOC dans la zone d'étude.

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ACRONYMS

AFF : Afforestation

ANOVA : Analysis of Variance

BD : Bulk density

C : Carbon

Ca : Calcium

CIMMYT : International Maize and Wheat Improvement Center

CO_2 : Carbon dioxide

DOC : Dissolved Organic Carbon

DOY : Day of Year

ECEC : Effective Cation Exchange Capacity

EDTA : Ethylene diamine tetra-acetic acid

FAO : Food and Agriculture Organisation

GDP : Gross Domestic Product

GHG : Green House Gases

GRZ : Grazing area

HF : Heavy fraction

ICBM : Introductory Carbon Balance Model

ICOUR : Irrigation Company of Upper Region

IPCC : Intergovernmental Panel on Climate Change

K : Potassium

KNUST : Kwame Nkrumah University of Science and Technology

LAI : Leaf Area Index

LF : Light fraction

Lsd : Least significant difference

MoFA : Ministry of Food and Agriculture

SNA : Semi natural area

N : Nitrogen

P : Phosphorus

PRA	Paddy Rain-fed Rice
PRI	Paddy Irrigated Rice
pH	potential hydrogen
SARI	Savanah Agricultural Research Institute
r-SOC	recalcitrant Soil Organic Carbon
S+A	Stable aggregate
s+c	Silt and clay
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
UDP	Urea deep placement
UN	United Nations
UNFCCC	United Nation Framework Convention on Climate Change
US	United States of America
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WRB	World Reference Base

DEDICATION

This work is dedicated to the memory of my late grandmother Faïty Ismaïl Cissé, my late uncle Mamadou Traoré and my late wife Kadidia Traoré.

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CHAPTER 1: INTRODUCTION

1.1. Background

Climate change is driven by man-made greenhouse gases (GHGs) (i.e. water vapour, carbon dioxide, nitrous oxide, methane and hydrofluorocarbons) and represents a major challenge for humanity. Much attention is on carbon dioxide (CO_2) because its level in the atmosphere has increased to approximately 30 % above natural background levels and will continue to rise (Anonymous, 2009; "An Introduction to The Global Carbon Cycle"). According to UNEP (2012) carbon dioxide is the most important anthropogenic GHG in terms of quantitative emission and accounts for about 76 % of total GHG emission in 2010. In the past 10 - 20 years in reference to 2004, evidence shows that high levels of carbon dioxide are being introduced by anthropogenic activities which could lead to notable changes in the near climatic condition (IPCC, 2007; Wallington *et al.*, 2004). Critical among human activities are burning of fossil fuel, cement production, agricultural and deforestation activities that are major contributors to CO_2 emissions. Globally, efforts are being made toward biological systems (living biomass, forest and soil) for carbon sequestration through the setting up of the Kyoto Protocol (Deresh and Böhm, 2001; Freibauer *et al.*, 2004). The vegetation together with the atmosphere usually store less quantity of carbon than the soil which holds it for a longer period. About a third of the total soil organic carbon is stored in tropical regions (Davidson *et al.*, 2000a; Amundson, 2001) hence as an opportunity to mitigate and adapt to climate change, as well as providing ecosystem services, the focus of CO_2 sequestration has progressively been shifted to soil (Sheikh *et al.*, 2009).

Soil plays an essential function in worldwide carbon cycle. Generally, the soil carbon stock is approximately thrice the quantity in the vegetation and about two times that of the atmosphere (Jamala *et al.*, 2013; Smith, 2008; Eswaran *et al.*, 1993). Henry e*t al.* (2009) and FAO (2012) indicated that in Africa, 68 % of the terrestrial carbon stock is attributed to the soil organic carbon (SOC) stock. According to the FAO (2012) and Thum *et al.* (2011), 6.0×10^{10} - 8.0×10^{10} tonnes of global carbon per year is attributed to CO_2 emissions from the decomposition of organic matter in soil. Generally, climate and vegetation usually act together to influence soil organic carbon. Therefore, the stocks of organic matter are balanced by inputs and outputs of organic carbon, but prediction of global soil net CO_2 flux is highly uncertain (Prechtel *et al.*, 2009). However, there is an agreement that microbial decomposition of soil organic matter is the main source of soil born CO_2 emission, but turnover of soil organic matter (SOM) can be highly heterogeneous. Amount and quality of litter input, soil properties such as clay content and pH influence the turnover of SOM. Additionally, soil moisture and soil temperature impact on the population of decomposers (fungi and bacteria) community and their activities for SOM turnover (Schindlbacher *et al.*, 2011). Regional climate change predictions are often certain, and all IPCC scenarios (IPCC, 2007) predict a temperature increase of about 1.5°C in arid and semi-arid regions by the end of the 21st century. This is therefore likely to influence future CO_2 emissions in these regions.

Soil carbon and it dynamics have been accepted for a long time as an important soil component (Andrén *and Kätterer.*, 1997; Tenney and Waksman, 1929 ; Henin and Dupuis, 1945 cited by Andrén *and Kätterer.*, 1997). In recent past, modelling of soil carbon dynamics has received a lot of attention (Andrén *et al.*, 2016) due to the fact that soils act as either sources or sinks for CO_2.

In Africa, most farming practices involve the use of low technologies and the continuous cropping resulting in soil degradation mostly due to the depletion of soil organic matter (SOM). Changes in agricultural practices such as reduced or no tillage, proper crop management (such as rotation), improved fallow that increases or sustains SOM can have positive influence on agricultural productivity and limit soil CO_2 emission (Henry et *al.*, 2008; Bationo *et al.*, 2006). Soil quality in terms of carbon stocks and properties is extremely affected by climate change and agricultural practices which directly influence soil physical and chemical properties. Soil organic matter is influenced by a number of factors, mainly climate (temperature and rainfall), vegetation types, soil type and human activities (Nielsen *et al.*, 2011; Lal, 2004b). The effect of climate and natural vegetation on the amounts of SOM is known over a wide geographic area (FAO, 2012). According to Lal (2009), Hoffmann e*t al.* (2014) and Shelukindo *et al.* (2014) the soil organic matter is higher in colder climates than in warmer climates under similar moisture conditions, comparable soils and vegetation. High rainfall promotes vegetation growth, production and accumulation of soil organic matter since plants (particularly natural vegetation) are the major source of soil organic matter. Additionally, vegetation type and their density affect the SOC stock, while soil drainage and texture also affect soil organic matter and SOC within the local landscapes (FAO, 2012). The reason is that the organic residues retained in fine-textured soils are higher than in coarse-textured soil (FAO, 2012) which lead to higher nutrient and water- holding capacities and promote better plant production (FAO, 2012). However, the formation of clay-humus complexes in fine-textured soils minimizes SOM degradation.

According to Olson and Janzen (1992) and Bationo *et al.* (2006), soil organic carbon positively correlates with crop yield, that is high SOC promotes soil water retaining capacity, boosting soil fertility through cation exchange and mineralisation process and improvement of soil structure (Lal, 2006). The variation of SOC is mainly controlled by topography, edaphic and climatic factors on a large scale (Giardina and Ryan, 2000; Wynn and Bird, 2007). However, at a local scale, biotic factors and management play a major function in the control of the amount and quality of carbon input and decomposition process (Allen *et al.,* 2010; Saiz *et al.,* 2012). Raising SOC in degraded soils is a fundamental goal in efforts to improve fertility in degraded soils (Lal, 2006). The accumulation of SOC in the soil results in a positive feedback with better role improving crop biomass production and increase organic matter inputs in the soil (Lal, 2006). However, the SOC storage is an essential terrestrial carbon sink, which plays significant role in climate change mitigation (Post and Kwon 2000; Yu *et al.*, 2009).

The amount of CO_2 flux released from the soil to the atmosphere is the principal mechanism of carbon loss from the soil (Parkin and Kaspar, 2003). It offers an early indicator for carbon sequestration in the soil when changes of soil organic carbon due to management practices are not detectable within a short period (Fortin *et al.*, 1996; Grant, 1997). In agricultural soils climatic factors are considered as central drivers of SOC decomposition and CO_2 fluxes regulation (Kelly *et al.*, 2000; Smith *et al.*, 2000; Campbell *et al.*, 2005; Lal *et al.*, 2007). This research is to study the impact of agricultural practices and climate change on SOC dynamics and soil CO_2 fluxes by modern techniques and methods (SOM fractionation and dynamic chamber CO_2 measurement).

1.2. Problem Statement and Justification

Soil organic carbon serves as a source and sink for nutrients and plays an important role in soil fertility. In West Africa, most agricultural practices are characterized by low technologies and continuous cropping that leads to the depletion of soil carbon. Except the forest area, most West African agro-ecosystems are characterized by inherent low soil organic carbon content.

In Ghana, although agriculture is the major source of employment for the population and contributes about 34.5 % of the Gross Domestic Product (MoFA, 2010), the sector has many challenges that affect food security based on local production. The agricultural sector is very sensitive to climate change (especially food crop production) such as decreasing length of growing season, seasonal and spatial variability of rainfall, prolonged seasonal drought risk, low soil fertility and poor management practices (Sagoe, 2006).

Increasing population, intensive cultivation, overgrazing and fuel wood harvesting put high pressure on land which has implications for SOC dynamics and soil fertility. In the Upper East Region, soils have low inherent fertility, less than 2 % OM in the top soil (Boateng, 1992; Senayah, *et al*., 2009). Organic matter turnover is low due to bush and residue burning, for land preparation (MoFA, 2007), total harvesting of crop, and overgrazing. Additionally, uncontrolled movement of livestock in the dry season reduces manure input that can help improve soil organic matter content. Also, most trees, even leguminous ones, have been removed from the farms in order to increase cropping area. The time scale and feedback mechanisms of changes in SOC as well as the steady state level for specific soil types, climates and land use are not well understood in the study area regardless of the importance for estimating future soil quality, degradation, long-term productivity and potential release of greenhouse gases. The current status and the near future trend of SOC under different management practices will provide knowledge on the best option for sustainable management of soil fertility. In addition to studies such as population-agricultural practices nexus (Codjoe, 2011, Prempeh, 2015), knowledge on soil respiration for different agricultural land uses and soil carbon inventory will provide quantitative information on soil carbon stock in the region. Therefore, it is important to study soil carbon change under agricultural land use systems and monitor soil CO_2 fluxes for selected cropping systems under different management practices to be able to make informed decisions on best practices for sustaining and/or improving soil fertility in the region.

1.3. Objectives of the Study

The general objective of the study was to assess soil carbon change and CO_2 emissions from selected cropping systems (rice, maize, millet and sorghum) in the Vea catchment.

The specific objectives were to:

1. Determine the proportion of soil types and agricultural land use/cover classes;
2. Determine crop yield and above ground biomass under different management practices for selected cropping systems (rice, maize, millet and sorghum);
3. Estimate the soil organic carbon stock and fractions under different agricultural land use/cover and project SOC trend for maize and sorghum cropping system in the Vea catchment;
4. Determine CO_2 fluxes from the selected cropping systems (rice, maize, millet and sorghum) under rain-fed and irrigation for different management practices in the Vea catchment.

1.4. Research Questions

The research questions addressed in the study were:

1. What is the proportion of agricultural land use classes under each soil type in Vea catchment?
2. What are the grain and above ground biomass for selected (rice, maize, millet and sorghum) cropping system under different management?
3. What is the current soil carbon stock and fractions under different agricultural land use / cover and how will be the SOC stock for maize and sorghum cropping in 30 years in the Vea catchment?
4. What are the soil CO_2 emissions from the selected (rice, maize, millet and sorghum) cropping systems under rain-fed and irrigation for different management practices?

1.5. Thesis Format

The thesis is in five chapters as follows:

Chapter 1: The chapter introduces the study and its relevance. It provides the background, problem statement and objectives of the research.

Chapter 2: This chapter provides the underlying concepts and relevant information from the literature on soil organic carbon in general and soil respiration. It further describes the concepts of land use and land cover patterns, cropping system and land tenure in the Upper East Region. The techniques of determining SOC and measuring soil respiration are also highlighted. The potential to use Introductory Carbon Balance Model to simulate the dynamics of soil organic carbon in the world is also discussed.

Chapter 3: This describes the overall methods used for the study with a presentation of the study area and the procedures used to collect and analyse data. The tools used for soil CO_2 measurement are also described.

Chapter 4: It presents the results, discusses it and provides the implication of the findings.

Chapter 5: This is the concluding chapter of the thesis. It provides conclusions of the study. The chapter presents also recommendations for policy and future research.

CHAPTER 2: LITERATURE REVIEW

This chapter reviews all the concepts, processes and background on soil organic matter, soil organic carbon, land use and land cover change, soil respiration and soil CO_2 fluxes. It also highlights land tenure and cropping system in the Upper East Region of Ghana, and Introductory Carbon Balance Model for simulation of soil carbon dynamics.

2.1. Soil Organic Matter (SOM)

SOM is the organic portion of soil exclusively composed of non-decomposed plant and animal residues. It consists of both living and non-living organic material in the soil at different states of decomposition and turnover time (Sanderman, *et al.*, 2010). Soil organic matter is mostly affected by climatic factors (e.g. temperature and rainfall), vegetation types, soil types and anthropogenic activities. In many geographic locations, the impact of climate and natural vegetation on the amount of soil organic matter is known. Usually, the amount of soil organic matter is higher in cooler climate than in warmer climate under similar moisture conditions, soils and vegetation (Dawidson and Nilsson, 2000). Plants (mainly natural vegetation) are the main source of soil organic matter. Soil organic carbon stock is increased by the type of vegetation and together with the plant density. In landscapes, soil drainage and texture also affect soil organic matter. Commonly, fine-textured soils are known to have higher soil organic matter content than sandy soils due to the fact that organic residues returned to fine-textured soils are higher than in coarse-textured soils. Therefore plant production is higher because of the greater nutrient and water holding capacity of fine-textured soils. In addition, soil organic matter degradation is reduced because of the formation of clay-humus complexes in fine-textured soils. Human activities such as land preparation techniques (tillage) and management options also influence soil organic carbon content. The amount of carbon in SOM varies between 40 - 60 %.

According to Bationo *et al.* (2007) in West Africa, soil fertility restoration and maintenance should be undertaken to reverse the decreasing trend in the agricultural system and maintain the environment for present and future generation. Soil fertility is highly dependent on soil organic matter, whose status is related to the biomass input and management, mineralisation, nutrient leaching and soil erosion (Andrén *et al.*, 2007).

2.2. Soil Organic Carbon (SOC)

Organic carbon is the carbon contained in soil organic matter (SOM). Many studies state SOC as the key indicator that has significant impact on soil quality and productivity (Quiroga *et al.*, 1994). Soil quality (fertility) and productivity are characterised by soil functions such as nutrients and water storage and biological activities. According to Gregorich *et al.* (1994), the main attributes of soil quality are the total SOC and its fractions. Organic carbon is produced in the soil by the decay of plant and animal residues, root decay, alive and dead microorganisms and soil biota. As mentioned in Doraiswamy *et al.* (2007) in West Africa, natural soil fertility and fertiliser input are low and for soil to deliver ecosystem services it is compulsory to increase or maintain the level of SOC but unfortunately the current farming practices are known to deplete soil nutrient and decline crop yields.

2.2.1. Functions of soil organic carbon

All aspects of soil fertility such as physical, chemical and biological fertilities are related to SOC. It acts as a buffer against toxic and harmful substance by decreasing their effect by sorption of toxin and heavy metals (Chan, 2008). SOC is strongly related to plant productivity and ecosystem services provision. It also helps in providing plant nutrients, improving cation exchange capacity, increasing soil aggregation and water holding capacity and supporting soil biological process (Lal, 2004a; Dudal and Deckers, 1993).

Considering the numerous functions of organic matter in soils of the United States, Albrecht (1938) cited that " soil organic matter is one of our most important national resources; its unwise exploitation has been devastating and it must be given its proper rank in any conservation policy" (Sanderman *et al.*, 2010).

2.2.2. Factors affecting SOC level

Soil carbon level is related to factors such as rainfall, temperature, vegetation and soil type and human activities. In many regions the effect of climate, natural vegetation and anthropogenic activities on the level of SOC is known. The major source of soil organic carbon is plants (especially natural vegetation). Vegetation type and their density determine the soil organic stock. Generally, clearing natural vegetation for agriculture results in enormous decrease of SOC levels and further declines may happen as a result of management practices (Chan, 2008). While some management practices as forest management can help to maintain or improve the initial carbon stock, conservation measures of native ecosystems, protection against desertification and soil erosion and agronomic practices can reduce carbon loss from soil. According to Cia *et al.* (2011) SOC varies as a function of the soil texture, the bulk density, the microbial activity and organic matter contained in the vegetation. In general, fine textured soils have high levels of soil organic carbon than sandy soils due to the formation of clay-humus complex which minimises organic matter degradation. Clay and silt also play a large role in the stabilisation of organic components and small difference in the topsoil texture could have great impact on SOC as stated in Bationo *et al.* (2007), Bationo and Buerkert (2001). Anthropogenic activities such as irrigation, land preparation activities and farming practices also have an impact on soil organic carbon content. For example, as highlighted by Kang (1997), Shepherd and Soul (1998), continuous cropping leads to a progressive decline of soil organic carbon content. Table 2.1 summarises cropland management practices for the maintenance or increase of soil organic carbon.

Table 2.1: Cropland management practices for the maintenance or increase of soil organic carbon

SOC loss reduction	SOC input increase
Reduced tillage/no-tillage	Organic manures/ Composts
Cover crops	Cover crops
Erosion reduction measures (mulching, contour cultivation on sloping land)	Crop residue returns
Reduced fallow periods	Increase crop productivity through irrigation/chemical fertilizer
Reduced burning of crop residues	

Source: Bationo *et al.* (2006)

2.2.3. Soil carbon stock in savannah agro-ecosystem

In territorial ecosystem soil organic carbon is a main component and any change on its quality and composition has a significant impact on many processes that take place within the system. The amount of organic matter and soil carbon stock results from a balance between inputs (mostly from plant growth) and outputs (decomposition and transport) to the system which are determined by diverse factors of natural or anthropogenic sources (Schlesinger, 2000; Amundson, 2001). The soil carbon pool for the savanna biome is 200 – 300 Gt C (Scurlock and Hall, 1998) or 10 - 30% of the world soil carbon (Anderson, 1991;

Eswaran *et al*., 1993). Furthermore, as a global average, native savannah soils contain at least as much carbon as that stored in above and below ground biomass (Anderson, 1991; Eswaran *et al*., 1993; Scholes and Hall, 1996).

In West African agro-ecosystem the equilibrium between input and output is in danger due to the availability of few inputs to compensate for harvested biomass as major output. Recovery of natural vegetation (i.e. fallow) seems to be unique way to restore soil fertility. Additionally, in many savannah agro-ecosystems, primary production is low due to low rainfall, poor soil fertility and inadequate management practices, which conduct to low soil organic matter (Scholes and Hall, 1996) and the soils become quickly infertile. In West African savannah, soils have low SOC and clay contents which seem to limit the potential capacity to store SOM. The sandy soils present low carbon saturation level due to low clay content (Six *et al*., 2002).

2.2.4. Effect of soil management practices on SOC

The depletion of soil organic carbon is mostly due to erosion, runoff and leaching (Roose and Barthes, 2001; Bationo *et al.*, 2006). Erosion and runoff have high impact on SOC in cultivated land as compared to natural forest and savannah. Bationo *et al.* (1995) demonstrated the evidence of faster depletion of SOC level with continuous cropping in West Africa (Bombelli and Valentini, 2008). In West Africa some practices such as continuous cultivation, crop residues burning/removal, overgrazing are common and decrease SOC by diminishing inputs to the soil as stated by studies (Chan, 2008; Chris du *et al.*, 2010; Sanderman *et al.*, 2010; Ardö and Olsson, 2003). Land clearance and continuous cultivation lead to accelerated mineralization and reduce SOC up to 30 % as stated by Gregorich *et al.* (1998) and Nandwa (2001). Similarly, in a study by Roose and Barthes (2001) carbon depletion by erosion from crop land can be 4 - 20 times higher than from a natural vegetation. In addition studies have demonstrated that lone use of mineral fertilizer can also deplete SOC by increasing nutrient leaching, decreasing the base saturation and aggravation of soil acidification (Mokwunye, 1981; Pichot *et al.,* 1981 and Bache and Heathcote, 1969). Cropping systems and agricultural management such as minimum tillage with mulch can influence erosion rate and SOC equilibrium (Roose and Barthes, 2001; Six *et al.,* 2002). Moreover, minimum tillage reduces the depletion of SOC due to less disturbance of the topsoil. Several studies reported the contribution of rotation and intercropping system in the conservation of SOC (Bationo and Buerkert, 2001; Bationo *et al.,* 2007). Crop covers also intervene in conservation of carbon stock through their mineralisation (Nandwa, 2001).

Soil organic carbon level in general is lower in agroecosystems than in comparable soil under natural vegetation. Soil carbon pool and CO_2 fluxes are influenced by carbon input, climate, soil texture, pH and drainage (Dawidson and Nilsson, 2000). Land use and management highly influence carbon in agricultural soil (Lal 2004b; Cole *et al.,* 1993).

