KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,
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# Soil respiration across predominant land-uses in the Vea catchment in the Sudan savannah zone, North-east Ghana

By

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**DOCTOR OF PHILOSOPHY**
**in**
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# CERTIFICATION

I hereby declare that this submission is my own work towards the Doctor of Philosophy in Climate Change and Land-use and that, to 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 other degree of the University, except where due acknowledgement has been made in the text.

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# ABSTRACT

A study to quantify soil respiration (SR) across predominant land-uses in the Vea catchment, a semi-arid Savannah ecosystem of Ghana, was carried out using the closed static chamber method and $CO_2$ transmitter (GMD 20, Vaisala). The goal was to determine the magnitude of the contribution of soil $CO_2$ flux from predominant land-uses to the global carbon budget. The annual soil $CO_2$ fluxes determined from the predominant land-uses were related to the soil organic carbon (SOC) stocks under the land-uses. Additionally, the impact of cropping systems, field management practices, topography, soil temperature and moisture as well as their seasonal and spatial variability on soil $CO_2$ fluxes were determined. The mean annual soil $CO_2$ fluxes for the major land-uses, were significantly different ($p=0.00$); these were 12.79 ± 0.89, 9.10 ± 0.42 and 5.61 ± 0.29 t $CO_2$ C $ha^{-1}$ $y^{-1}$ for woodland, graze-land and cropland respectively and these correlated strongly with SOC stock density of 37.91 ± 1.29 (woodland), 29.31 ± 1.74 (graze-land) and 27.36 ± 1.70 Mg C $ha^{-1}$ (cropland). The overall mean annual soil $CO_2$ flux from the catchment was 9.23 ± 0.53 t $CO_2$ C $ha^{-1}$ $y^{-1}$. Carbon losses from land-use conversions of woodland to other land-uses were more pronounced in the cropland than in graze-land, which is poorly-managed native vegetation. Using the current (2013) SOC as the base year and assuming business as usual scenario, the IPCC SOC tool was used to estimate the decadal SOC dynamics of the land-uses for next 60 years. The mean soil $CO_2$ flux under mixed cropping system was highest (114.67 ± 3.51) followed by rice monoculture (108.08 ± 2.82) whilst groundnut monoculture had the least (83.17 ± 2.85 [$mgCO_2$ C $m^{-2}$ $h^{-1}$]). Fisher's multiple tests revealed that mean soil $CO_2$ fluxes were significantly different ($p<0.05$). The Soil $CO_2$ fluxes were more sensitive to soil moisture stress than soil temperature at temperatures above 35 °C. Topography had significant impact on soil $CO_2$ flux; lowland mean soil $CO_2$ flux (86.3 [$gCO_2$ C $m^{-2}month^{-1}$]) was over 30 percent higher than up-land mean soil $CO_2$ flux (64.8 [$gCO_2$ C $m^{-2}$ $month^{-1}$]) for all the land-uses and statistically, the $CO_2$ fluxes were different ($p<0.05$) across the study field. There were marked seasonal and spatial variations in soil $CO_2$ flux due to variations in local climate and soil attributes as influenced by the different land-uses. The mean C emission across the study field ranged between 8- 32 g $m^{-2}$ $week^{-1}$ depending on land-use type. The study concluded that land-uses and cropping systems, topography, porosity and soil moisture and temperature variations influence SR dynamics, SOC stocks and soil $CO_2$ flux exchanges between land and atmosphere.

# DEDICATION

I dedicate this thesis to my family. To my parents, particularly my mother, Madam Comfort Adwoa Asamoah, who introduced me to formal Education despite my resentment and taught me to work hard no matter what I am doing, which had become a lifetime gift. I also dedicate this thesis to my beloved wife, Vida for the unflinching support, encouragement and sacrificing countless hours of family activities to make time for me to pursue and complete the studies successfully, my siblings, especially Stella and Debbie for the prayer support and sacrifices and finally, to my cherished children, Kofi, Adwoa and Abbie; I pray that this achievement serves as a springboard to propel and motivate you to achieve all your aspirations in life!