2.3. Soil Fertility and Sustainable Agriculture

Soil is the foundation of land uses (Herrick, 2000). The most important natural resource of our physical environment is soil and water combined (Arshad and Martin, 2002). For sustainable development, feeding the growing population and maintaining ecosystem services, soil should be used judiciously and rationally. The way in which soils are managed has an impact on agricultural productivity and sustainability (Scholes *et al.,* 1994). The maintaining and enhancement of soil quality is the key indicator for sustainable agriculture which encompasses soil physical, chemical and biological properties (Ouédraogo, 2004).

2.4. Methods for Assessing Changes in Soil Carbon

Assessment of soil carbon variation requires the use of appropriate techniques that distinguish the response of soil carbon from different land use and management practices.

Variations in soil carbon come from imbalance between the carbon flux that enters into the soil and the one goes out of the soil. Thus, carbon accumulates in the soil when more carbon is entered into the soil than released, and vice versa. Methods for determining SOC changes have to consider the problem of trying to detect a small change (i.e. net change over time) in a big number (i.e. soil carbon stock). There are several methods for determining SOC stock changes (Post *et al.*, 2001) and can be divided into direct and indirect methods.

Direct methods include field and laboratory monitoring of total carbon, various physical and chemical fractions, carbon isotopes and CO_2 fluxes. The most common direct method is to take soil sample, measure the carbon content and soil bulk density and compute the mass of carbon per unit area (Post *et al.*, 2001).

Indirect methods consist of simple and stratified accounting, use of environment and topographic relationships and modeling approaches.

1. Flux approach: Indirectly, by determination of all carbon fluxes entering and leaving the soil over a certain time period, Hanson *et al*. (2000) suggested determining changes in soil carbon stocks via the following equation:

$$SOC = (L_A + L_B) - (R_S - R_R) \qquad [2.1]$$

Where: SOC is net carbon change (g C m^{-2} y^{-1}) over time;

L_A is above-ground litter; L_B is below-ground litter;

R_S is total soil CO_2 efflux; R_R is root respiration.

2. Repeated inventory approach: Directly, this involves repeated measurements of SOC in the soil sample at the same location over a long period of time (i.e. five years for IPCC (2003) and ten to twenty years for UNFCCC (2006) monitoring interval). Studies such as

Post *et al.* (2001) and Smith (2004) stated that at least five to ten years interval is required for detecting statistically significant variations in soil carbon stocks through the relatively small annual carbon inputs and outputs compared to soil carbon stock. The soil carbon stock on an area basis (SC; kg C m^{-2}) to a depth can be computed using the following equation:

$$SC = CC\ Bd\ VHF \qquad [2.2]$$

Where: CC is soil organic carbon concentration (kg C kg soil $^{-1}$);

Bd is soil bulk density (kg m^{-3});

V is the volume of a soil layer;

HF is calculated as (1 – (stone volume + root volume)/V) and is a dimensionless factor representing the fine soil fraction in a certain soil volume (note that stone and root volumes must be in m^3).

3. Examining changes in specific fractions of carbon: Indirectly, this involves determination of changes in sensitive soil carbon pools or specific fractions (Six *et al.,* 2002), which might present first indications for long term changes of total carbon stocks. The most common methods to separate soil organic carbon into fractions are chemical, physical or a combination of fractionation methods (Von Lutzow *et al.*, 2007and Kutsch, 2000). The chemical methods are built on the extraction of SOM in aqueous solution with or without electrolyte in organic solvent or the resistance of SOM to oxidation. The simplest chemical fractionation of SOM uses cold distilled or deionized water to isolate dissolved organic matter (DOM) as a pool of readily decomposable carbon (Chantigny, 2003). The physical methods are based on the density and dimension of particles related to different chemical, physical and biological properties. The objective of physical methods is to attain great dispersion of soil with minimum alteration of the associate organic matter. Presently, in most studies (Elliot and Cambardella, 1991; Christensen, 1992; Amelung and Zech, 1999;

Wurster *et al,*. 2010) dispersion is achieved through the ultrasonic action of bulk soil in water at a constant output of energy for a determined time interval. The procedure to separate soil organic matter into different fractions using the combination of physical and chemical methods is stated in Zimmermann *et al.* (2007) and Saiz *et al.* (2012).

There are many methods to analyse SOM and SOC concentration each with advantages and disadvantages (MacDicken, 1997, Palmer 2002 and Bisutti *et al.,* 2004). Table 2.2 highlights the methods for determining soil carbon content based on the principle, advantages and disadvantages.

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Table 2.2: Main methods for determining soil carbon content

Method	Carbon	Principle	Advantages	Disadvantages
Walkky-Black (not heated)	Organic SOM	Organic matter is oxidised to CO_2 with dichromate in an acid medium	Very rapid and simple. No need of particular equipment	Likely incomplete oxidation of organic carbon. Need for correction factors. Disposal of Cr solution.
Walkky-Black (heated)	Organic SOM	As above but in heated solution.	Rapid and simple. Complete oxidation of organic matter occurs.	Chloride. Fe^{2+} and MnO_2 interfere with method. Need for correction factors. Specialised equipment needed. Disposal of Cr solution.
Dry combustion	Total (organic, inorganic, charcoal) carbon and SOC	Soil heating at 1000 - 1500° C with a catalyst mixture in a stream of O_2 and measurement of CO_2 evolved	Rapid and simple, good precision. Only 10-20 mg of soil needed	Automated instruments are very expensive. Requires inorganic carbon correction.
LOI (weight loss on ignition	Organic SOM	Soil samples heated in a muffle furnace (eg. 400°C for 16 h). Organic matter estimated by weight loss	Rapid and inexpensive method.	SOM needs to be converted into SOC with individual conversion factors (regression based). Influence of inorganic C and moisture in clay.

Source: Kutsch (2010) from Mac Dicken (1997) and Palmer (2002)

2.5. Overview of Soil Respiration

Soil respiration is defined as the sum of the respiration of living organism and plant respiration in the soil (i.e. roots, microbes and soil fauna). It means that the release of CO_2 by living biomass of soil and gain of energy by soil organism from catabolising organic matter to support life. Most often in contrast with above ground respiration, soil respiration is called below ground respiration. Physiologically, respiration is defined as a series of metabolic processes that break down organic molecules to release energy, water and carbon dioxide in a cell. In this context respiration is based on the production of CO_2.

Many studies (Jassal *et al.,* 2005; Maier *et al.,* 2011) consider the measured soil CO_2 efflux as the rapid soil respiration. In the long term, all CO_2 produced by the below and above ground CO_2 efflux must be equal to soil respiration. However, in the short term, the CO_2 efflux differs from the soil respiration as soon as the quantity of CO_2 stored in the soil pore space is changing.

2.5.1. Methods for soil respiration measurement

Scientists have developed several varieties of measurement methods in the past decades. The chamber methods are generally used and procure direct measurement of CO_2 emission at the soil surface (Luo and Zhou, 2006; Suh *et al*., 2006). Chamber techniques are either dynamic or static, depending on the presence or absence of air circulation through the chamber. The dynamic chamber methods allow air to circulate between the chamber and a measuring sensor, which is normally an infrared gas analyser (IRGA), to monitor CO_2 concentration in the chamber over time (Luo and Zhou, 2006). Presently, the most commonly used method in laboratory and field measurements is the closed dynamic chamber (CDC) method. This method operates in a fully enclosed mode on soil surface and measures changes in CO_2 concentration in the chamber over a short time. However, the open dynamic chamber (ODC) method is also used in some studies to measure soil CO_2 emission. It operates in a continuously ventilated quasi-steady-state mode and monitor differential variations in CO_2 concentration as air passes over the soil surface (Luo and Zhou, 2006; Suh *et al*., 2006). The closed static chamber (CSC) method isolates an amount of atmosphere from the environment during a measurement period as alkali solution or soda lime is used to trap CO_2. A rate of soil efflux is then estimated from the trapped CO_2. With a static chamber, CO_2 concentration is measured from air samples at two or more different times during enclosure using syringe samples, which are analysed with either a gas chromatograph (GC) or IRGA to estimate the rate of soil CO_2 efflux (Luo and Zhou, 2006; Suh *et al*., 2006).

The soil CO_2 efflux is also used to assess soil carbon by gas well (GW) method from the gradients concentration of CO_2 along a soil vertical profile (Luo and Zhou, 2006). Indirectly soil CO_2 emission is estimated from measurement of net ecosystem exchange (NEE) of carbon through micrometeorological methods such as eddy covariance (Baldocchi *et al.*, 1986, Wohlfahrt *et al.*, 2005) and Bowenratio/energy balance (Dugas 1993, Gilmanov *et al.*, 2005). The measured NEE is ecosystem respiration at night or the difference between canopy photosynthesis and ecosystem respiration during daytime (Luo and Zhou, 2006). The measured NEE is divided into photosynthesis, aboveground respiration, and soil respiration (Luo and Zhou, 2006).

2.5.2. Factors influencing soil respiration

Soil respiration varies temporally and spatially on a plot and landscape level and vertically with soil depth (Maier *et al.*, 2011). On the temporal scale, soil temperature and soil moisture are the major abiotic factors controlling soil respiration (Maier *et al.*, 2011; Smith *et al.*, 2003). Also, photosynthetic activity, plant phenology and substrate supply can influence soil respiration (Davidson *et al.*, 2006; DeForest *et al.*, 2006; Maier *et al.*, 2011; Vargas *et al.*, 2010). For example a linear relationship exists between increase in soil respiration and amount of litter added to the soil surface (Luo and Zhou, 2006; Maier and Kress, 2000). Similar relationships between the litter amount and soil respiration equally exist (Boone *et al.*, 1998; Sulzman *et al.*, 2005). Soil temperature and soil moisture, though, are also the major abiotic factors controlling soil CO_2 concentration (Maier *et al.*, 2011). Soil moisture influences soil respiration directly through physiological processes of roots and microorganisms, and indirectly via diffusion of substrates and O_2. Soil CO_2 concentrations often indicate a temperature-driven seasonal trend (Davidson *et al.*, 2006; Maier *et al.*, 2011). In addition, rainfall and irrigation do not only stimulate soil respiration (Liu et al., 2002; Borken *et al.*, 2002; Lee *et al.*, 2004) but also lead to increase in soil CO_2 concentration (Jassal *et al*., 2005; Flechard *et al*., 2007; Maier *et al.*, 2010).

2.5.3. Spatio-temporal variation in soil respiration

Many studies highlighted high variability of soil respiration with time and in space. Spatio-temporal variation of soil respiration is due to fluctuation of environmental variables, biochemical processes of respiration and transport process of CO_2 gas (Luo and Zhou, 2006).

a. Spatial variability

Spatial variability in soil respiration occurs on various scales, from a few square centimetres to several hectares up to the global scale (Luo and Zhou, 2006; Rochette *et al.*, 1999, Rayment and Jarvis, 2000). It is characterised by four spatial scales: stands, landscapes, regions, and biomes (Luo and Zhou, 2006).

Luo and Zhou (2006) demonstrated that the high spatial variability in soil respiration results from large variations in soil physical properties (e.g., soil water content, thermal conditions, porosity, texture, and chemistry), biological conditions (e.g., fine-root biomass, fungi, and bacteria), nutrient availability (e.g., deposit litter and nitrogen mineralisation), and others (e.g., disturbed history and weathering). The spatial variability in soil respiration on the landscape scale level is caused largely by variations in climate, topography, soil characteristics, vegetation types, extent and edges of patches, and disturbance history (Luo and Zhou, 2006).

Soil respiration varies greatly with different ecosystem types, reflecting intrinsic characteristics of the ecosystems in the prevailing environments and biological activities (Luo and Zhou, 2006). Mean rates of annual soil respiration differ twenty-fold among major vegetation biomes. Soil respiration is lowest in the cold tundra and northern bogs and highest in tropical moist forests, where both temperature and moisture availability are high year-round (Luo and Zhou, 2006; Raich and Potter 1995). On a global scale, mean rates of annual soil respiration correlates positively with mean plant productivity among different biomes (Luo and Zhou, 2006).

b. Temporal variation

Generally temporal variability is characterised by four time-scales: diurnal or weekly, seasonal, inter-annual, and decadal or centennial (Luo and Zhou, 2006). The diurnal variation in soil respiration is explained as a close function of soil temperature, because soil temperature changes often in a diurnal scale (Rayment, 2000). Soil respiration is also correlated with photosynthesis with time delay by 7 to 12 hours (Luo and Zhou, 2006; Tang *et al.*, 2005). The diurnal pattern of soil CO_2 emission is also affected by the fluctuation of atmospheric pressure and humidity

(Baldocchi *et al.,* 2001). In arid ecosystems, soil CO_2 emission may be higher in the night than daytime due to increased relative humidity at night (Luo and Zhou, 2006).

The fluctuation of CO_2 flux from soil on a weekly scale might be due to changes from synoptic weather associated with passage of low and high pressure systems, distinct periods of clear sky, overcast and partly cloudy (Subke *et al.*, 2003). These conditions cause changes in air temperature, humidity and atmospheric pressure, which consequently affect photosynthesis and soil CO_2 emission. The rate of root respiration depend largely on the availability of recently produced photosynthates during the previous 7 to 12 hours (Tang *et al.*, 2005; Luo and Zhou, 2006) 1 to 6 days (Ekblad *et al.*, 2005) or 5 to 10 days (Bowling *et al.*, 2002).

Soil temperature, moisture and photosynthetic production are the most important factors controlling the rate of soil respiration (Borken *et al.*, 2002; Campbell *et al.*, 2004; Dilustro *et al.*, 2005). Seasonal changes in these factors affect productivity of terrestrial ecosystems and decomposition rate of soil organic matter, thereby driving the temporal variations of soil respiration (Wiseman and Seiler 2004; Tang and Baldocchi, 2005; Yan *et al.* 2006). The main factors controlling seasonal variability of soil CO_2 emission depend on the type of ecosystem and climate (Luo and Zhou, 2006). In the arid and semi-arid zone, the seasonal patterns of soil respiration strictly follow the dynamics of soil moisture (Davidson *et al.*, 2000b). The seasonality of soil respiration is also regulated by the type of vegetation (Grogan and Chapin, 1999) and is closely related to the increase in biomass and root production (Thomas *et al.*, 2000)

2.6. Land Use and Land Cover (LULC) Pattern

Land cover is defined as the biophysical state of the Earth’s surface and immediate subsurface (Tuner *et al.*, 1995). According to FAO (1990), land use refers to the function or purpose for which land is used by human population. LULC change is related to climate, vegetation and weather condition in addition to human factors. LULC change refers to the quantitative changes in the aerial extent of a given type of land use or land cover. However, LULC change can result in two broad categories: conversion (change from one category to another) or modification (alteration of structure or function). The typologies of causes of land use change are presented in Table 2.3.

Table 2.3: Typology of the causes of land-use change

	Slow	Fast
Resource scarcity causing pressure of production of resources	Natural population growth increase in commercialisation. Domestic life cycles that lead to changes in labour availability. Loss of land productivity on sensitive areas following excessive or inappropriate use. Failure to restore or maintain protective works of environmental resources. Heavy surplus extraction away from land manager	Spontaneous migration, forced population displacement, refugees. Decrease in land availability due to encroachment by other land uses (e.g. natural reserves)
Changing opportunities created by markets	Increase in commercialisation and agroindustrialization. Improvement and accessibility through road construction. Changes in market prices for inputs or outputs. Off-farm wages and employment opportunities.	Capital investment Changes in national or global macro-economic and trade conditions that lead to changes in prices (e.g. surge in energy prices or global financial crisis) New technologies for intensification of resource use
Outside policy intervention	Economic development programme Perverse subsides, policy-induced price distortions and fiscal incentives. Frontier development (e.g. for geopolitical reasons or to promote interest groups) Poor governance and corruption. Insecurity in land tenure.	Rapid policy changes (e.g. devaluation, Government instability)
Loss of adaptive capacity and increased vulnerability	Impoverishment (e.g. creeping household debts no access to credit, lack of alternative income sources, and weak buffering capacity). Breakdown of informal social security networks. Dependence on external resources or on assistance. Social discrimination (ethnic minorities, women, member of low class or castes).	Internal conflicts. Illness (e.g., HIV). Risk associated with natural hazards (e.g., leading to crop failure, loss of resource, or loss of productive capacity)
Changes in social organization, in resource access, and in attitudes	Changes in Institutions governing access to resources by different managers (e.g. shift from communal to private rights, tenure, holdings and titles). Growth of urban aspiration. Breakdown of extended family. Growth of individualism and materialism Lack of public education and poor information flow on the environment.	Loss entitlements to environmental resources (e.g., expropriation for large scale agriculture, large dams, forestry projects, tourism and wildlife conservation, which leads to an ecological marginalization of the poor)

Source: Lambin *et al* (2003)

2.7. Land Tenure System in the Upper East Region of Ghana

Allodial title is held by tendanas or earth priests in the Upper East Region, (Kasanga *et al.*, 1996; Kasanga and Kotey, 2001). The tendana or earth priest gives land out to groups, and the group leaders then control access to the land. The tendamba lineage and family headmen are the key players in land matters in the Upper East Region (Kassanga and Kotey, 2001). Generally, the tendamba seems to have control over the land, particularly vacant communal land. Most agricultural and town lands are however in the effective control of lineage and family headmen. Individual rights in appropriated land are quite pronounced and are inheritable and secure. Disputes over farm boundaries, rights in land and trespass on another's land are said to be rare. An individual hardly sells or cannot sell land to a migrant without informing his family head and, in some cases, the chief (Kotey, 1995). Under the customary law, each member of a land holding unit is permitted to occupy and exploit any portion of this land. It is generally not difficult for indigenes to access land (Kotey, 1995). On the other hand, migrants have no inherent rights to use land but can acquire land with the permission of the landowner. The tenure systems allow migrants to farm on terms agreed on with the owners. It is not allowed in most communities for migrants to plant trees as it is believed that the practice can result in their claiming of ownership of the land. They, however, are allowed to plant trees with the permission of the landlord who gave them the land on such terms as may be agreed. Opportunities for leasing land for tree planting also exist (Kotey, 1995). Land owners are willing to grant leases of land for woodlots and plantations on the payment of a mutually acceptable consideration (Kotey, 1995). Otherwise, where a stranger plants trees without the requisite consent or permission, the trees are said to belong to the landowner (Kotey, 1995). Women usually receive land for farming from their husbands. Unmarried women may receive land from their fathers or families. For purposes of access to and use of land, married women are treated as belonging to their husbands' family rather than their father's family (Kotey, 1995). Even where women gain access to land in their own families and clans, their rights tend to lapse once they marry and move to join their husbands. Generally, a wife who is given land by his husband has no right to permanently appropriate the land.

The inheritance of land in the UER is patrilineal; with only few women being in charge of the land in cases where the husband died or is disabled and the male children are still of young age (Schindler, 2009). These land tenure systems have generally been maintained up to the present. Although land is bought and sold around larger urban settlements, such as Bolgatanga, intense pressure on land in rural areas has not led to monetarisation and individualisation of land rights as has been reported elsewhere in West Africa (Blench and Dendo, 2006).

2.8. Cropping Systems in the Upper East Region of Ghana

In the UER of Ghana, agriculture is mainly rain-fed with irrigated rice and vegetable cultivation during the dry season within the irrigation scheme. The main cropping system is rain-fed mixed crop. Due to the low level of mechanisation and the use of rudimentary tools for farming, the farm size is often generally small (Bationo *et al*,. 2003; Forkuor, 2014).

During the rainy season, mixed crop and intercropping are often common and serve as insurance for crop failure. Different authors have clearly underlined the importance of intercropping in view of its maximum utilisation of resources and stabilisation of yields (Bationo *et al*., 2003; Forkuor, 2014). The most common associations in the area are cereal - cereal such as early millet/late millet/ sorghum/maize and occasionally cereal - legume such as millet/ sorghum/ cowpea cereal/cowpea, cereal/groundnut. Leguminous crops, maize and rice are normally for sale.

Shifting cultivation is also a practice in the region. It is a system where a piece of land is cultivated for some years until the soil fertility start to decline, then the farmer moves to another plot leaving the first plot as fallow for a short periods to regenerate natural vegetation and restore the soil fertility. The system is still practiced with a drastic shortening of fallow period as a result of the increasing population and land demand (Youdeowei *et al.*, 1995; Igue *et al.*, 2000; Kanchebe, 2010).

Groundnut is the main cash crop in the Upper East Region. It is most often intercropped with other legumes and cereals and at other times as mono-crop close to the hamlets or located far away. Mono-cropping is the growing of one annual or perennial crop on a piece of land. Rice is cultivated in a rain-fed mono-cropping system with long period of fallow but continuously with short fallow in the Vea irrigation scheme. The types of rice cultures in Upper East Region Ghana are:

Upland rain-fed rice culture: in this type of culture, rice is normally grown under rain-fed condition in inland valleys and also upland portions of soils where there is no water table in the root zone, naturally well drained soils without surface water accumulation. The yield under this rice culture is very low at about 1 t ha^{-1} y^{-1} (Ofori *et al.*, 2010).

Rain-fed lowland culture: in this type of culture, the lands are often flooded for two to three months during the growing season. The practice also includes lands at lower slopes with water table in their root zones during a significant part of the growing season. Rain-fed lowlands have a great diversity of growing conditions that vary by amount and duration of rainfall, depth and duration of standing water, time of flooding, soil type and topography.

Irrigated rice culture: this requires layouts to ensure that the growers have control over water allowed on the plot under cultivation according to the water supply schedule of the irrigating scheme (Vea and Tono) for dry season cultivation of rice. In this type of rice culture, farmers use various management techniques based on the availability of resources. Some use transplanting in rows or raster even broadcasting of seeds in ploughed and harrowed land. In this system the input is higher than the previous and the yield also is higher. In Vea scheme the yield for the past 5 years was between 3.8- 4.2 t ha^{-1} (ICOUR, 2014).

The land preparation for rice cultivation in the irrigated rice culture is a bit different from the one that is practiced for rain-fed paddy rice.

The rice sector is facing many challenges:

- Low yield and profitability due to non-intensive cropping practices;
- Inadequate land preparation with little or no fertilizer and late weed control;
- Use of mixed and unimproved varieties possessing different colours and shapes which give poor quality of grain after milling;
- Poor processing technics;
- Lack of access to credit to farmers to purchase inputs for production;
- Lack of well-organised farmer organisations such as rice growers or rice processers associations which will promote interest rice actors in the policies on rice.
- Lack of markets and poor producer prices.

2.9. Introductory Carbon Balance Model (ICBM)

Introductory Carbon Balance Model (ICBM) is an approach for calculating soil carbon balances in a 30 years perspective (Andrén and Kätterer, 1997). The model has five parameters and two state variables (young and old carbon). The five parameters of the model are i (carbon input from crop and manure), h (humification coefficient), kY (decomposition rate constant for young), kO (decomposition rate constant for old), and re (climate factor affecting decomposition of young and old) (Andrén and Kätterer, 1997). In the original IBCM kY, kO and re were called k_1, k_2 and r respectively. ICBM has been efficaciously applied to agricultural field data from diverse regions such as: Sweden (Karlsson *et al.*, 2003; Andrén *et al.*, 2004, 2008; Kätterer *et al.*, 2004), European field trials (Kätterer and Andrén, 1999), Western and Eastern Canadian agricultural regions (Bolinder *et al.*, 2006, 2007, 2008; Campbell *et al.*, 2007), Norwegian arable land (Borgen et al., 2012) and it has been adapted to sub-Saharan African conditions (i.e. Kenya, Congo, Chad, Togo and Senegal) (Andrén *et al.*, 2007). It simulates current and future potential of soil C and N cycles in various ecosystems under different scenarios.

The model structure with governing equations is presented in Figure 3.1.

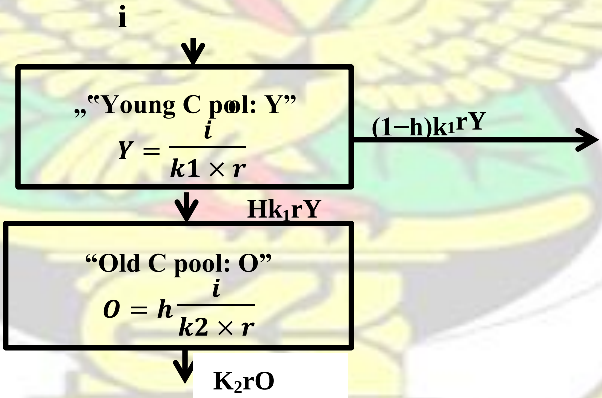


Figure 3.1: Structure and equations of ICBM (Source: Andrén and Kätterer, 1997)

Flux equations are positioned close to their respective arrow and equations at the steady state condition are inside the boxes.

CHAPTER 3: MATERIALS AND METHODS

3.1. Site Description

The study was carried out at two locations (Bongo Nyarega and Vea

Nyarega), both in the Vea catchment of Upper East Region, Ghana. Upper East Region (UER) is among the three poorest regions (GSS, 2010) in Ghana. The region is the second lowest ranked in terms of mean annual income of approximately US$157. UER is situated in the center of the Volta Basin in the north-eastern corner of Ghana. It is bordered by Burkina Faso to the north and Togo to the east, to the south by the Northern Region, and in the west by the Upper West Region. According to the 2010 national population census report the UER of Ghana had a population of about 1,046,545 habitants (506 405 male and 540 140 female) (GSS, 2012).

The Vea catchment is part of Nawini sub-basin (Figure 3.2) which is a sub basin of the White Volta basin. Nawini sub-basin covers two administrative regions (i.e. Northern and Upper East Regions) and 16 districts in Ghana. Geographically, Vea catchment is a transboundary catchment between Ghana and Burkina Faso and covers about 305 km2. It lies between latitudes 11°00’55” and 10°42’30”N and longitudes 0°59’57” and 0°45’20”W (Prempeh, 2015; Forkuor, 2014). The catchment extends over Bolgatanga and Bongo districts with a small portion in the south central part of Burkina Faso in the Nahouri Province. The major towns close to the watershed are:, Navrongo, Zuarungu, Pwalugu in Ghana and Dakola in Burkina Faso. The catchment is highlighted in Figure 3.2. Bolgatanga and Bongo municipalities have a population of 216 055 representing 20.7 % of the region’s total population according to the 2010 national population census and have a population density of 96.6 inhabitants/km^2 and a growth rate of 3 %.

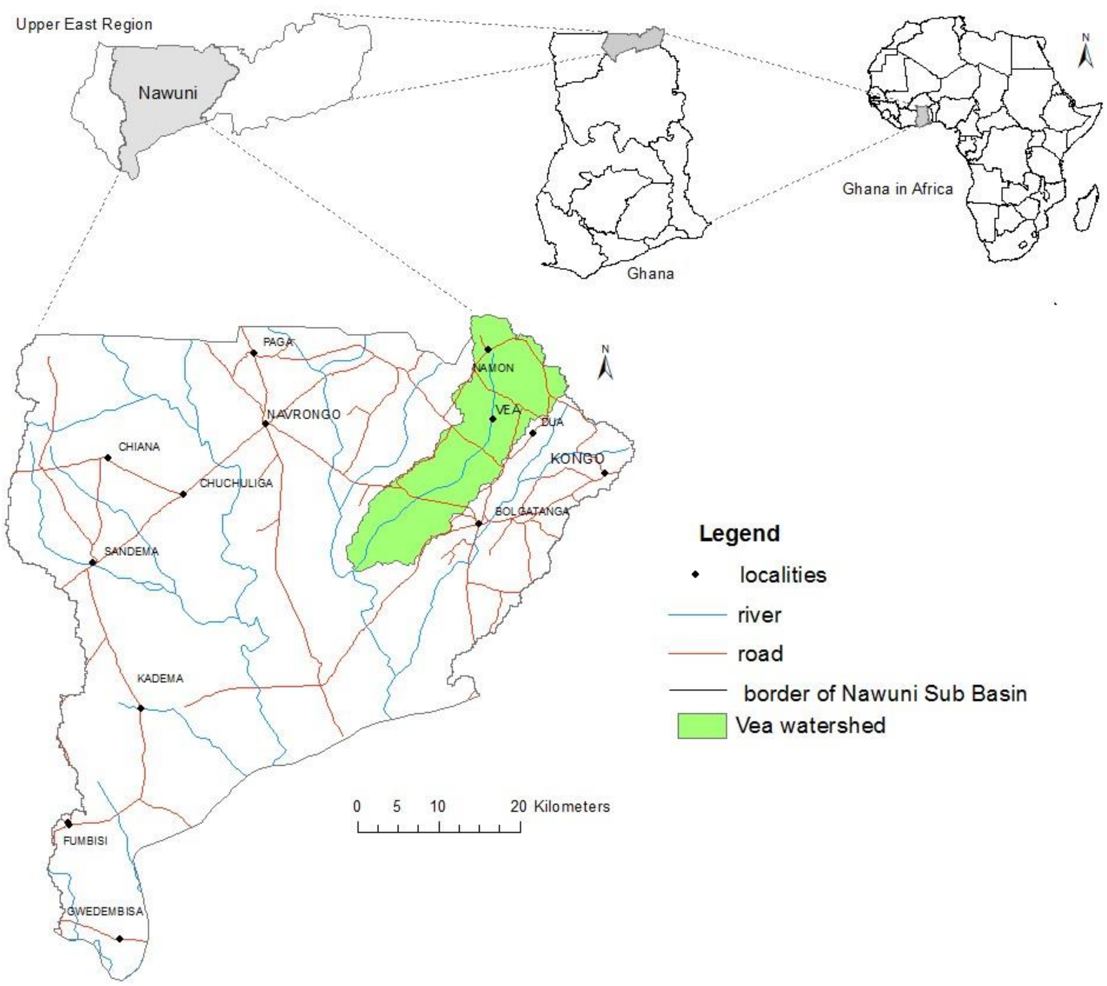


Figure 3.2: Location of the study area in the Vea catchment

3.1.1. Climate of Upper East Region

Climatologically, the area is characterised by high temperature and unimodal rainfall distribution. The annual average rainfall over the past 40 years ranges between 800 mm and 1044 mm, which are suitable for a single wet season crop (IFAD, .2007). It rains usually from the months of May/June to September/October. The dry season is a long spell from November to April/May characterised by cold night and high day-time temperature, dry and dusty harmattan winds. The humidity is also very low during this period making the season uncomfortable. The humidity is high during the rainy season, but very low in the dry season (Barry *et al.,* 2010).

The mean monthly temperature is between 24°C in the wet season and 36°C in the dry season and can reach 45°C during the day in April according to WASCAL Sumbrungu EC data (2013). The UER has an average annual potential evaporation between 2000 and 2050 mm (Barry *et al*., 2010).

3.1.2. Vegetation of Upper East Region

The study area is in the Sudan-Savanah agro ecological zone of Ghana and the vegetation consists of short drought and fire resistant deciduous trees, interspersed with open savanna grassland (Inusah *et al*., 2015). The dominant tree species are locust-bean (*Parkia biglobosa*), shea (*Vitellaria paradoxa*), kapok (*Ceiba pentandra*), baobab (*Adansonia digitata*) and whitethorn (*Faidherbia albida*) with perennial grasses such as *Andropogon gayanus* as ground cover. These tree species are not eliminated from the farming area because of their economic and social values (Schindler, 2009). The grass is very sparse, with most areas exhibiting bare, severely eroded soils (Adwubi *et al*., 2009; Quansah *et al*., 2015).

3.1.3. Geological formation and soil

The geological formation covering the UER comprises three main groups, i.e. Granitic, Voltaian sandstone and Birimian rocks. The soils in the study area are developed over granite and Birrimian phyllite (Senayah *et al*., 2009). They are associated to the following soil based on the FAO soil classification: Lixisols, Leptosols and Luvisols which are developed over granites, sandstones and Precambrian basement rocks respectively (Martin, 2006). Most of the soils in Upper East have low inherent fertility due to low accumulation of organic matter; mostly less than 2 % in the surface horizons (Senayah *et al*., 2009; Boateng and Ayamga, 1992; Adu, 1969). Organic materials from crop residue are scarce due to multiple competitive uses for fodder, construction materials and fuel for cooking (Bationo and Buerkert, 2001).

The dominant soil type in the region of interest is Lixisols (90 %) with a sandy loam to sandy clay loam texture and low organic matter content (Martin, 2006). Lixisols have low clay content in the topsoil, but higher values in the subsoil (WRB, 2006). Generally, they are characteristically light-textured and have inherently of low natural fertility, poor structure, low organic matter and low level of available nutrient, which is aggravated by low cation exchange capacity (Agboola and Aiyelari, 2000; Asiamah *et al*., 2000; Sant' Anna 2001; Seneyah *et al.,* 2005). In the Vea catchment, Fluvisols occur in the low lying areas along streams and rivers (inland valleys). Fluvisols have high clay content and its compact nature results in water logging condition during the rainy season. Cultivation of rice on Fluvisols is common. Leptosols occur in the elevated areas. These soils are shallow, gravelly and have a texture of loamy sand to sandy loam (Martin, 2006). Late millet and other crops are usually cultivated on these soils.

In the cultivated areas, much of the plant material is removed for human (fuel) or animal consumption and relatively less is returned to the soil. Bush and crop residue burning are also an important factor that results in a continuous decline of SOM that leads to low soil fertility (Bationo *et al.,* 2011; Bird *et al.*, 2000).

3.1.4. Socio economic activities

The family is the basic social grouping among the people with the nuclear and the extended family systems and patrilineal system of customary inheritance.

The traditional system of governance revolves around the chiefs. While the Adakoya festival is celebrated by the people of Bolgatanga after farming, the Naba Yesika is celebrated annually by the people of Sirigu. Three main religious groupings namely; christianity, traditional religion and islam are found in the region.

According to GSS (2014), agricultural related activities are the main economic activities in the region. About 80 % of the economically active population are engaged in agriculture. In the Bolgatanga municipality, the proportion of the population that is economically active are nearly three times (i.e. about 74 %) higher than the proportion of the population not economically active (26.0 %) according to the population and housing census (GSS, 2010). Small scale agro processing of agricultural products like groundnut, rice, locust-bean etc. and handicraft are also some of the other economic activities of the active population.

3.2. Methods of Data Collection and Analysis

3.2.1. Survey of the study area

a. Community entry

The research was started with a community entry of the study area. During this survey, meetings were held with stakeholders in the area to explain the aim of the study. The stakeholders included Agricultural Extension Officers from Ministry of Food and Agriculture (MoFA), Irrigation Company of Upper East Region (ICOUR) Vea staff, farmers, chiefs and opinion leaders.

b. Community Survey

Before the commencement of the field work a focus group discussion was held with farmers in two communities (Bolga-Nyarega and Bongo-Nyarega). A check list seeking information on land use, cropping system and land tenure was used. As a result, farmers willing to participate in the research were selected from these two communities. Based on the farmer’s willingness to farm the same piece of land during the dry season, the sites were selected to set up the experimental plots. After the selection of the sites, an individual interview was conducted with the farmers of the selected sites to obtain information on the land use history and management practices of their farm.

3.2.2. Agricultural land use land cover classification and soil types

Agricultural land use data were obtained from the land use/cover map produced by Fokuor (2014). This map was derived from RapidEye images based on Random Forest classification. This land use/cover map has been selected because it is a recent map based on high resolution images and with a good classification accuracy (Kappa = 0.88; overall accuracy = 90.6 %). In addition, the agricultural land use classes corresponded to the focus of the present study. However, ground control GPS points were taken with hand hold GPS (Garmin) within the different land uses in the catchment and projected in the LULC map to check the accuracy. The overall accuracy achieved was estimated to be 92 %.

The land use/cover classes consisted of cereals (maize, millet and sorghum), rice, groundnut, grassland, mixed vegetation and forest, water bodies and artificial surfaces.

To obtain the statistics of agricultural land use under each soil type, the LULC map and the soil map of Vea were combined; that is to say, both maps were projected to the same coordinate system (UTM WGS84 Zone 30 North) and overlaid. The coverage of land use per soil type was determined by pixel count of each land use per soil and deriving the percentage.

3.2.3. Rice cropping systems

Based on the practices in the area the following cropping systems were used in the rice experiment.

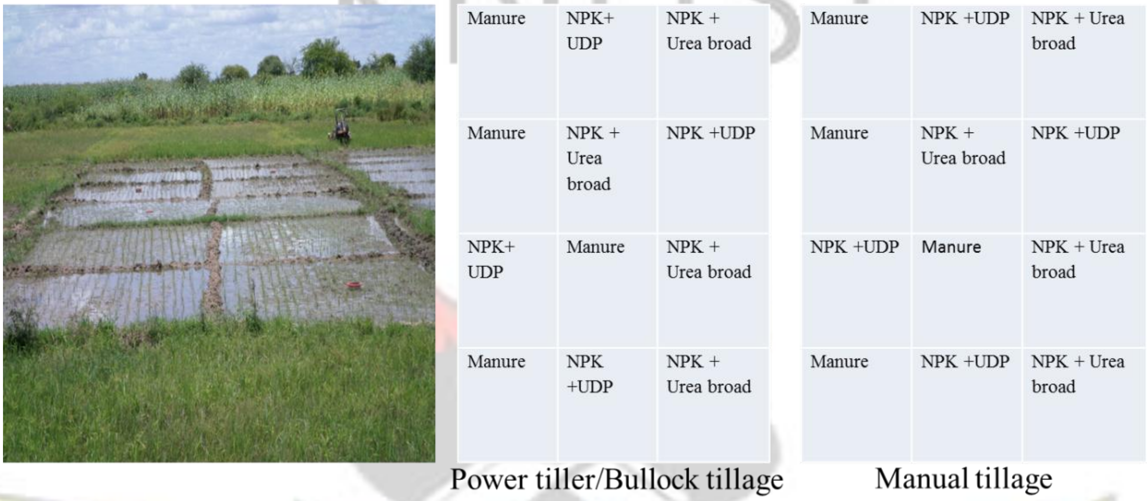
a. Continuous rice

Three rice fields were selected based on the farmer willingness to farm on the same plot during the dry season. In these fields, rice is grown continuously with a short transition period between the dry season rice harvest which normally precedes the preparation of the land for the rainy season cultivation. Three methods of seedbed preparation for the rice trial were performed as follows:

i. Conventional tillage by power tiller and bullock plough (Plates 3 and 4 in the appendix) followed by manual levelling with the hoe was performed. The soil was prepared using two different methods; power tiller at 12 cm depth and bullock plough at 8 cm depth. After ploughing, the land was levelled with the hoe before manual rice transplanting was done in rows with 2-3 plants per hill at 20 cm apart.
ii. Manual tillage (Plate 5 in the appendix) was performed by hoe ploughing and levelling the plot with a hoe at about 6 cm depth. Three weeks old rice seedlings were transplanted with 2-3 plants per hill with 20 cm inter and intra row spacing.

Chemical fertilization was done according to technical recommendation by the project management in the area. For basal fertilization, 250 kg/ha of compound fertilizer (15-15-15) was applied to the plots with chemical fertilizer and 5 t/ha of manure (cow dung) on the day of transplanting. After 40 days of transplanting, 125 kg/ha of urea was applied using the broadcasting method for top dressing; and 113 kg/ha of urea briquettes were applied by deep placement (i.e. 3 - 5 cm) at the rate of one briquette for four hills instead of broadcasting urea. Weed control was done before the top dressing (i.e. 40 days after transplanting) and when it became necessary by using the manual rotary weeder/hoe in the rows and intra rows and weedicide 2,4 D (Ervextra) at the rate of 1 L/ ha.

The manure was sampled and analysed in the laboratory for the nutrient content. Randomly, three locations within each of the 10 bags of manure were sampled and composited to determine the macro nutrient (NPK) content and the pH. iii. Experimental design for rice management system



Manure	NPK+ UDP	NPK + Urea broad
Manure	NPK + Urea broad	NPK +UDP
NPK+ UDP	Manure	NPK + Urea broad
Manure	NPK +UDP	NPK + Urea broad

Power tiller/Bullock tillage

Manure	NPK +UDP	NPK + Urea broad
Manure	NPK + Urea broad	NPK +UDP
NPK +UDP	Manure	NPK + Urea broad
Manure	NPK +UDP	NPK + Urea broad

Manual tillage

Tillage systems: Power tiller tillage, bullock tillage and manual tillage with hoe

Fertilization: basal- NPK= 250 kg/ha, urea= 125 kg/ha, UDP: 113 kg/ha and manure (cow dung): 5 t/ha

Figure 3. 3: Experimental setup for rice trial

To determine the dominant cropping system and monitor the soil CO_2 flux under such system in the area, experimental plots were set up for selected crops (rice, maize and sorghum) in the irrigation scheme of the Vea dam. For the rice trial (Figure 3.3) at each of the 3 sites, a 3 x 3 factorial experiment in Randomised Complete Block Design with four replications was used. The first factor consisted of three tillage systems: bullock tillage, power tiller tillage at a depth of 8 and 12 cm respectively and manual tillage (i.e. hoe) at 6 cm depth. The second factor consisted of three types of amendment: NPK + urea broadcast, NPK + briquette of urea in deep placement (UDP) and manure. NPK was used for basal fertilization on the day of transplanting and urea for top dressing 40 days after transplanting (ICOUR recommendation not published). In all, there were 36 experimental plots. Each plot measured 6 m × 4 m with 0.5 m path.

3.2.4. Maize and sorghum cropping system

The maize and sorghum experiment was conducted in three farmers' fields with three treatments in each field.

a. Maize - tomato/ kenaf cropping system

The Maize - tomato/ kenaf management system for upland soils under the irrigation scheme, around the dam include maize /sorghum + millet (rain season) and tomato/ kenaf during the dry season in the study area. In each of the three selected maize fields based on farmer willingness to farm on the same plot during the dry season, a 20 m × 20 m plot was set out. Land preparation for maize was done by tractor ploughing followed by harrowing. After harrowing the land, maize seeds were manually sown in rows. The maize was sown at a spacing of 50 cm × 30 cm. The seeds were sown at 2-3 per hill and at mean sowing depth of 4 cm. The Dadaba improved maize variety from Ghana Seed Breeders Association was used in two fields but, in the third field, the local yellow variety (Pana) seeds were sown.

Two of the three farmers controlled weed by doing two sections of weed control i.e. the first, weedicide (atrazine) at the rate of 52 g/ knapsack in 18 L of water at crop emergence (i.e. a week after sowing) and hoeing and earthing-up for the second before the fertilizer application (i.e. four weeks after crop emergence). There was no basal fertilizer application. A 100 kg/ ha of NPK (15-15-15) was applied by hand broadcast at panicle stage i.e. 6 weeks after germination. The last farmer, controlled weed only by hoeing and earthing up.

At the full maturity stage, the maize was harvested with the straw and gathered in small bundles to air dry. After 30 days the cobs were separated from the stalk and the spathe removed.

For maize and sorghum the plot size of 400 m^2 (20 m × 20 m) was used. In the dry season, land preparation for starts by collecting residues as fodder for cattle, followed by watering the plot for tillage. Then, the land is ploughed by a tractor and harrowed; tomato or kenaf (*Hibicus ssp*) was transplanted on ridges. For tomato, the transplanting was done at a spacing of 50 ×30 cm and for kenaf the spacing of transplantation is 30 × 30 cm.

b. Sorghum - tomato/ kenaf

Land preparation was the same as that for maize. Three sorghum fields were selected based on farmer willingness to farm on the same plot during the dry season using a 20 m × 20 m plot. In the area, pure sorghum or millet field is rare, (since farmers practice mixed cropping i.e. sorghum + early millet or late millet + early millet) during the main season. In the dry season, tomatoes or kenaf are usually grown under irrigation on the previous sorghum field.

3.2.5. Agronomic data collection

The agronomic parameters that were taken during the experiment include: plant height, number of leaves per plant, above ground biomass, leaf area index, days to flag leaf appearance, days of physiological maturity and yield.

a. Plant height

The plant height was measured from ground surface to the tip of the growing point or panicle. For maize and sorghum, the plant height was recorded from the soil surface of ten tagged plants to the tip of the growing point initially using a ruler and then later a graduated stick. Plant height for rice was taken for five tagged plant hill in the middle rows. This was achieved simply by holding together a handful of stems for the tagged rice hill. A graduated stick is then placed against the bundle and height recorded (Gbanguba *et al.*, 2014).

b. Number of leaves determination

To determine the growth (phenology) stage of maize and sorghum the Leaf Collar Method and flag leaf appearance for the tagged plants in each plot were used. This method determines the leaf stage in maize and sorghum by counting the number of leaves with visible leaf collar from the lowermost to uppermost leaf (Nielsen, 2014; Abendroth *et al.*, 2011). Leaves within the whorl, not yet fully expanded are not included in this method. The specific leaf stage for an entire field is defined by the value which represents the majority of plants in the field (Abendroth *et al.*, 2011). Rice phenology observation was done by visual identification of vegetative and reproductive growth stage with morphological markers (collar, flag leaf, panicle, caryopsis, grain) (Moldenhauer *et al.*, n.d.).

c. Above-ground biomass determination

Maize, sorghum and rice biomass was collected from the row next to the border rows from 1 m length for three samples per plot. Samples were taken at two weeks interval up to the flowering stage. All wet samples were weighed and oven dried to a constant weight at 70 °C in an oven for 72 hours. For the first two samples (i.e. 2nd and 4th week) the total sample was oven dried, but in the advanced growth stage, a sub-sample was taken and dried. The oven dried samples were weighed to compute the above ground biomass in kilogrammes per hectare.

d. Date to flag leaf appearance

In maize and sorghum fields the 10 tagged plants and five tagged rice plant hill in the middle rows were monitored from germination to the date of flag leaf appearance and number of days recorded.

e. Date of physiological maturity

Physiological maturity is the time when grains have ceased accumulation of carbon and begin drying. The assessment of it in the field was done by observation of maturity signs in the tagged plants (maize and sorghum/millet) and tagged plant hills (rice) for each plot and the days to physiological maturity were recorded. For maize the signs of physiological maturity are black dot/layer visible at the base of kernels visible by removing grains from the cob and scraping the base with fingernail, i.e. at 60 % dry matter. For sorghum/millet and rice sign of maturity is when 60 % of the whole grain in the panicle is hard.

f. Grain yield and yield components

At harvest, in 8 m × 2 m within the plot two central rows were harvested for maize and sorghum to determine the grain yield per hectare. Plants were harvested at physiological maturity. The cobs (maize) and panicles (i.e. sorghum and millet) from harvested plants were harvested, air dried and dehusked to obtain the grains. The grains were weighed. The moisture content of the grains was determined and brought to the 18 % moisture for computation of 1000 grain mass and grain yield.

The harvested area for rice was 5 m × 1 m (Plate 10) in the centre of the plot. The harvested rice was air dried for two days, threshed and winnowed to separate the filled grains from the unfilled grains. The filled grains, unfilled grains and straw were weighed to determine the biological and economic yield, and 1000 grain mass.

To assess yield components for rice, three 2 × 2 (i.e. a total 12 hills per plot) were sampled at random from the test area (excluding borders) of each plot as recommended by Gomez (1972). The total number of panicles (P) from all sample hills was counted. From each sample hill, the central panicle (based on height of the individual tillers) was separated from the rest of the panicles. Grains from the 12 central panicles were threshed and bulked. The filled grains and unfilled grains from the central panicles were separated manually. This was followed by counting of the filled grains (f) and the unfilled grains (u); and the filled grains (w) weighed.

Grains from the remaining sampled panicles were threshed and separated to give unfilled grains and filled grains. The unfilled grains (U) were counted and the filled grains (W) were weighed. Then, the number of panicles per hill was computed, number of filled grains per panicle, percentage of unfilled grains and

1000-grain mass by using the following equations as given by Gomez (1972):

$$N\ of\ panicles\ hill^{o}\ /\ \square\ {}_{3}\ \frac{P}{4} \qquad [3.1]$$

$$N\ of\ filled\ grains\ panicle^{o}\ /\ \square\ \square\ \frac{\square w\quad f\ W}{w\quad P} \qquad [3.2]$$

$$Percentageof\ unfilled\ grains\square\ \frac{\square u}{U)/\ \square\ \square u}\ \square 100\ \ U\ f\ W(\ \square w\ W \qquad [3.3]$$

$$1000\square\ grainmass\square\ \square 1000\ \frac{w}{f} \qquad [3.4]$$

3.2.6. Soil CO2 flux measurement

Soil CO_2 flux measurement was done using three collars (i.e. three replicates) in each treatment for the rice, maize and sorghum fields (Plates 6, 7 and 8). The soil CO_2 flux was measured using CO_2 transmitter GMD20 (Vaisala, Helsinki, Finland) that has silicon CARBOCAP mounted in a custom made PVC chamber by the Forschungszentrum Julich, Germany. The GMD 20 is designed to operate from the nominal 24 V AC/DC power supply. To prevent the pressure fluctuation in the chamber, a plastic vent tube (50 cm length and 0.5 cm internal diameter) is fixed. According to Davidson *et al*. (2002), unventilated chamber can result in the development of pressure differentials caused by circulating gases or by cooling or warming of the chamber air. The collars were inserted into the ground at least one day before the first measurement and it remained in the same position for the entire period of measurement except for temporary removal when mechanised farm operations were performed as described by Ussiri and Lal (2009) and used by Prempeh (2015) and Dossou-Yovo *et al*. (2015).

During the soil surface CO_2 monitoring, the soil respiration static chamber was fixed onto the PVC collar. The output voltage signals from the CO_2 sensor were recorded using the digital voltmeter and converted to the CO_2 in ppm by multiplying the output voltage by the calibrated factor of 200 ppmv (Prempeh, 2015). The chambers were closed for 25 minutes to minimise flux underestimation (Senevirathna *et al.*, 2006) and readings were taken in 5 minutes intervals but the first reading was taken as soon as the chamber was lowered. The influence of plants on soil respiration was eliminated by removal of all living plants inside the collar a day before soil respiration measurement as stated by Frank *et al*. (2006). Soil CO_2 fluxes were measured from 9 am to 12 am and 3 pm to 6 pm weekly at all sites to take into account variability in CO_2 flux due to diurnal changes in temperature (Parkin and Kaspar, 2003). Water levels inside the collar were measured during flood conditions (Sapkota *et al.*, 2014).

During the soil CO_2 flux measurement, the temperature and relative humidity inside the chamber were measured along the soil collars as the CO_2 efflux was being monitored using the Vaisala INTERCAP Humidity and Temperature Transmitter, HMD 53 Vaisala Intercap1 Sensor (Vaisala, 2011) connected to the chamber. It is duct mounted to the chamber. The measurement range for the humidity is 0 to 100 % RH and for the temperature is -20 to +80 °C. At all locations where CO_2 readings were recorded, soil temperature near the collar at the depth of 5 cm and ambient temperature at 1.2 m above the ground surface were taken using the Omegaette HH306A Thermometer/Data Logger (Omegaette, 2008).

Volumetric soil moisture content was also measured simultaneously at 5 cm depth on the same day of CO_2 flux measurement at 4 points near the collar with a portable Moisture Meter type HH2 (Delta-T Devices, 2013) (Plate 9)**.** The mean of soil moisture content from twelve points (i.e. 4 points close to the chamber and 3 chambers per plot) were used as the value for the plot.

3.2.7. Soil CO2 flux computation

The collected time series data of CO_2 concentration in ppm for 25 minute were used to compute the soil CO_2 flux by using the following equation stated by Flessa *et al*. (1998):

$$F = \frac{dC}{dt} \times \frac{273.15}{273.15 + T} \times \frac{V}{A} \times \frac{1}{V_m} \times M_c \times 60 \times 1000 \quad [3.5]$$

Where: F is the soil CO_2 flux (mg CO_2-C m^{-2} h^{-1}); dC/dt is the change of CO_2-concentration in time (10^{-6} min^{-1})

T is the temperature inside the soil respiration chamber (°C)

V is the chamber volume (m^3)

A is the chamber base area (m^2)

V_m is the molar volume of air at 0°C ($0.0224\ m^3\ mol^{-1}$)

M_c is the molar mass of carbon ($12\ g\ mol^{-1}$)

The 60 is the conversion factor from minute to hour and 1000 is the conversion factor from gram to milligram.

The correlation coefficient (R^2) was calculated for flux and time for each series of 25 minutes, if R^2 is ≥ 0.95 then the flux (F) was calculated using Flessa *et al.* (1998) equation.

During the study period the cumulative CO_2 emissions were computed by using the equation given by Grote and Al-Kaisi, (2007)

$$M = \sum_{i=1}^{n} \frac{F_{i+1} + F_i}{2} \times (t_{i+1} - t_i) \qquad [3.6]$$

Where:

M is the cumulative emission of CO_2–C ($mg\ CO_2\text{-}C\ m^{-2}$),

F_i is the first CO_2 emission value ($mg\ CO_2\text{–}C\ m^{-2}\ h^{-1}$) at time t_i (h),

F_{i+1} is the following value at time t_{i+1} (h); n is the total number of CO_2 emission values.

To identify treatment which induced lower soil CO_2 emission per unit grain yield, the amount of soil CO_2 emission per unit grain was calculated using equation given by IPCC (2007)

$$R = \frac{M}{Y} \qquad [3.7]$$

Where:

M = Cumulative emission CO_2-C (t/ha) and

Y= grain yield (t/ha).

3.2.8. Soil data collection

a. Soil sampling

Based on land use land cover classification map from Fokuor (2014) and soil map of Vea catchment from FAO classification (1971 - 1981), three sites per land use type were selected for monitoring of soil carbon dynamics in the dominant soil type within the catchment. The total number of land uses selected was 24. These sites were made-up of croplands, which included irrigated and rain-fed rice, maize and sorghum, eucalyptus forest, grazing land, abandoned agricultural sites, and semi natural vegetation. The study was conducted in two separate soil sampling campaigns. The first one focused on croplands, and the second involved croplands and the rest of land uses. At the beginning of the study, selected croplands were sampled for determination of initial soil carbon and chemical properties at the following depth intervals: 0 - 10 cm, 10 - 20 cm and at 5 locations within each plot. Following this preliminary study, samples were collected and processed according to a protocol specifically developed for small household farms (Saiz and Albrecht, 2015). Briefly, samples were collected in four locations at each of the 24 selected sites. The first sampling point (replicate 1) was located at the centre of the plot (Plate 12) and the other three replicates were laid out according to a pattern of three axes separated by 120° with respect to an initial axis pointing north. The final sampling point was georeferenced using handheld GPS (etrex 20 GARMIN). At each of these 4 locations, surface litter was removed by hand and the following depth intervals were sampled: 0 - 5, 5 - 20 and 20 - 30 cm. The reason for using these sampling depths is because most of the top-soil is within 0 - 20 cm, organic matter is in 0 - 5 cm and roots of crops are located within top 30 cm. The procedure for taking samples at each of the four sampling locations was as follows:

- 2 samples at 0 - 5 cm

For 0 - 5 cm, two samples were taken within 1 meter distance and put inside the same sampling bag to reduce local heterogeneity, which is particularly pronounced at this depth. Samples were taken using a core sampler (5 cm inner diameter) for the entire sampling interval.

Soil samples were initially air-dried for some days by opening and rolling down the bags. Soil clods were progressively broken by gently squeezing the sample inside the bag. Subsequently, samples were oven dried at 40 ˚C for 2 - 3 days and then weighed with the sampling bag. An aliquot of this material (about 1/4 of total sample) was weighed and placed in a labelled paper bag for drying at 105 ˚C for 24 hours, after which the sample was re-weighed for calculation of soil water content to correct for the initial air-dried sample and determine soil bulk density. The air dried samples were sieved through 2 mm mesh for analysis. Soil samples for the initial carbon assessment were analysed at the soil laboratory of Savanna Agricultural Research Institute in Nyankpala (Tamale). Moreover, soil samples collected were sent out to the Bio-geochemistry laboratory of the Karlsruhe Institute of Technology (KIT) Germany for further processing and analysis.

b. Sample processing

Soil clods were manually broken and air-dried samples were initially weighed prior to being sieved to using 2 mm sieve. All the obtained fractions were weighed separately, including those > 2 mm (gravel and coarse roots).

Bulking or pooling was done using dry sieved samples according to two separate procedures. The first one was done to get a bulk sample per depth and per site. This was done by putting together 5 g of sieved samples collected by plot per sampling depth for all replicates. The second one was performed to obtain 80 g of “Master Sample” from 0 - 30 cm depth interval. The “Master Sample” was composed of 1/6 = 13 g of sample (0 - 5 cm) plus 3/6 = 27 g sample (5 - 20 cm) and 2/6 = 40 g sample (20 - 30 cm).

The average SOC stock for a given depth interval (d) was calculated according to the following formula stated by Saiz and Albrecht (2015):

$$\mu d = BDd \times OCd \times D \times (1 - gr) / 10 \qquad [3.8]$$

Where µd is SOC stock (Mg OC ha^{-1});

BD_d is soil bulk density (g cm^{-3});

OC_d is the concentration of OC in soil (< 2 mm; mg OC g^{-1} soil);

D is soil depth interval (cm); gr is fractional gravel content, the soil fraction > 2mm.

c. Soil characterisation

To characterise the soil type, two sample profile pits (2 m × 1 m) with 1.5 m soil depth (Plate 11) and six mini pits (1 m × 0.6 m) were dug at different locations within the study area. One profile pit was dug in Bolga Nyarega and the second one at Bongo Nyarega. The pits were georeferenced. Genetic horizons of the profile and soil type were characterised according to the guidelines of WRB/FAO (2014). The horizons of profiles were sampled and analysed at the Soil Research Institute for physical and chemical properties.

3.2.9. Soil physical analysis

a. Bulk density determination

Two procedures were used to determine the bulk density. For the genetic horizons of the sample profile pits, the bulk density was determined by drying the core sampler with its content at 105 °C for 48 hours to constant weight. The bulk density, ρ (g/cm^3) was computed using the formula:

$$\rho = \frac{M_2 - M_1}{V} \quad [3.9]$$

Where M$_2$ = Mass of the core sampler with oven dried soil

M$_1$= Mass of empty core sampler

V= Volume of core sampler

The approach for soil bulk density determination of soil samples for selected land uses is as follow:

The aliquot with its paper bag was dried at 105 °C for one day and after drying the aliquots were weighed. The bulk density ρ (g/cm^3) was computed as:

$$\rho = \frac{M}{V} \quad [3.10]$$

Where: M = Mass of oven dried soil at 105°C

V (cm^3) = Volume of core cylinder = ($\pi \times r^2 \times$ h),

Π = 3.142

r = radius of the core cylinder (cm) h

= height of the core cylinder (cm).

b. Particle size distribution

The particle size distribution was determined by particle settling rate in an aqueous solution using adapted hydrometer method (Bouyoucous, 1962) where the sand fraction is taken at 40 seconds and the clay fraction after five hours. The method is based on a dispersion of soil aggregates using sodium hexametaphosphate and the measurement is based on the change in suspension density (Landon, 1991). The samples were pre-treated with hydrogen peroxide to remove the organic matter before the dispersion. The soils were classified into different textural classes using the USDA textural triangle.

3.2.10. Soil chemical analysis

a. Soil pH

The soil pH was determined by two different methods. The first one was done using 1:2.5 soil: water ratio where 10 g of sample was added to 25 ml of distilled water, stirred and left to stand for about an hour. A standardised pH electrode was dipped into the setup and the reading taken (i.e. samples for initial carbon determination). The second one was done by using a digital pH meter in a 1:2 soil water solution to determine the soil pH in the dry sieved sample (2 mm) (Saiz *et al.*, 2012). The solution was stirred vigorously before dipping the pH meter in the solution and the readings taken (i.e. samples from the twenty five land uses for carbon stock determination).

b. Soil organic carbon determination

This was determined using the modified Wakley and Black (1934) method. A known sample weight is put into a conical flask, 10 ml of 1N $K_2O_7Cr_2$ and 20 ml of H_2SO_4 is added and left in the fume chamber to cool. After cooling, 100 ml of distilled water is added and allowed to cool. Then, 2 - 3 drops of diphenilamine indicator was then added and titrated against 0.5N Fe_2SO_4.

Calculation:

$$\%organicC = \frac{(me\,K_2CrO_7 - me\,FeSO_4)\,(1.32)\,0.003}{weight of soil} \quad [3.11]$$

Where:

m.e. = molarity of the solution× ml of solution used

0.003 = m.e weight of C in grams (12/4000)

1.32 = correction factor

c. Total nitrogen determination

Nitrogen was determined by the wet oxidation using the Kjedahl method. A known sample weight is put into digestion tube and digested with the Kjedahl digestion mixture from dark brown to colourless solution at 360 ˚C. The sample was then topped to the 100 mark with distilled water; an aliquot was then taken and distilled through the vapodest into a conical flask containing boric acid. As the boric acid receives the nitrogen, it turns from pink to green and then it was titrated with 0.1M HCl from green colour to pink giving the nitrogen titre value.

d. Determination of available phosphorus

A known sample weight is put into a shaking bottle and 35 ml of Bray P-1 (0.03 M NH_4F and 0.25 M HCl) extraction solution was added and shaken on a mechanical shaker for 8 minutes and immediately filtered through filter paper Whatman number 42. The blue colour was developed and measured on the Ultraviolet Visible Spectrometer. The concentration of P in the extract was determined by comparison of the result with a standard curve.

e. Determination of potassium and sodium exchange capacity

Flame photometric method was used to determine potassium (K) and sodium (Na) in the soil solution. A known sample weight is put into a conical flask and 50 ml of 1N NH_4OAC extraction solution was added and shaken on a mechanical shaker for

2 hours and then filtered through filter paper Whatman number 42, potassium and sodium were measured directly on the Flame Photometer.

Calculations:

$$Exchangeable K\ Mg\ kgsoil(\ /\ ) = \frac{\qquad}{Graphreading \times 100 \times \times W\ 10}$$

[3.12] 39.1

$$Exchangeable Na\ Mg\ kg\ soil(\ /\ ) = \frac{\qquad}{Graphreading \times 100 \times \times W\ 10}$$

[3.13] 23

Where:

W = weight of air-dried soil sample in grams

39.1 = molecular weight of potassium

23 = molecular weight of sodium.

f. Determination of exchangeable calcium by the versenate (EDTA) method

Exchangeable calcium (Ca) was determined in 1.0 M Ammonium Acetate extract. To determine calcium (Ca), 5 g of air-dried soil sample was put in a 150-ml conical flask and 25 ml of neutral normal ammonium acetate solution was added. The solution was shaken on a mechanical shaker for 5 minutes and filtered through No 1 filter paper. An aliquot (5 ml) of potassium hydroxide solution was pipetted and 2 - 3 crystals of carbonate and 5 ml of 16 % NaOH solution were added. Cal-red indicator powder 40 - 50 mg was also added and titrated with 0.01N Ethylene Diamine Tetra-Acetic acid (EDTA) solution in drops at 5 - 10 s intervals until the colour gradually changed from orange-red to reddish-violet (purple). The end point was compared with a blank reading to check whether the solution was over titrated.

The concentration of calcium was computed using the following equation:

$$Ca\ cmol\ kg\ soil(/) = \frac{0.01 \times (V_a - V_b) \times 1000}{W} \qquad [3.14]$$

Where:

W= weight (g) of air dried sample used

V_a= ml of 0.1N EDTA used in sample titration

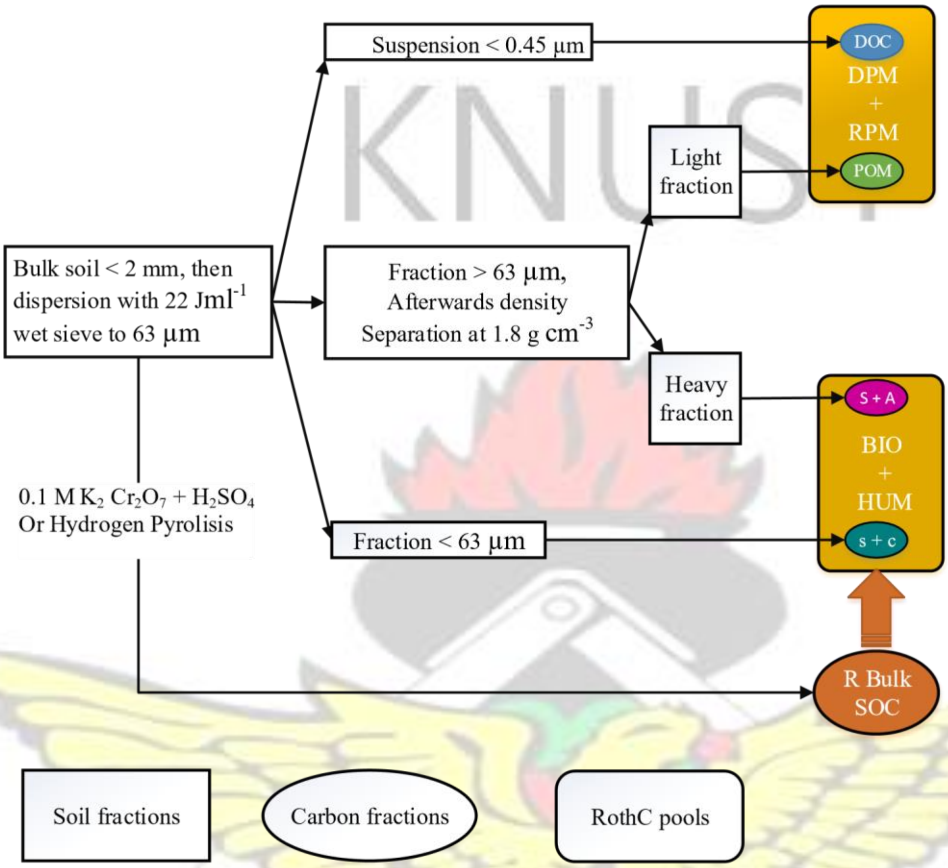
V_b= ml of 0.01N EDTA used in blank titration

0.01= concentration of EDTA.

g. Soil carbon fractionation

Soil samples were fractionated by combining wet sieving and density separation following procedure adapted by Gustavo Saiz (per com) from Zimmermann *et al.* (2007) and illustrated in Figure 3.4. Thirty grams of dry-sieved soil (<2 mm) was added to 161 ml of ultra-purified water and dispersed using a Bandelin type calibrated ultrasonic probe with output energy of 22 J ml^{-1} to disrupt and break up labile aggregates (Amelung and Zech, 1999). The dispersed suspension was then wet sieved using 63 µm sieve mesh until the rinsing water is clear. The fraction > 63 µm containing the sand fraction (S) and stable aggregates (A) together with the Particulate Organic Matter (POM) was dried at 50°C and weighed. The suspension < 63 µm was filtrated through a 0.45 µm aperture nylon mesh and the material > 0.45 µm was dried and weighted. An aliquot of the filtrate was frozen to determine the amount of Dissolved Organic Carbon (DOC). All particles passing through the 63 µm sieve corresponded to the silt and clay fraction (s + c).

The POM was separated by adding sodium polytungstate (SPT) with a density of 1.8 g cm^{-3}. The mixture was centrifuged for 15 minutes and the light fraction was decanted. Both fractions were washed with ultra-purified water to remove all SPT and dried at 50 °C and weighed.



DOC: Dissolved organic carbon; POM: non-protected particulate organic matter; S + A: stable aggregate fractions; s + c: Silt + Clay; **Figure 3.4: Diagram of fractionation procedure** source: Zimmermann *et al* (2007) and Saiz *et al* (2012)

The chemical resistant carbon fraction (rSOC) was extracted from the dry sieved sample (2 mm) by adding 50 ml of 0.1M $K_2Cr_2O_7$ and 2M H_2SO_4 to 500 mg soil sample (Saiz *et al.*, 2012) in centrifuge tubes. The mixture was heated to 60 °C in a temperature-controlled orbital shaker for 72 hours (Plate 13). At the end of incubation, all samples were washed with distilled water and dried at 60 °C. Periodically, the tubes were opened to discharge evolved gases. Carbon and nitrogen contents in all solid fractions were accurately weighted and measured by CN combustion in elemental analyser.

3.2.11. Soil carbon projection

Introductory Carbon Balance Model was used through an Excel spreadsheet for estimating the current and projecting 30 years soil carbon status for maize and sorghum cropping system under different management practices. The initial carbon was set to the average of measured value for maize sorghum/ vegetable cropping system. The annual carbon input was estimated as sum of carbon inputs from crops and manure. The approach is to apply allometric equations to yield data by using estimates of the relations between crop yield, roots, stubble and straw (Kuzyakov and Domanski, 2000; Andrén *et al.*, 2004; Bolinder *et al.,* 2007). The yields data are from Agyare *et al*. 2006 and own data. The calculations for annual carbon input from crop to soil are made in Excel workbook *Afallo_1* (Andrén *et al.*, 2012). The humification coefficient and external influence coefficient were derived from literature (Andrén *et al.,* 2007). The weighted average humification quotient (h) for cereals is 0.128 (Andrén *et al.,* 2012) and it is assumed that the quotient is higher for natural fallow about 0.2. Six scenarios of management including fallow every five (5) years were set-up:

1. Fertilised maize in rotation with groundnut for 10 years,
2. Fertilised maize in rotation with sorghum for 10 years,
3. Fertilised maize plus sorghum in rotation with groundnut for 10 years,
4. Continuous fertilised maize for 10 years,
5. Sorghum: no input with inert fraction of carbon,
6. Sorghum: no input with inert fraction and straw removed,
7. Fallow for five years after 10 years production.

3.2.12. Data analysis

The statistical package Minitab 16 and GenStat 9.2 (2007) was used to analyse the data using the General Linear Factorial Model ANOVA procedure to determine the significant effect of treatment on rice performance, soil temperature and moisture at 5 cm depth, cumulative soil CO_2 flux for the selected (rice, maize, millet or sorghum) cropping system under different management practices. Treatment means were separated by Least Significant Difference (LSD) test at $p < 0.05$.

Soil CO_2 flux measurements for rice, maize and sorghum were correlated with soil temperature and soil volumetric moisture content to estimate the dependency of soil respiration variability on soil temperature and soil moisture at 5 cm. R values above 0.8 indicated a strong correlation, those between 0.5 and 0.8 a moderate correlation and values smaller than 0.5 a weak correlation.

3.3. Limitation of the Study

In this study, the soil map used is the available FAO one with a small scale and low resolution to determine the types of soil in the area. Again, in the study, the soil CO_2 emission was computed from both heterotrophic and autotrophic respiration because it is impossible to separate them with the measurement equipment available for the net ecosystem exchange estimation.

In addition, the study monitored only CO_2 emission for rice under irrigation as GHG knowing nitrous oxide and methane are very important GHGs for irrigated rice. Besides, the projection of SOC was made only for maize and sorghum cropping system under different scenarios.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Proportion of Soil Types and Land Use / Land Cover in the Study Area

Land use is an important parameter that influences the rate of carbon sequestration at the local and landscape scale. Figure 4.1 presents the LULC and soil type in the Vea catchment. The image was classified into eight main land use classes which are: cereals, groundnuts, rice, grassland, mixed vegetation, forest, artificial surfaces and water body. The figure shows that most parts of the landscape are occupied by cropland over three types of soil. The dominant soil type in the area is Lixisols followed by Fluvisols.

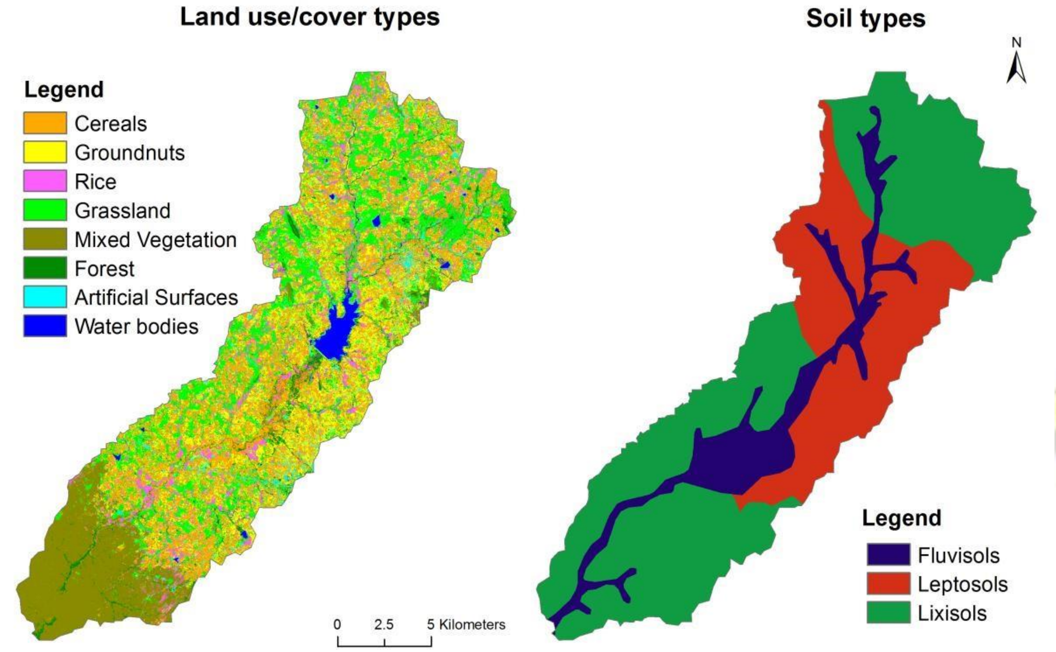


Figure 4.1: Land use/cover and soil map of the Vea catchment

Source: adopted from Forkuor (2014) and FAO (1988)

The statistics for land cover (Table 4.1) show that cropland (sorghum/millet and maize (SM + M), rice and groundnuts) is the largest with about 41.1 % of total land area; followed by forest and artificial surfaces with 18.1 % and 17.1 % respectively. This is because sorghum/millet, rice, maize and groundnut are the main source of food and cash for the communities in the area.

Table 4. 1: Coverage of land use and land cover types in the Vea catchment

	*SM +M	Rice	Groundnuts	Grassland	Mixed-vegetation	Settlements	Water bodies	Forest
Pixel count	802443	108673	206239	260206	191410	467171	197028	492498
%	29.5	4	7.6	9.5	7	17.1	7.2	18.1

*SM + M refer to sorghum/millet and maize

Table 4.2 provides the percentage of land use and land cover type in each soil type within the catchment. The Table reveals that all the land use classes can be found in all the three soil types.

Table 4. 2: Soil types and LULC proportion in the Vea catchment

Soil Types	**Land use/land cover**								**%**
	***SM + M**	**Rice**	**Ground-nut**	**Grass-land**	**Mixed-Vegetation**	**Forestry**	**Settlements**	**Water body**	
Lixisols	23.6	9.1	13.4	24.4	22.6	3.5	3.1	0.4	100
Fluvisols	25.3	11.3	15.2	18.6	15.3	4.7	2.9	6.7	100
Leptosols	27.3	8.6	27.3	19.5	4.0	5.3	6.2	1.8	100

* SM + M refer to sorghum/millet and maize

Sorghum/Millet and Maize are approximatively in the same proportion in all types of soil in the area. This can be explained by the fact that sorghum /millet and maize are the main staple and are cultivated by every household for consumption with their straws used as fuel or fodder for animals. The cultivation of sorghum and millet can be a monocrop or intercrop. Maize is not very common in the Vea catchment because of its high demand for external input (such as labour and fertilizer) (Aihou, 2003). The majority of groundnut fields are located on Leptosols. Groundnut is the main legume and together with other leguminous species are the source of protein and cash for the household (Marfo, 1992; Callo-Concha *et al.*, 2012). SM +M and groundnut occupied the largest area (37.1 %) and they are not fertilised by farmers. Rice is found mainly on Fluvisols (about 11 %) in the catchment area, cultivated mostly in valley bottom under rain-fed conditions. The reason for the location of rice under Fluvisols is due to its good fertility, higher water availability and suitability for irrigation (i.e. irrigation scheme). Under the irrigation scheme, rice is the main crop and is cultivated continuously with irrigation in the dry season and rain-fed during the rainy season. Grassland and mixed vegetation are mostly on the Lixisols for livestock grazing. The majority of water bodies are located in Fluvisols and some on Leptosols. Artificial surface and forestry are dominant on Leptosols but can also be found to a lesser extent on other soils.

4.2. Crop yield, dry biomass and some yield components under different management systems

4.2.1. Rice grain yield and dry biomass under different management systems

The combined effect of tillage practices and amendment for rice grain yield during the rainy season and dry season under irrigation was significant (Table 4.3 and 4.4). During the dry season (Table 4.3) significant difference was found for grain yield among treatments at 95 % significant level. The highest rice grain yield of 5675 kg/ha was observed under manual tillage with NPK + UDP as amendment during the dry season. The least grain yield was observed with bullock tillage and NPK + UDP amendment with 3535 kg/ha during the dry season under irrigation.

Table 4.3: Grain yield under different tillage practices and amendment types in the dry season under irrigation

Tillage	**Grain Yield (kg/ha) for different Amendment**			
	NPK + Urea	NPK + UDP	Manure	Mean
Manual	4450	5675	4725	4950
Power	4564	4652	4350	4522
Bullock	3535	5467	4428	4476
Mean	4183	5265	4501	
	Lsd (p = 0.05) Amendment = 527 Tillage = 527 Amendment × Tillage = 913			

The highest yields were obtained with NPK + UDP amendment with 4832 kg/ha and 4002 kg/ha for bullock and manual tillage respectively (Table 4.4) during the rainy season. This can be explained based on the fact that the seedbed under bullock tillage is likely to be well prepared than manual one and also, according to IFDC (2007), the deep placement of briquette increased the nitrogen use efficiency by keeping most of urea nitrogen close to the plant roots. Also, UDP briquette releases nutrient gradually into the root zone as it dissolves and this coincides with the crop's requirement during the growing season. The least yields were observed with manure amendment across tillage practices with 2610 kg/ha and 3036 kg/ha for manual and bullock tillage respectively during the rainy season. No significant difference was observed between the grain yield under manual tillage and bullock tillage with NPK + urea and manure during the rainy season, but the grain yield was significantly different for the tillage system and under NPK + UDP.

Table 4.4: Grain yield for tillage practices with different amendments during the rainy season

Tillage	Grain yield (kg/ha) for different treatment Amendment			
	NPK + Urea	NPK + UDP	Manure	Mean
Manual	2880	4002	2610	3164
Bullock	3128	4832	3036	3665
Mean	3004	4417	2823	
	Lsd (p = 0.05) Amendment = 523 Tillage = 427 Amendment × Tillage = 740			

Tables 4.3 and 4.4 reveal that the grain yield is higher across treatments during the dry season under irrigation than for the rainy season for the same treatment. The least grain yield for the dry season under irrigation corresponds almost to the highest grain yield during the rainy season. This fact is explained by the reduction of the effect of water deficit during the rice growth period and more photosynthetic activity during the dry season than the rainy season (Acheampong *et al.,* 2013).

Biomass yield for tillage practices with different amendments during the dry season under irrigation is shown in Table 4.5. The result revealed that there is significant difference in biomass yield across treatments during the dry season under irrigation at 95 % confidence level. The highest biomass yield was observed under manual tillage with manure as amendment during the dry season. The least biomass yield was observed under bullock tillage with manure as amendment during the dry season under irrigation.

Table 4.5: Biomass yield for tillage practices with different amendments during the dry season under irrigation Tillage Straw weight (kg/ha) for different Amendment

	NPK + Urea	NPK + UDP	Manure	Mean
Manual	10400	11550	12150	11367
Power	11575	12275	9825	11225
Bullock	9850	11475	7025	9450
Mean	10608	11767	9667	

Lsd (p=0.05) Amendment = 789 Tillage = 789; Amendment × Tillage = 1367

During the rainy season the total above-ground biomass yield was also significantly different across treatments at 95 % confidence level. The highest straw yield was observed with NPK + UDP amendment with 5450 kg/ha for bullock tillage (Table 4.6) and the least biomass yields were obtained with NPK + UDP amendment with 3400 kg/ha for manual tillage during the rainy season.

Table 4.6: Biomass yield for tillage practices with different amendments during the rainy season

Tillage	Biomass yield (kg/ha) for different treatment			
	Amendment			
	NPK + Urea	NPK + UDP	Manure	Mean
Manual	4944	3400	3427	3924

Bullock	5328	5450	4553	5110
Mean	5136	4425	3990	
	Lsd (p=0.05) Amendment = 1013 Tillage = 827 Amendment × Tillage = 1432			

4.2.2. Fertiliser effect on some yield components and above ground biomass of maize

Table 4.7 shows the data on the effect of fertiliser (i.e. 50 kg/ha of NPK) on maize variety and number of grain per cob, grain weight per cob, 1000-grain mass, grain yield and above-ground biomass. Fertiliser effects were significant at $p < 0.001$ for all the parameters studied except for above-ground biomass where the interaction was not significant at $p < 0.01$. Grain yield, grain weight per cob and number of grains per cob were significantly influenced by the use of fertiliser. The mean higher grain yield with the value of 1375 kg/ha was obtained with the use of fertiliser (i.e. 50 kg/ha of NPK) and the lower with the value of 865 kg/ha for the unfertilised maize. The significant differences in the number of grains per cob, grain weight per cob, 1000-grain mass and grain yield between fertilised and unfertilised maize could be due to the dissolution of fertiliser and nutrient use efficiency during the cob initialisation. Also, it should be noted that the significant difference between the treatments can be explained by the differences in the sowing date and varieties.

Table 4.7: Effect of fertiliser on some yield components and above-ground biomass for maize

Fertiliser treatment	Number of Grains per cob	Grain weight per cob (g)	1000-Grain mass (g)	Grain yield (kg/ha)	Above-ground biomass (kg/ha)
Fertilised	451 A	104 A	230	1375 A	4620 A
Unfertilised	214 B	68 B	179	865 B	3710 A
Statistics	P= 0.000; F= 55.86	P= 0.000; F= 74.70		P= 0.009; F= 29.12	P= 0.154; F= 3.09

Means that do not share a letter are significantly different

The above-ground biomass was not significantly different; the higher value of 4620 kg/ha was obtained for fertilised maize while the lower value of 3710 kg/ha was obtained in unfertilised maize representing 19.7 % reduction as compared to fertilised field. This can be explained by the fact that nitrogen fertiliser increases LAI and biomass accumulation.

4.2.3. Sorghum yield, some yield components and above-ground biomass

Table 4.8: Sorghum yield components, yield and above-ground biomass

Sites	Number of Grains per panicle	Panicle weight (g)	1000 Grain mass (g)	Grain yield (kg/ha)	Above-ground biomass (kg/ha)
Site 1	659.3 AB	32.8 A	42 A	970 A	9312 A
Site 2	1041 A	26.3 A	11.7 A	888 A	8574 A
Site 3	338.5 B	9.7 B	12.8 A	633 A	11466 A
Statistics	P= 0.03; F= 6.64	P= 0.011; F= 10.37	P= 0.109; F= 3.27	P= 0.02; F= 2.13	P= 0.556; F= 0.65

Means that do not share a letter are significantly different

The number of grain per panicle, panicle weight and grain yield were significantly different across sites with higher value of grain yield in site 1 compared to the value in the other 2 sites (Table 4.8). This may be due to the fact that the grain mass from site 1 are higher compared to the one from the other sites. The 1000-grain mass, grain yield and above-ground biomass were not significant, the higher value of 1000-grain mass and grain yield was obtained in site 1, the lower values were obtained in site 2 for 1000-grain mass and site 3 for grain yield. The differences in the values of yield and yield component can be attributed to the difference in sowing date and varieties. The highest value of above-ground biomass was obtained in site 3 and the lowest in site 2 but the grain yield did not show the same trend due to flooding in site 3 during the grain filling stage.

4.3.4. Soil Carbon Balance and Projections

The initial measured soil carbon mass was 15.96 t/ha (MSV land use organic carbon stock). Assuming that 50 % of this is inert (Andrén *et al.*, 2012), the initial mass of young and old soil carbon, thus was calculated as 7.98 t/ha without the inert. The annual carbon input to the soil was computed by applying allometric functions to yield data of maize and sorghum (Kuzyakov and Domanski 2000; Andrén *et al.*, 2004; Bolinder *et al.*, 2007; Gentile *et al.*, 2011). The calculations of climatic factors were based on the effects of soil temperature, soil water and cultivation intensity.

The projection (Figures 4.2 and 4.3) reveals that for all scenarios, the total carbon is decreasing from the initial level except for the scenario i.e. fertilised maize in rotation with groundnut where the accumulation of carbon is observed during the production period (10 years) before introducing fallow for 5 years. Fertilised maize in rotation with groundnut and fertilised maize plus sorghum after groundnut showed a continuous accumulation of carbon in opposite to the fertilised maize in rotation with cereals (Figure 4.2). This is due to the fact that the use of fertiliser and rotation of maize with groundnut maximised the growth and development of maize and more carbon input from plant to soil. Also, maize benefits from the nitrogen fixed by groundnut and decomposition of nutrient rich biomass, roots and nodules of groundnut. These results corroborate with the results of other studies (Agyare *et al*., 2006; Gentile *et al.*, 2011; Andrén *et al.*, 2012). The result (Figure 4.2) reveals that the depletion of carbon is about 8 % and 13 % for the scenarios of maize in rotation with sorghum and continuous maize cropping systems respectively for ten years period. The carbon depletion under these scenarios is likely due the less carbon input to the soil for maize in rotation with cereals. After introducing fallow, the carbon stock increases during the five years period but did not reach the initial level before production of crops. This can be explained by the fact that the carbon input from bush fallow is not sufficient to lead to full recovery of the carbon during the five years fallowing in the area. The depletion of carbon also shows similar trends about 15 %

depletion during 10 years simulation period (Figure 4.3) under the scenario of continuous sorghum production without fertiliser input before partial restoration during the five years fallow period. After introducing fallow for five years period, the carbon stock goes up faster in the first year fallowing (11 %) and slowly during the rest of the fallowed period but the level did not reach the initial level of carbon.

The results demonstrate that if the above management scenarios for production of maize and sorghum in the area is maintained, the depletion of the total soil carbon will occur with at the level of about 8 %, 13 % and 15 % of initial soil carbon for continuous fertilised maize in rotation with sorghum and maize, and with continuous sorghum without fertiliser input respectively for the 10 years simulation period. The result (Figures 4.2 and 4.3) also indicated that five years fallow period is insufficient for full restoration of the carbon stock under the above scenarios. However the cereal-legume (i.e. fertilised maize-groundnut) rotation is better management option compared fallowing.

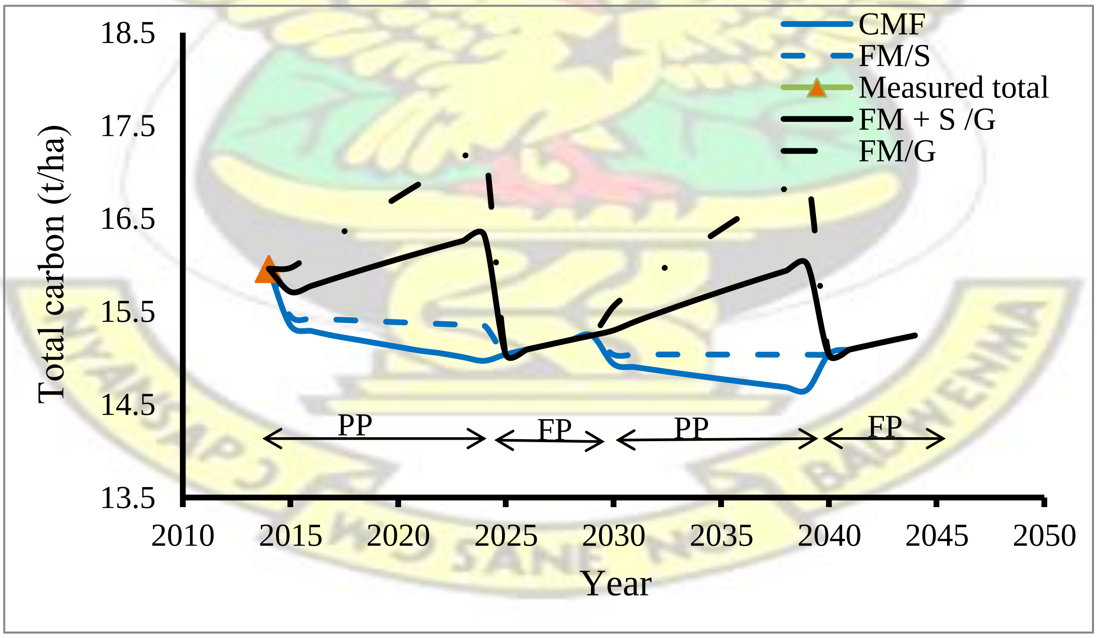


Figure 4.2. Soil carbon balance projection for maize under different management practices

CFM: Continuous fertilised maize; FM/S: Fertilised Maize in rotation with sorghum;

FM + S/G: Fertilised Maize + Sorghum in rotation with Groundnut; FM/G: Fertilised Maize in rotation with Groundnut; PP: Production Period; FP: Fallow Period

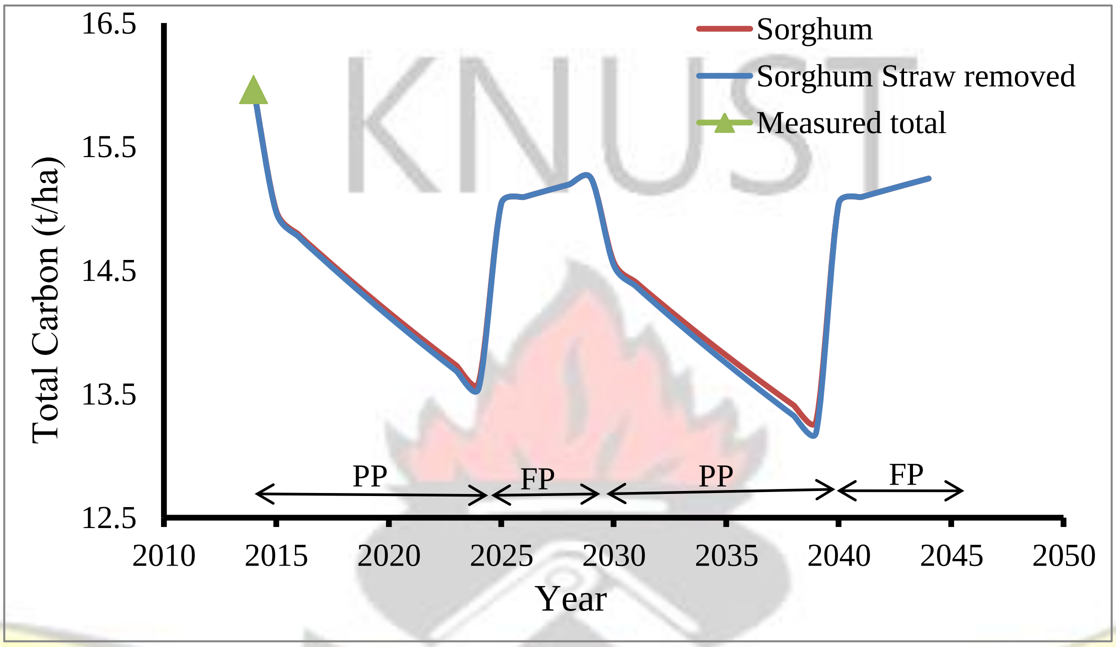


Figure 4.3. Soil carbon balance projection for sorghum under different management practices
PP: Production Period; FP: Fallow Period

4.3. Soil Carbon Change under Different Land Uses

4.3.1. Soil characterisation

Soil profile pits were dug and characterised to confirm soil types in the area to enable the use existing soil maps as secondary information source. The soil profile description of the two sample pits is presented in Tables 4.9 and 4.10 and also shown in Plates 1 and 2.

Table 4. 9: Soil profile description for sample Pit 1

Horizon	Depth	Description
Apg	0 - 13 cm	Brown (10YR 5/3), dark yellowish brown (10YR 4/4) paint mottle, sandy loam, very fine quartz gravels, weak fine granular, very friable, few fine intestinal pores, many very fine few fine and common medium roots, clear and smooth boundary
BAg	13 - 36 cm	Greyish brown (10YR 5/2), dark yellowish brown (10YR 4/4) faint mottle, sandy loam, common fine quartz gravels, fine granular, friable, high pores, very few fine roots, few worm cast, termites, clear smooth boundary
Btg	36 - 64 cm	Olive brown (2.5YR 4/3), dark yellowish brown (10YR 4/4), yellowish brown (10YR 5/4) faint mottle, sandy clay loam, common fine quartz gravels, weak sub angular blocky, very firm, slightly sticky non plastic, many high intestinal pores, very few fine roots, very few worm cast, clear and smooth boundary
Btcsg1	64 - 91 cm	Light olive brown (2.5Y 5/4), brownish yellow (10YR 6/6) faint mottle, clay loam, common very fine quartz gravels, moderately sub angular blocky, firm, slightly sticky slightly plastic, very iron and manganese dioxide, high pores, very few fine roots, very few worm cast, clear and smooth boundary
Btcsg2	91 - 123 cm	Light olive brown (2.5Y 5/4), gray (2.5Y 6/1) olive yellow (2.5Y 6/8) prominent mottle, clay, massive, firm, sticky plastic, very few iron and manganese dioxide, many high pores, few mick flakes.

Plate 1: Eutric Gleysol (WRB/FAO 2014) soil profile

Table 4.10: Soil profile description for sample Pit 2

Horizon	Depth	Description
Ap	0 - 20 cm	Dark yellowish brown (10YR 4/4), sandy loam, few fine quartz gravels, weak fine granular, loose, many high interstitial pores, very few very fine few fine common medium roots, worm cast, clear and smooth boundary
BAg	20 - 43 cm	Olive brown (2.5Y 4/4), faint yellowish brown (10YR 5/6) yellowish red (5YR 4/6) mottles, sandy clay loam, few fine quartz gravels, weak to moderately sub-angular blocky, friable, few medium pores, very few very fine roots, few worm cast, termites, clear and smooth boundary.
Btcsg1	43 - 116 cm	Light olive brown (2.5Y 5/4), faint yellowish red (5YR 4/6) mottles, clay, few fine quartz gravels, massive, hard, sticky, plastic, few iron and MnO_2 concretions, gradual and smooth boundary
Btcsg2	66 - 116 cm	Light olive brown (2.5Y 5/6),faint yellowish red (5YR 4/6) mottles, clay, common fine quartz gravels and few stones, massive, hard, sticky, plastic, few iron and manganese dioxide concretions, few calcium carbonate minerals, diffuse and smooth boundary
C	89 - 116 cm	Olive brown (2.5Y 4/3), sandy clay loam, weak sub angular blocky, weak fine granular friable, abundant calcium carbonate and few mica flakes
R	116 - 144 cm	Decomposing of parent material

Plate 2: Calcic Gleysol (WRB/FAO 2014) soil profile

The generic horizons of the profiles and soil types were determined using the WRB/FAO (2014) guidelines. The soil sample Pit 1 was classified as Eutric Gleysol and Pit 2 as Calcic Gleysol. Both pits have high bulk density giving rise to low pore space with poor soil drainage due to high clay content in the soils. The soil can hold more water especially during the rainy season but during the dry season the soil dries up due to poor capillarity. The soils are naturally fertile due to high clay content as they are able to hold well soil moisture and nutrients (Stutter and Richards, 2012).

Results of laboratory analysis of selected soil physical and chemical properties used to characterise the two sample profiles are presented in Tables 4.11 and 4.12.

Table 4.11: Physical properties for the sample profile pits

Depths	% Sand	% Clay	% Silt	Texture	Bulk Density
Pit 1					
0 - 13 cm	27.88	33.89	38.23	Clay loam	2.08
13 - 36 cm	23.65	39.82	36.53	Clay loam	2.14
36 - 64 cm	19.52	41.56	38.92	Clay	1.96
64 - 91 cm	40.32	31.25	28.43	Clay loam	1.87
91 - 123 cm	21.59	39.25	39.16	Clay loam	1.98
Pit 2					
0 - 20 cm	28.15	37.35	34.50	Clay loam	1.82
20 - 43 cm	71.26	13.65	15.09	Sandy loam	1.98
43 - 66 cm	61.59	15.29	23.12	sandy loam	2.05
66 - 89 cm	49.85	23.15	27.00	Loam	1.98
89 - 116 cm	43.65	29.31	27.04	Clay loam	2.02

The soil texture for Pit 1 is predominantly Clay loam with high bulk density (1.87 - 2.08 gcm^{-3}) within the generic horizons while Pit 2 has Clay loam in the top soil underlain by Sandy loam in the mid-portion with loam and Clay loam after 60 cm depth with high bulk density (1.82 - 2.02 gcm^{-3}). The high bulk density for predominantly clay must have been due to soil compaction because clay soils generally have low bulk densities in their natural undisturbed states. Thus, the soils from the two pits are naturally fertile due to high clay content which enhances their ability to hold soil moisture and soil nutrients (Stutter and Richards, 2012). The bulk density values for the two pits are high, not ideal for plant growth (USDA, 1999; Evanylo and McGuinn, 2009; Pravin, *et al.*, 2013); the values are all in the range that inhibits root growth and development (USDA, 1999). Hence nutrient uptake from soil to the plant will be affected (Reintam *et al.*, 2005).

The two profiles had pH values in the range of 6.4 to 8.31, resulting in low exchangeable acidity levels. The pH values for the horizons of both pits are considered as low acid to low basic which is desirable for majority of crops. The soils have organic carbon content in the range of 0.16 % to 0.57 % within the generic horizon. Both pits have higher carbon content in the top soil with values of

0.40 % and 0.57 % for Pit 1 and Pit 2 respectively.

Table 4.12: Chemical properties for sample profile pits

Depths	pH1:1 H_2O	% Organic Carbon	% Total Nitrogen	cmol/kg ECEC	% Base Saturation
Pit 1					
0 - 13 cm	6.83	0.40	0.04	4.67	98.93
13 - 36 cm	7.90	0.18	0.02	3.94	99.49
36 - 64 cm	7.95	0.21	0.02	7.55	99.74
64 - 91 cm	8.20	0.21	0.02	11.27	99.82
91 - 123 cm	8.31	0.20	0.02	13.69	99.85
Pit 2					
0 - 20 cm	6.77	0.57	0.05	5.01	99.00
20 - 43 cm	6.40	0.36	0.03	8.81	99.32
43 - 66 cm	6.70	0.29	0.03	8.48	99.41
66 - 89 cm	7.04	0.16	0.02	28.00	99.82
89 - 116 cm	7.46	0.21	0.02	24.34	99.79

The carbon content for Pit 1 is similar within the subsoil horizon with that at topsoil (0.4 %) and almost twice that of the subsoil. For Pit 2, the carbon content decreases from the topsoil with depth. This variation could be related to differences in the input rates and turnover times of carbon since Pit 2 is located in a compound farm, close to a house and benefits from regular organic input from the household. This is similar to the findings of Mordelet and Menaut (1995) who reported large spatial variability of organic matter input in heterogeneous tropical environment.

Total N levels in the soil layers for the two pits were very low (i.e. 0.02 % to 0.05 %) with a mean of 0.03 %. Total N levels declined with soil depth from 0.05 % to 0.02 % at the two sampled areas. Total N levels followed a trend similar to that of soil organic carbon.

The effective CEC values were moderately high to high in all layers, thus implying a higher nutrient holding capacity (Leticia *et al.*, 2014) for the two pits (i.e. 3.94 to 28.0 meq/100g). In the top 60 cm soil depth for both pits ECEC values were moderately low (<10 cmol kg^{-1}). Pit 2 had higher ECEC values than pit 1. The percentage base saturation values were in the nineties which imply that all the soils are highly basic with very low acidity which promotes high turnover of organic matter in the soil (Hoorman and Islam, 2010).

4.3.2 Soil organic matter fractionation

a. Particle size distribution and texture for different land use type

Table 4.13 shows the particle size distribution and soil texture of the bulked 0 - 30 cm depth intervals for the different land uses. The table reveals that the texture for the majority of land uses is Sandy Loam to Loam with moderately acidic to neutral pH. The pH values for all land uses are suitable for the general growth of most of crops grown in the area (USDA, 1999).

Table 4.13: Particle size distribution and texture for 0 - 30 cm depth under different land use type

L U*	Sand	Silt	Clay	Texture

PIR	58.8 ± 2.8	33.9 ± 3.1	7.4 ± 0.3	Sandy Loam
PRA	35.1 ± 5.4	44.1 ± 2.4	20.8 ± 3.0	Loam
MSV	65.3 ± 5.7	25.3 ± 5.2	9.5 ± 1.1	Sandy Loam
GRL	59.8 ± 2.2	29.5 ± 1.6	10.7 ± 0.9	Sandy Loam
EFF	67.4 ± 2.2	23.7 ± 1,1	8.9 ± 1.2	Sandy Loam
SNA	49.8 ± 7.2	32.3 ± 6.4	17.9 ± 0.9	Loam

* LU: Land use, PRI: Paddy Irrigated Rice, PRA: Paddy Rain-fed Rice; SM/V: Sorghum/ Maize -Vegetable rotation, GRL: Grazing Land; EFF: Eucalyptus Forest; SNA: Semi Natural Area, ±: Standard error.

Paddy rain-fed rice (PRA) and semi natural vegetation compared to the other land uses are found in the area with higher clay and silt contents (Table 4.13). This may suggest higher organic carbon content by the mechanism of protection of natural fertility of the soil under these land uses. Soil texture may represent a positive effect on the productivity of a given soil and in particular the interaction of clay and silt fraction and SOM (Sakin and Sakin, 2015). Across all land uses in the area the texture is Sandy Loam to Loam and they are relatively easy to handle in terms of tillage operations. Coarser soils are far less efficient at storing water than clay soils. The stands with semi natural vegetation may be more rich in OM than cropped sites because of the lighter textures of their soils and larger organic inputs, while the high carbon stock of rain-fed paddy rice might be due to the accumulation of nutrient rich soil deposits into the valley and the protective effect of clay and silt on OM (Zhao, 2006) in PRA.

b. Soil bulk density and carbon stocks for different land use types

Table 4.14 presents the soil bulk density (SBD) for the different land uses for the 0 - 30 cm depth interval. The lowest SBD values (i.e. about 1 g/cm^3) are shown by land uses dominated by trees (eucalyptus forest and semi natural vegetation sites). Higher bulk densities were observed in grasslands and paddy irrigated followed by vegetable. Sites with croplands and grasslands are affected by soil management activities and animals trampling in these sites.

The results indicate that SOC is higher for lower soil bulk density which is supported by other studies (Sakİn, 2012; Saiz *et al.*, 2012; Chaudhari *et al.*, 2013; Askin and Özdemir 2003; Prempeh, 2015).

With the exception of paddy rain-fed rice, croplands showed lower soil carbon stocks compared to tree-dominated sites (Table 4.14). The total carbon stocks in eucalyptus forest and semi natural areas were 44.6 % and 35.5 % higher than those of croplands (i.e. MSV) respectively.

Table 4.14: Soil Organic Carbon Stock (SOC) and bulk density in the top soil (0 - 30 cm) of different land use types

*LU	SOC (t/ha)	BD (gcm^{-3})	pH
PIR	14.96 ± 3.4 AB	1.48 ± 0.2 AB	7.1 ± 0.2 A
PRA	23.54 ± 10. A	1.31 ± 0.2 AB	5.8 ± 0.0 BC
MSV	10.24 ± 1.4 B	1.30 ± 0.1 AB	6.1 ± 0.2 B
GRL	16.53 ± 2.8 AB	1.54 ± 0.2 A	6.8 ± 0.2 A
EFF	18.50 ± 6.0 AB	1.05 ± 0.1 B	5.4 ± 0.1 C
SNA	15.88 ± 2.6 AB	1.09 ± 0.1 B	6.1 ± 0.2 BC
Statistics	P= 0.274; F=1.44	P= 0.113; F= 2,23	P= 0.002; F= 6.91

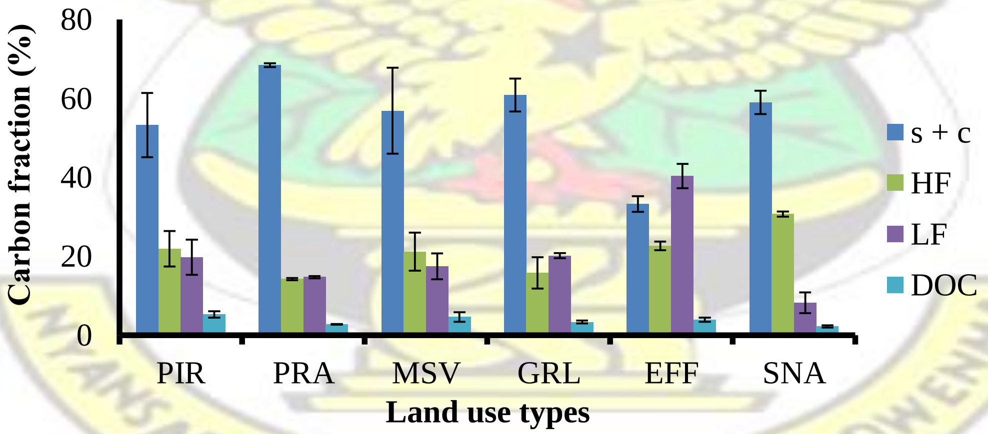
* LU: Land use; PIR: Paddy Irrigated Rice; PRA: Paddy Rain-fed Rice; MSV: Maize/Sorghum-Vegetable rotation; GRL: Grazing Land; EFF: Eucalyptus Forest; SNA: Semi natural area; ±: standard error; Means that do not share a letter are significantly different.

High values of soil carbon stocks were found both in the tree-dominant areas and in the rain-fed paddy rice with values of 15.88 ± 2.1 t/ha to 18.5 ± 4.9 t/ha and 23.5 ± 7.1 t/ ha respectively compared to other land uses. These areas have also low pH and bulk density compared to other land uses. The result of the carbon stock is consistent with that of Roose and Bathes (2001), who observed values of 15- 46 t/ha in a 0 - 30 cm over a rainfall gradient in Sudano-Sahelian savanna of Burkina Faso and a Sub- Equatorial forest in Cote d'Ivoire.

The result shows higher SOC stocks with increasing clay content in all land uses. Soils with low sand content tend to store relatively more SOC, which may be explained by the formation of a passive carbon pool via the adsorption and aggregation of SOM by clay minerals (Saiz *et al.*, 2012; Schimel *et al*., 1994; Feller and Beare, 1997). For example, the soil of paddy rain-fed rice with relatively high clay content (20.8 %) stored 23.5 t/ha of SOC compared to the 14.9 t/ha shown by irrigated paddy rice fields with lower clay content (7.4 %). High content of clay promotes the accumulation of organic matter through different mechanisms of protection (Matias *et al.*, 2013). An exception to that trend was the eucalyptus forest, which exhibited high SOC values with relatively low clay content (8.9 %). The high stock of SOC in eucalyptus forest can be due to the availability of more OM inputs. This result corroborates the results of other studies conducted elsewhere (Negi *et al.*, 2013, Shelukindo *et al*., 2014). Also, the high SOC in eucalyptus forest compared to semi natural vegetation and grassland may be due to the high grazing and fire intensity in semi natural vegetation compared to eucalyptus forest. Saiz *et al.* (2015) reported that fire and/or overgrazing have a negative impact on the amount of fresh organic inputs to the soil. Additionally, it could be due to planting of fast growing species (eucalyptus) that provide a large amount of organic matter to the soil. The low SOC stock in the cultivated upland may be due to high intensity of tillage in these areas which may reduce SOC stock by about 50 % compared to natural vegetation (Bayer *et al.*, 2002; Baker *et al.*, 2007).

c. Soil Organic Carbon fractions for different land use

Figure 4.4 presents the four fractions of SOC. The dominant part is the stable Silt and Clay (s + c) fraction (< 53) constituting more than 50 % of the total carbon pool. For the Silt and Clay fraction there are three groups in which the means are not significantly different from one another (Table 4.15). The partitioning of total SOC into fractions reveals that about 75 % of the total SOC is made up of the silt and clay fraction (s + c) and heavy fraction which is composed of sand and stable aggregates. The light fraction (particulate organic matter) contributes about 20 % and the dissolved organic carbon is about 5 %. In general, these results agree well with other studies (Christensen, 1992; Zimmermann *et al*., 2007). The relative contribution of the silt and clay fraction to the total carbon pool is higher in paddy rain-fed sites compared to other land use types. Similarly, the silt and clay fraction is also the largest for all land use types, except for the eucalyptus forest where it is not significantly different from the Light Fraction (LF), which represents the dominant fraction of these stands.



PIR: Paddy Irrigated Rice; **PRA**: Paddy Rain-fed Rice; **MSV:** Maize/SorghumVegetable rotation; **GRL:** Grazing Land, **EFF**: Eucalyptus Forest and **SNA**: Semi
Natural area. Errors bar represent standard error**. s + c:** Silt + Clay; **HF**: Heavy Fraction; **LF:** Light Fraction; **DOC**: Dissolved Organic Carbon

Figure 4.4: Soil organic carbon fractions per land use

The Dissolved Organic Carbon (DOC) represents the smallest part of the fraction of SOC, with the higher values found in irrigated paddy and maize/sorghum in rotation with irrigated dry season vegetable. There are no significant pairwise differences among the mean DOC (Table 4.15) but high level of DOC under irrigated paddy rice (PIR) and maize/sorghum in rotation with irrigated dry season vegetable land uses may be due to the use of irrigation in these areas, and the fast turnover time of DOC (Juescheke *et al.*, 2008; Junod *et al.,* 2009). For all the land use types the rate of recovery is better than 90 % of the total soil organic carbon.

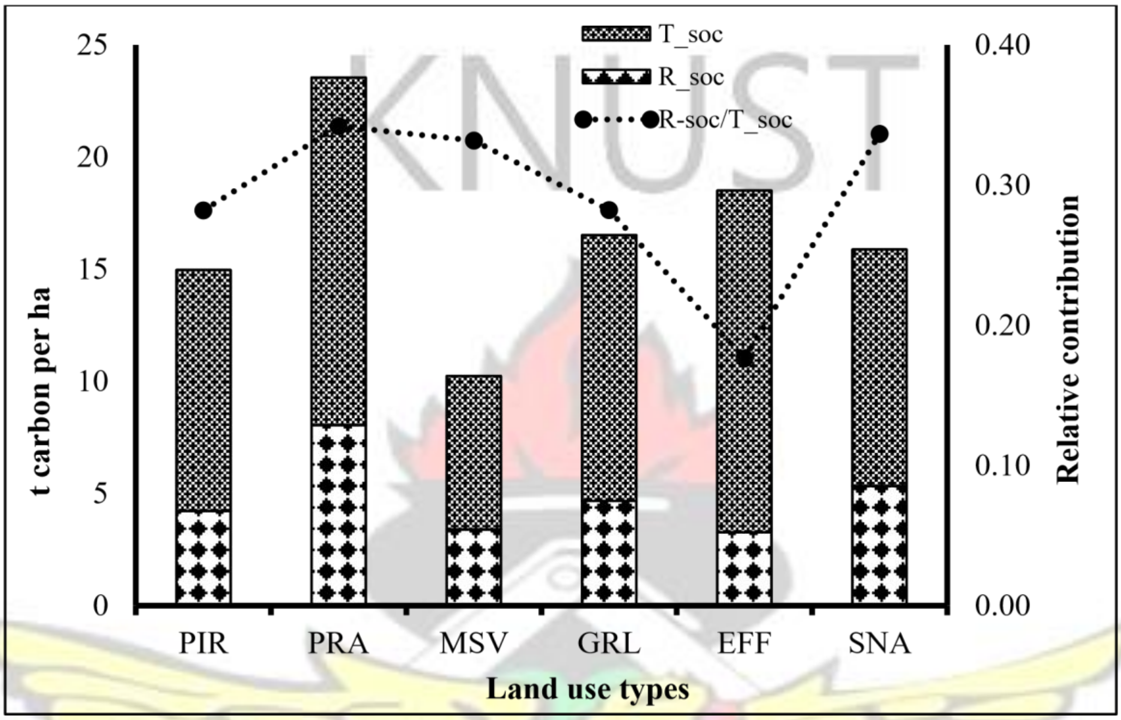
Table 4.15: Mean comparisons of four soil fractions under different land use system

Land use	DOC	HF	LF	S + C
PIR	5.22 A	21.84 AB	19.71 B	53.22 B
MSV	4.57 A	21.14 B	17.44 B	56.87 B
EFF	3.89 A	22.58 AB	40.32 A	33.22 C
GRL	3.31 A	15.76 B	20.12 B	60.81 AB
PRA	2.72 A	14.20 B	14.67 BC	68.41 A
NAT	2.20 A	30.66 A	8.19 C	58.95 AB
LSD(0.05)	**3.48**	**12.99**	**7.61**	**13.78**

PIR: Paddy Irrigated Rice; **PRA:** Paddy Rain-fed Rice; **MSV:** Maize/SorghumVegetable rotation; **GRL**: Grazing Land; **EFF:** Eucalyptus Forest; **SNA:** Semi natural area; **LSD:** Least Significant Difference; **DOC**: Dissolved Organic Carbon; **HF:** Heavy Fraction; **LF:** Light Fraction; **S + C:** Silt and Clay; Means that are not share a letter are significant different.

d. Relative contribution of resistant SOC (R_soc) to total SOC (T_soc)

Absolute R_soc values were lower than 5 t carbon ha^{-1} except in PRA and SNA which seem to have a heavy regime of fire compared to other land uses. The relative contribution of R_soc to the T_soc pool ranges from 28 - 34 % for all land uses except Eucalyptus Forest (EFF) (Figure 4.5), which is 18 %. The high R_soc contribution to T_soc in all land uses provides evidence that, the main factor behind the high content of R_soc is fire being (Saiz *et al.*, 2012). These land uses are characterised by frequent fire events which are in agreement with crop residues and bush burning before cultivation.



PIR: Paddy Irrigated Rice; PRA: Paddy Rain-fed Rice; MSV: Maize/SorghumVegetable rotation; GRL: Grazing Land, EFF: Eucalyptus Forest and SNA: Semi Natural Area.

Figure 4.5: Relative contribution of Resistant SOC (R_soc) to Total SOC (T_soc)

e. Variation of C/N ratio in soil and SOM fraction

The C/N ratio in the bulk soil is higher in tree-dominated sites (eucalyptus forest and semi natural vegetation stands) compared to other land uses (Table 4.15). The stable s + c fraction had about 50 % lower C/N ratios than those shown by the light fraction (LF) in all land uses. In all the investigated land uses, C/N ratio tends to decrease with decreasing of fraction (s +c and LF) size. The C/N ratio for the different fractions had similar value across all land uses except semi natural area, which showed higher ratios in the different fractions.

Table 4.16: Variation in C/N ratio in bulk soil and SOM fractions

Land use	C/N			
	s + c	**LF**	**HF**	**Bulk**
Irrigated Paddy Rice	9.8	24.1	14.7	10.8
Rain-fed Paddy Rice	11.9	22.3	13.0	12.4
Maize/Sorghum-Vegetable rotation	9.8	21.1	12.6	10.8
Grassland	10.5	21.0	12.9	11.9
Eucalyptus forest	11.2	24.6	12.6	15.4
Semi Natural Area	13.0	34.9	14.8	14.0

The C/N ratio in the tree dominated land use types is higher than the other land uses. This can be explained based on the high carbon input from the tree and the existence of suitable environmental conditions for the activities of organic matter decomposers in this area. The C/N ratio decreases with decreasing particle size as stated by Feller and Beare (1997). The C/N ratio in the LF is higher in all land use types because it is the fraction that reflects recent organic input into the soil.

4.4. Soil CO2 Emission for Crops under Different Management Systems

4.4.1. Soil CO2 emission from maize and sorghum field

Figure 4.6 illustrates the mean daily soil CO_2 emission from maize and sorghum fields during the rainy and dry seasons for three sampling points over three sites. The soil CO_2 emission from maize and sorghum fields follows a similar trend during the period of measurement. During the growing season, soil CO_2 emission increased with the crop development and reached the maximum at the grain filling stage (i.e. September, around 224 - 250 days of year). Thus, it increased from germination until flowering when it starts to decrease. This result corroborates with the studies by Dossou-Yovo *et al.* (2015) in Benin and Iqbal *et al*. (2009) in China they also observed similar trend of evolution of soil CO_2 emission with the growth of plant till flowering stage The soil CO_2 flux varied from 109 to 258.9 mg CO_2 - $Cm^{-2}h^{-1}$ for maize and 126.4 to 286.3 mg CO_2 - $Cm^{-2}h^{-1}$ for sorghum during the growing season.

The relatively higher soil CO_2 emission for sorghum compared to maize fields may be due to higher density of plants in sorghum fields. Thus the likelihood of more roots in sorghum field giving the higher CO_2, since soil CO_2 is mostly from root and microbial respiration (Hui and Luo, 2004; Davidson and Janssens, 2007; Jiang *et al*., 2013).

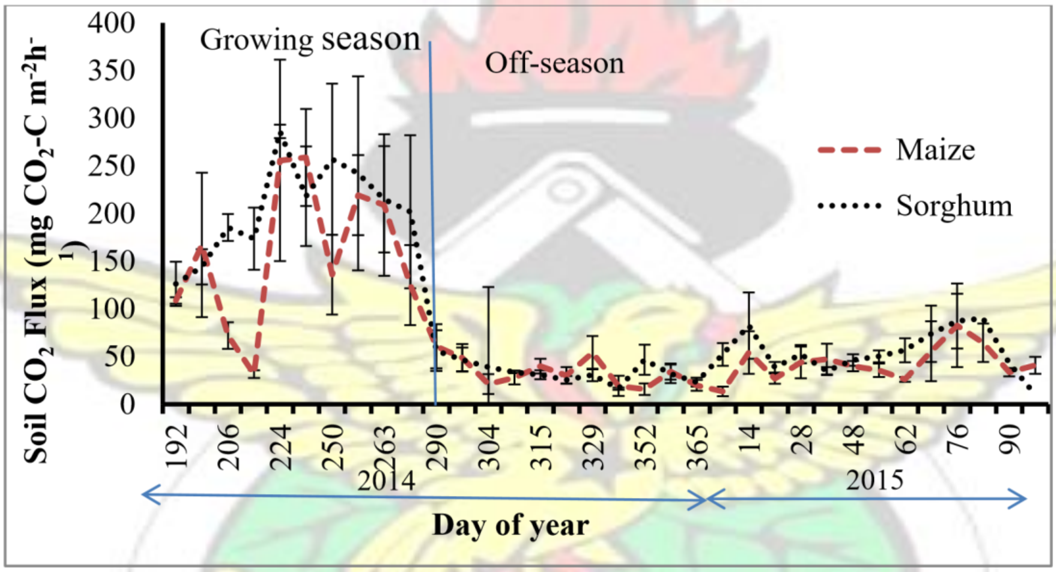


Figure 4.6: Daily soil CO_2 emission trend for maize and sorghum during the study period

During the off-season the soil CO_2 flux was low with a decreasing trend after harvesting in the middle of October (i.e. around 290 Day of year). The trend of soil CO_2 emission after harvesting maize or sorghum and introducing kenaf follows a similar trend. The CO_2 reached its maximum value of 82.8 mg CO_2- $Cm^{-2}h^{-1}$ and 90 mg CO_2- $Cm^{-2}h^{-1}$ on kenaf. The higher values of soil CO_2 emission during the offseason are less than the lower values for the growing season.

a. Effect of soil moisture content on soil respiration pattern

Soil moisture is one of the most important factors that influence soil respiration (Kang *et al.*, 2003). The response of soil respiration to changes in soil volumetric water content at the depth of 5 cm was very significant at $p < 0.001$ with correlation coefficient (R) values 0.24, 0.50 and 0.71 for rice, maize and sorghum field respectively.

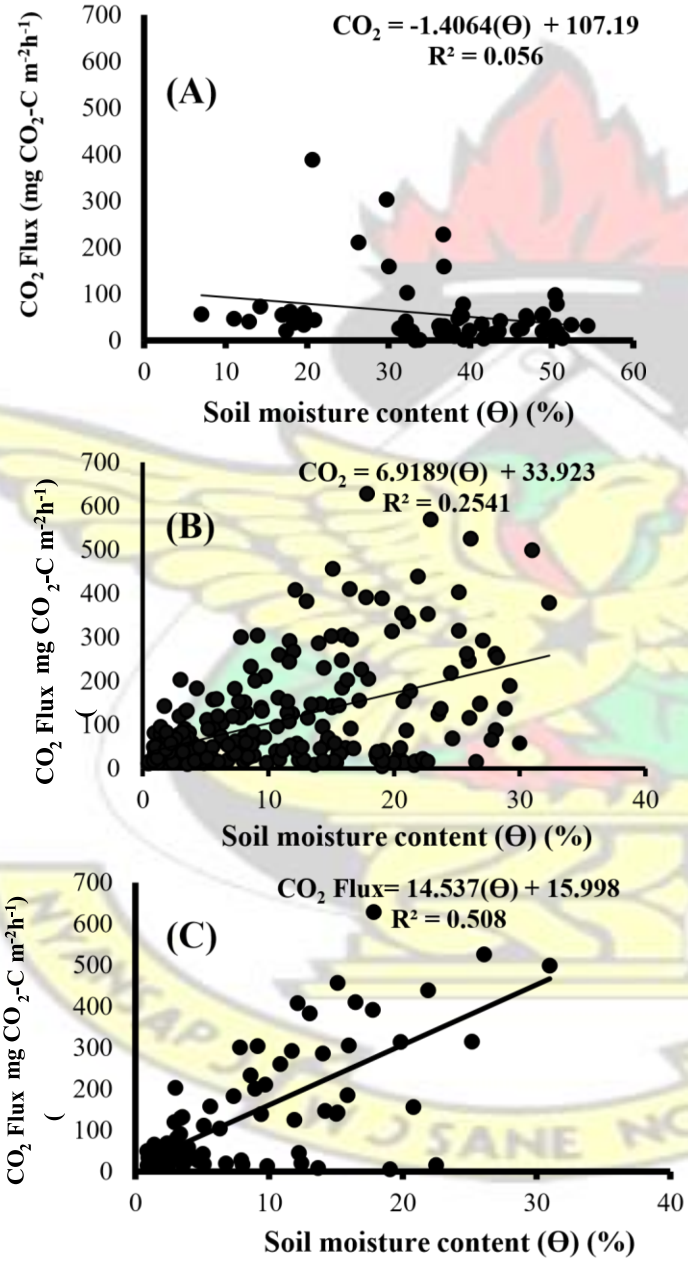


Figure 4.7: Response of soil respiration to volumetric soil moisture content (Θ) at 5 cm depth for rice (A), maize (B) and sorghum (C) field

The response of soil CO_2 emission to changes in soil water content at 5 cm soil depth for the study period is shown in Figure 4.7. The result shows that the soil CO_2 emission was sensitive to soil moisture for maize and sorghum cropping system but not sensitive to rice cropping system. The sensitivity of soil CO_2 emission to soil moisture for maize and sorghum can be due to the absence of a barrier to gas transport from soil to the air. The non-sensitivity of soil CO_2 emission to soil moisture under flooded rice could be explained by flooding cutting off the oxygen supply from the atmosphere and microbial activities switching from aerobic to facultative or anaerobic condition (Liu *et al.,* 2013; Kögel-Knabner *et al*., 2010) that has consequence for the inhibition of the release of CO_2. On the other hand, CO_2 diffusion rates are very low in water than in air and a part of CO_2 produced is stored in the soil under flooding. Additionally according to Epule *et al*. (2011) under standing water some microorganism (Methanogenic archea) use the carbon from
(CO_2 and acetane) as electron donor to produce methane in anaerobic respiration.

b. Effect of soil temperature on soil respiration pattern

Soil temperature is the main environmental factor affecting soil CO_2 emission due to its influence on the decomposition activities. Some studies have reported a strong soil respiration dependence on temperature, such that as the soil temperature increases soil respiration also increases (Davidson *et al.,* 1998; Lloyd and Taylor, 1994). Other studies such as Qi *et al* (2002), Prempeh (2015) observed a negative response. This study also had a negative response of soil CO_2 emission to soil temperature which may be due to high variability of soil temperature during the study period.

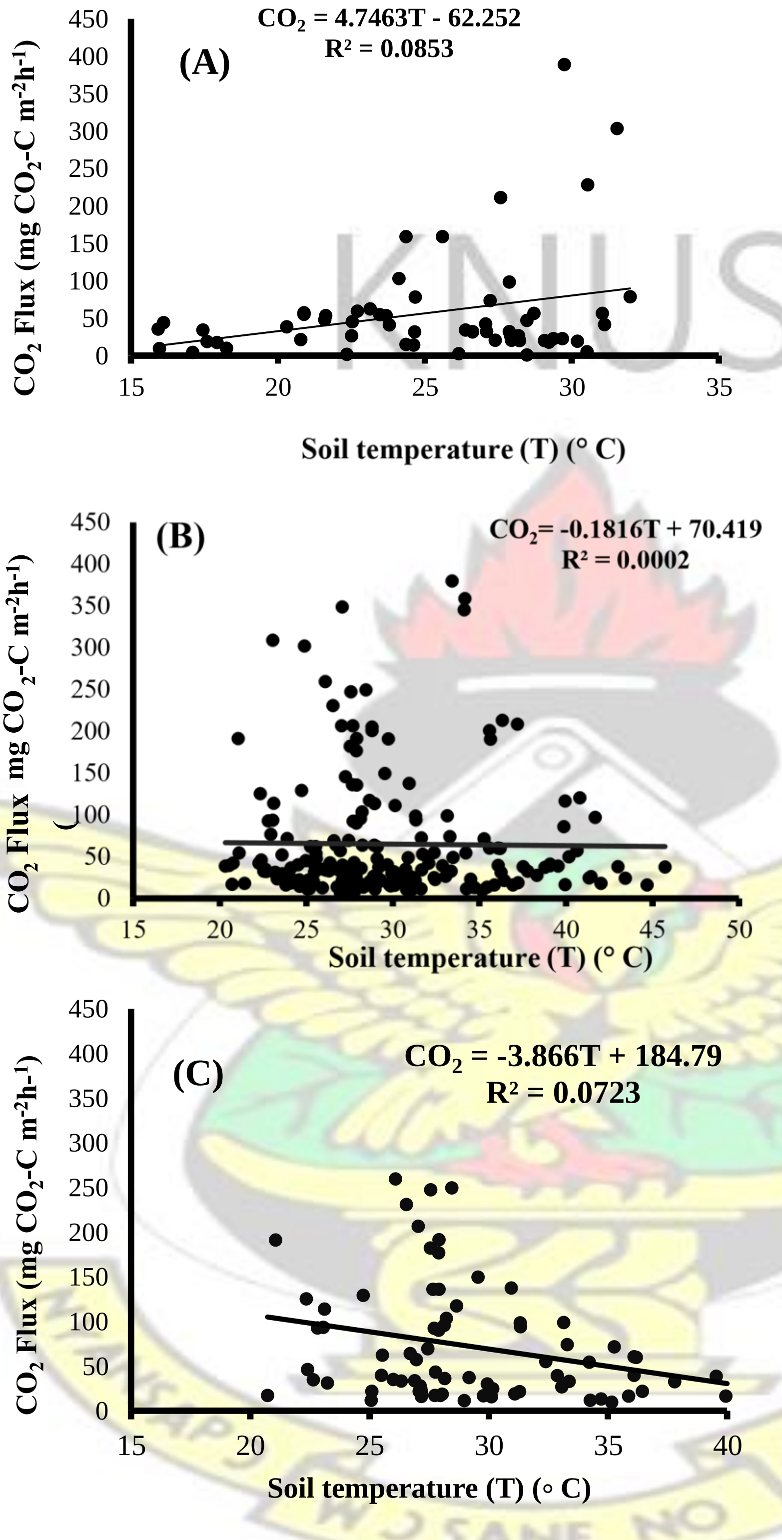


Figure 4.8: Soil respiration response to changes in soil temperature (T_{soil}) at 5 cm soil depth for rice (A), maize (B) and sorghum (C)

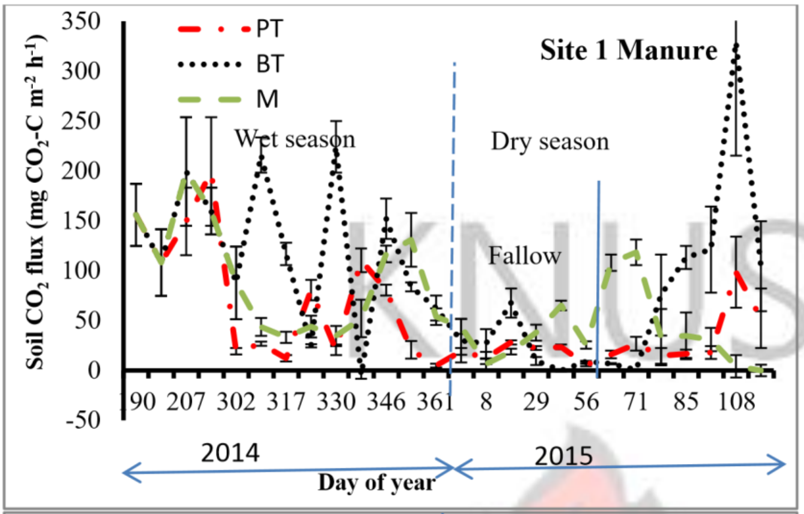
The results show that, soil respiration was not sensitive to soil temperature change (Figure 4.8). This may be explained by the fact that the soil environment is a complex system with different community of soil organisms and these organisms may have different temperature sensitivities for their activities (Kirschbaum, 1995) and presumably limited CO_2 emission because of standing water for flooded rice. For flooded rice, once the field is drained, the soil begins to warm up. In that case soil CO_2 flux is likely to increase with increasing soil temperature as shown by Figure 4.8 A.

4.4.2. Soil CO2 emission for rice under different management systems

Figure 4.9 presents the daily evolution of soil CO_2 emission during the growing period of rice under different management systems during rainy season and dry season under irrigation for the two sites (Site 1 and Site 2). During the wet season soil CO_2 emission significantly increased with crop growth after transplanting (213 DoY) until grain filling stage (346 DoY) and started to decrease across treatment. The trend of soil CO_2 emission is similar across treatment with higher emission under NPK + Urea followed by NPK + UDP and manure amendment for power tiller and bullock tillage. This could be attributed to the fact that the two tillage systems are similar in terms of depth of ploughing and also due to the higher level of soil disturbance for conventional tillage compared to that of manual tillage (i.e. hoe). During the fallowing period, the soil CO_2 emission was lower compared to the growing period for both sites across treatment due to less microbial and root-derived CO_2 respiration (Al-Kaisi and Yin, 2005).

During the dry season under irrigation, the soil CO_2 emission increased with plant growth but the values were lower compared to the wet season across treatments. Higher values were observed under NPK + urea in broadcast followed by manure and NPK + UDP amendment. This can be due to the loss of carbon as CO_2 during mineralisation of manure (Eghball *et al.*, 2002) and urea compared to

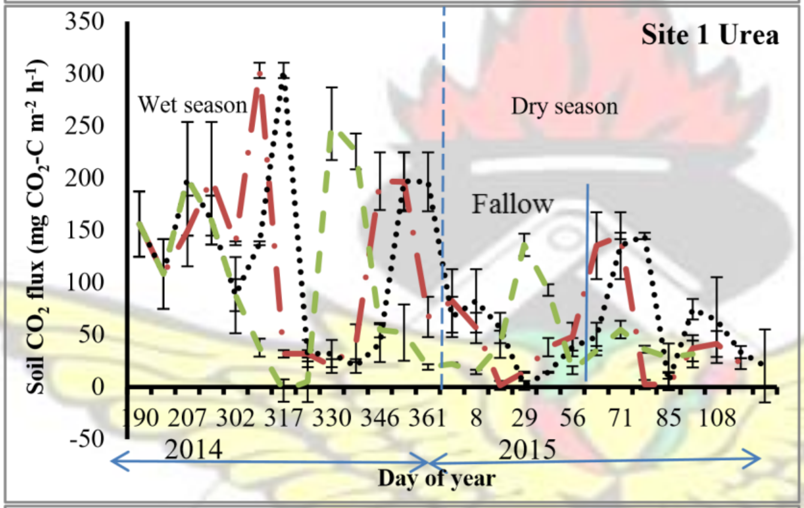
UDP (IFDC, 2007).



PT: 51.58 ± 10.6 (B)

BT: 95.38 ± 16.5 (A)

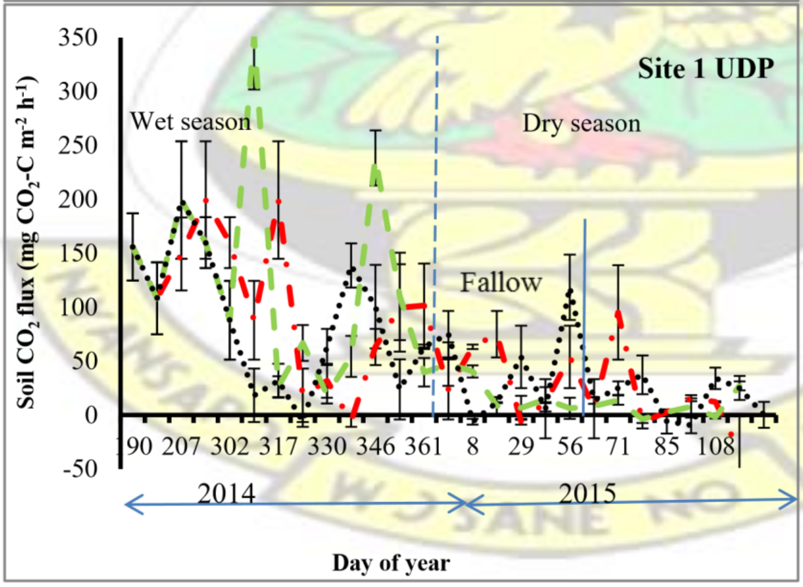
M: 67.18 ± 10.5 (AB)



PT: 64.64 ± 13.1 (A)

BT: 56.42 ± 11.3 (A)

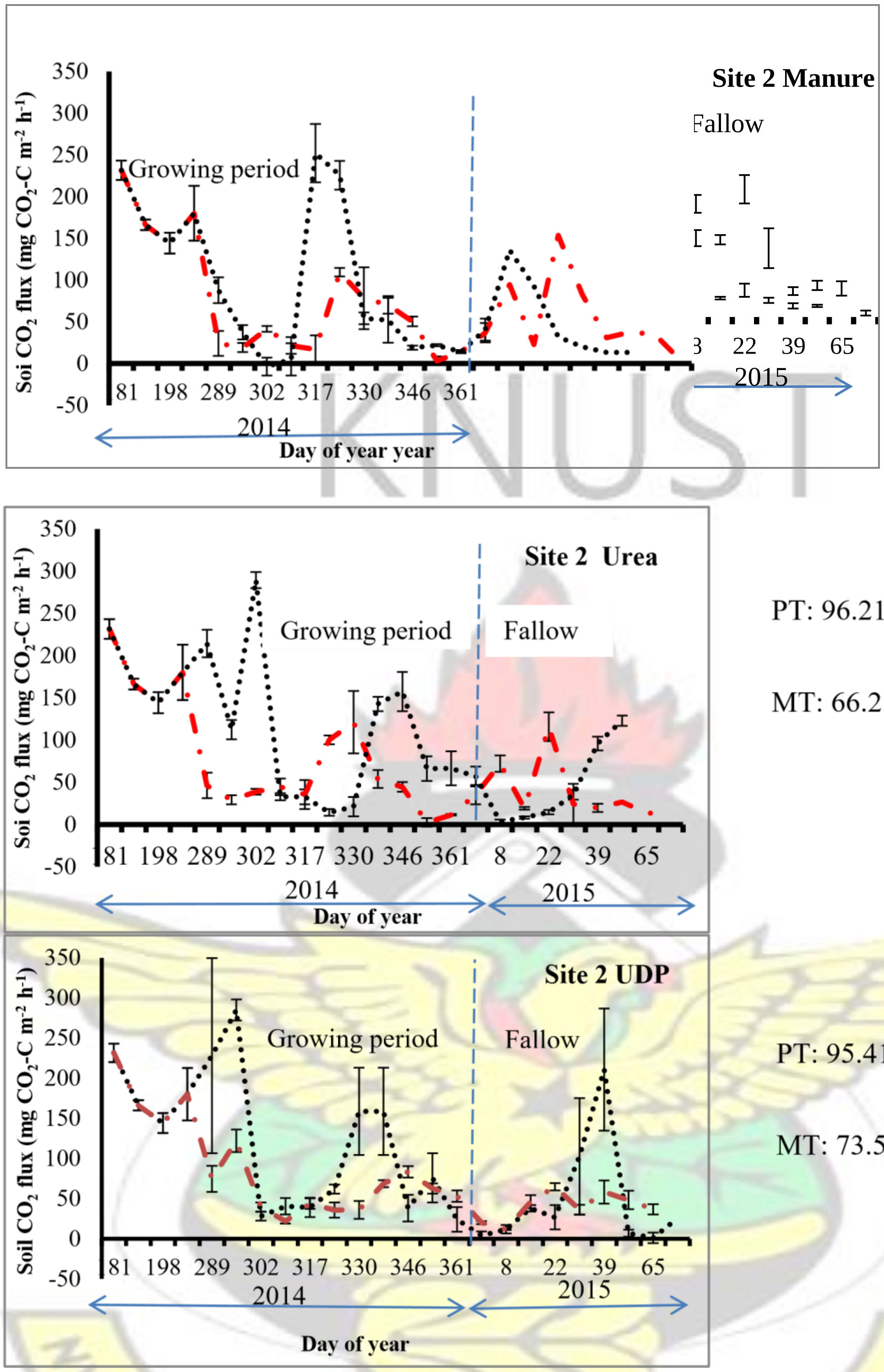
M: 69.03 ± 17.2 (A)



PT: 87.12 ± 15.4 (A)

BT: 90.95 ± 14.5 (A)

M: 77.51 ± 14.9 (A)



PT: 83.51 ± 18.5

MT: 69.62 ± 12.9

PT: 96.21 ± 17.2

MT: 66.2 ± 12.7

PT: 95.41 ± 17.7

MT: 73.54 ± 11.9

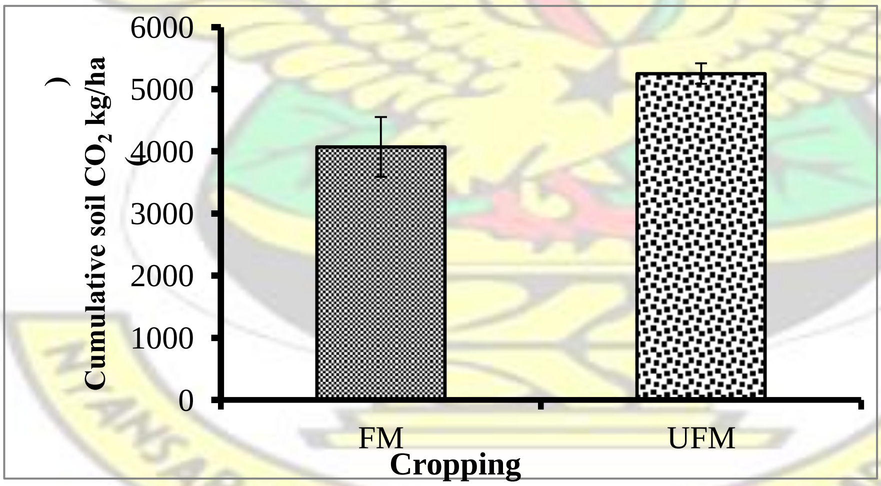
DoY: Day of Year; A: Manual tillage, B: Power tiller tillage, C: Bullock tillage The error bars represent the standard error.

Figure 4.9: Daily soil CO_2 emission trend as affected by different tillage methods and fertilisation under cultivation of rice

Soil CO_2 emission for bullock and power tiller tillage followed similar trend with no significant difference with respect to the amendment type for both wet and dry seasons. This can be due to the fact that the two tillage systems are close in terms depth of ploughing. The emission is higher for bullock and power tiller tillage compared to manual with different amendment due to the greater level of soil disturbance for conventional tillage compared to manual.

4.4.3. Effect of fertilizer on cumulative soil CO2 emission for maize

As illustrated in Figure 4.10 the cumulative soil CO_2 emission was lower for fertilised maize with 50 kg/ha of sulphate ammonia than the maize without application of chemical. The cumulative CO_2 emission ranged from 4072 kg/ha to 5251 kg/ha for fertilised and unfertilised maize respectively. The results indicated the suppressing effect of fertiliser on the cumulative CO_2 emission for maize. Fertilisation has shown contradictory effect on soil CO_2 emission. Some studies reported the suppressive effect of nitrogen fertilisation (Al-Kaisi *et al.*, 2008; Fisk and Fahey, 2001), no effect (Lee *et al.*, 2007) and others the stimulating effect (Dossou-Yovo *et al.*, 2015; Iqbal *et al.*, 2009; Mulvaney *et al.*, 2009) on soil CO_2 emission.

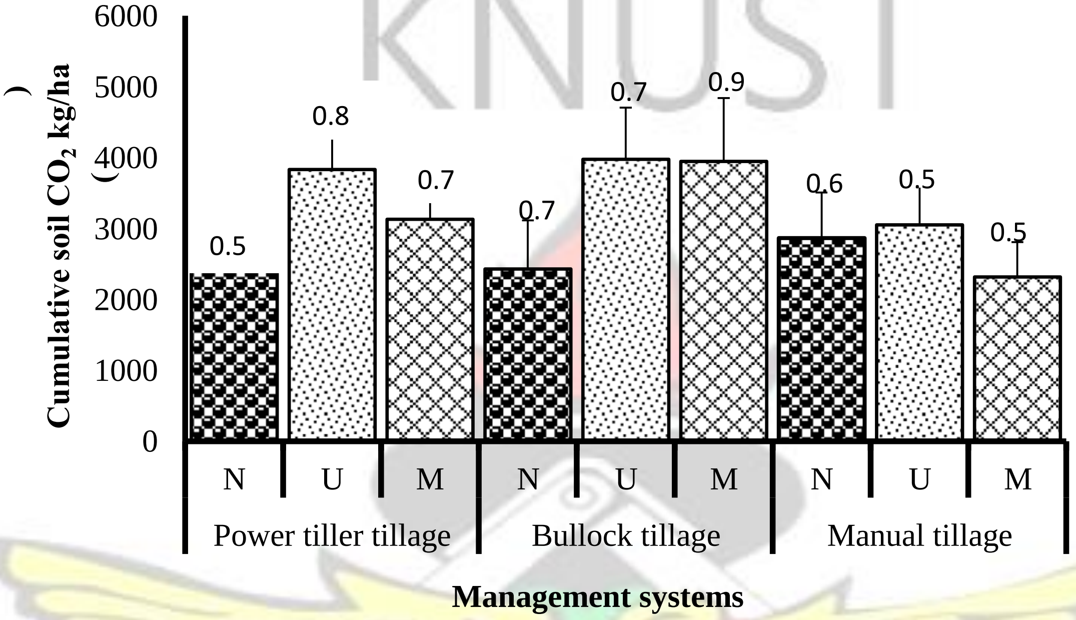


FM: maize fertilised with nitrogen, **UFM**: unfertilised maize. **Bars**: standard errors.

Figure 4.10: Nitrogen amendment effect on cumulative soil CO_2 emission for maize

4.4.4. Tillage systems and amendment effect on cumulative soil CO2 emissions for rice

Figure 4.11 shows that the cumulative CO_2 emission is higher using tillage with power tiller followed by bullock and manual tillage. For power tillage with the use of 113 kg of UDP/ha and 5 t/ha of manure, the cumulative CO_2 is the same but higher than that of power tillage with the use of 250 kg/ha of urea.



N: application of NPK + Urea; **U**: application of NPK + UDP; **M**: application of manure; **Bars**: ratio between cumulative CO_2 emission and grain yield

Figure 4.11: Tillage systems and amendment effect on cumulative soil CO_2 emission from July 2014 to April 2015

The cumulative soil CO_2 emission for bullock and power tiller have similar trend with greater accumulation under UDP and manure. For the manual tillage, the highest cumulative soil CO_2 efflux is observed for UDP. The soil CO_2 emission per unit grain (Figure 4.11) is low under power tillage with NPK + urea and manual tillage with manure as amendment.

The amount of soil CO_2 emission per unit grain was higher under bullock tillage with manure as amendment and lower values were obtained under manual tillage with NPK + UDP and manure as amendment. Also, power tillage with NPK + urea gives low soil emission CO_2 per unit grain.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

In line with the specific objectives, the following conclusions can be drawn:

1. More than 41 % of land in the Vea catchment is cropland. Also, 63 %, 51.8 % and 46 % of Leptosols, Fluvisols and Lixisols respectively which are the dominant soil types are cultivated.
2. With regard to rice grain yield, basal application of NPK and top dressing with urea by deep placement under manual tillage produced the highest values of 5675 kg/ha during the dry season under irrigation. In the rainy season the highest rice grain yield of 4832 kg/ha was obtained under bullock tillage using NPK + UDP. Also maize cropping system with the use of fertiliser (NPK) produced the highest grain yield of 1375 kg/ha and 4620 kg/ha of biomass yield compared to unfertilised maize.
3. The SOC stock is influenced by land use type and is higher in tree dominated area (i.e. 18.5 t/ha for forest) compared to cropland (i.e. 10.2 t/ha). Soil organic carbon composed of four fractions (i.e. silt + clay, heavy fraction, light fraction and dissolved organic carbon) with up to 75 % of it being silt and clay, and heavy fraction. The soil carbon fractionation showed that the dissolved organic carbon is higher in irrigated area than non-irrigated areas. Eucalyptus forest had high SOC but this is mainly composed of non-stable fraction (light) implying that it could be mineralised faster under increasing temperature. Under the farm management system for maize production with fertilised maize and fertilised maize plus sorghum in rotation with groundnut indicated this system to be better than the introduction fallow to limit the depletion of soil carbon in area. Also, continuous cereal (maize or sorghum) production with or without fertilisation leads to decline SOC content

of about 8 - 15 % over the 10 years projection. For appreciable restoration soil carbon stock, 5 years fallowing period is not sufficient under the management practices for maize and sorghum production in the area.

4. The measured soil CO_2 emissions were different for the different crops and management practices combination. For the rice, the highest cumulative emission was 3977 kg/ha for bullock tillage and NPK + UDP application. However, the lowest value was 2317 kg/ha for manual tillage with the manure as amendment. Meanwhile, fertilised and unfertilised maize, and sorghum emitted high CO_2 amounts of 4072, 5251 and 6313 kg/ha respectively. The soil CO_2 emission of maize and sorghum fields followed similar trend for sorghum and increased with the crop growth stage until maturity stage.

5.2. Recommendations

The following recommendations are made based on the results of this study:

1. Farmers should adopt the use of bullock tillage with NPK + UDP as amendment for high rice grain yield and low soil CO_2 emission during the dry season and the use of power tillage and NPK + Urea as amendment during the rainy season;
2. Farmers in the study area should improve their management practices (i.e. fertiliser application, crop rotation and intercropping system, improved fallow) to limit declining soil organic carbon;
3. Natural vegetation protection should be embarked upon as soil carbon pool improvement and climate change mitigation strategy since it has higher carbon stock and stable fractions on the organic carbon;
4. Further studies should also look at monitoring the impact of fire on soil CO_2 emission for carbon and nitrogen dynamics.

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APPENDICES

Plate 3: Power tiller tillage

Plate 4: Bullock tillage

Plate 5: Manual tillage with the hoe

Plate 6: Soil CO_2 flux monitoring under maize

Plate 7: Soil CO_2 flux monitoring under rice

Plate 8: Soil CO_2 flux monitoring under sorghum

Plate 9: Soil moisture measurement using Delta T device

Plate 10: Harvest area for rice yield assessment

Plate 11: Soil profile

Plate 12: Soil sampling

Plate 13: Soil samples incubation