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# COMMONLY USED ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ANOVA | Analysis of Variance |
| BAU | Business as Usual |
| BMPs | Best Management Practices |
| BREB | Bowen-Ratio/Energy Balance |
| C | Carbon |
| CA | Cluster Analysis |
| CBD | Convention on Biological Diversity |
| CC | Climate Change |
| CDM | Clean Development Mechanism |
| CEC | Cation Exchange Capacity |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| CSA | Climate Smart Agriculture |
| DEM | Digital Elevation Model |
| DF | Degree of Freedom |
| DGPS | Differential Global Positioning System |
| DOC | Dissolved Organic Carbon |
| EC | Eddy Covariance |
| FAO | Food and Agriculture Organisation |
| GHGs | Greenhouse Gases |
| GIS | Geographic Information System |
| GPP | Gross Primary Productivity |
| GPS | Global Positioning System |

|  |  |
|---|---|
| Gt | Gigatonnes |
| IDW | Inverse Distance Weighting |
| IPCC | Intergovernmental Panel on Climate Change |
| IRGA | Infra Red Gas Analysers |
| IUCN | International Union of Conservation of Nature |
| JD | Julian Days |
| LAI | Leaf Area Index |
| LSD | Least Significant Difference |
| LUCF | Land-use change and forestry |
| LULCC | Land-use and land-cover change |
| MgC | Mega gram carbon (1 Mg = 1,000 kg = 1 ton) |
| NEE | Net Ecosystem Exchange |
| NPP | Net Primary Productivity |
| PCA | Principal Component Analysis |
| Pg | Peta gram (1 Pg = 1Gt = $10^{15}$ g of organic carbon) |
| ppm | parts per million |
| PVC | Polyvinyl chloride |
| $R^2$ | Regression Co-efficient |
| REDD | Reduced Emission from Deforestation and Degradation. |
| RCBD | Randomised Complete Block Design |
| SE | Standard Error |
| SD | Standard Deviation |
| SIC | Soil inorganic carbon |
| SOC | Soil Organic Carbon |

| | |
|---|---|
| SOM | Soil Organic Matter |
| SPSS | Statistical Package for Social Scientists |
| SR | Soil respiration |
| SSA | Sub-Saharan African |
| SSE | Sum of Squared Error |
| TAR | Third assessment report of the IPCC |
| UNFCCC | United Nations Framework Convention on Climate change |
| UNEP | United Nations environment programme |
| UNEP-WCMC | United Nations Environment Programme World Conservation Monitoring Centre |
| UN | United Nations |
| VMC | Volumetric Moisture content |
| VWC | Volumetric Water Content |
| WHO | World Health Organization |
| WMO | World Metrological Organization |
| WRI | World Resources Institute |

# 1. GENERAL INTRODUCTION

## 1.1 Background

The global environment is constantly changing and the earth is steadily getting warmer at an unprecedented rate since the turn of the industrial revolution (post 1850). The phenomenon has been of global concern in recent times as this could adversely affect the stability of the Earth's climate system, human's health and the sustainability socioeconomic and terrestrial ecological systems (MEA, 2005; IPCC, 2014). The observed warming has been attributed to greenhouse gases (GHGs) concentration in the atmosphere particularly carbon dioxide ($CO_2$) as the rapid and inexorable rise in atmospheric $CO_2$ concentration has coincided with global temperature increases (Conway and Tans, 2012).

Atmospheric CO2 concentration has steadily increased by over 40 percent from 278 ppm during the pre-industrial era (1750) to about 390 ppm in 2011 with a current figure of about 400 ppm (Global Carbon Project, 2012) at annual incremental rate of 0.5 percent. The rise in $CO_2$ emission is leading to global warming as the gas is a long-lived heat trapping stock pollutant (Le Quéré *et al.*, 2012). According to the IPCC (2013), the warming of the climate system since the mid-20th century is unequivocal, unprecedented and the cause of climate change. It has been realised that since 1850 each of the last three decades has been successively warmer at the Earth's surface than any preceding decade with attendant effects such as warming of the atmosphere and ocean, diminishing snow and ice and rising sea levels (IPCC, 2013). Le Quéré*, et al.* (2012) contend that although the net carbon sinks have increased over the last few decades in line with increasing emissions, it is uncertain how efficient the sinks will be in the future as the greater proportion of $CO_2$ emissions from anthropogenic sources remains in the atmosphere with negative implications on global climate system through feedback mechanism.

Carbon (C) dynamics in terrestrial ecosystems has been one of the major factors affecting $CO_2$ concentration in the atmosphere (Houghton, 1999; IPCC, 2001). Human activities such as burning of fossil fuels and biomass, cement manufacturing, and land-use changes are estimated to release over 8.5 billion metric tons of $CO_2$ annually to the atmosphere (Cunningham and Siago, 1990) which affect the global carbon budget with serious implications on the local and regional climate.

Soil is a fundamental component of the terrestrial ecosystem and the global carbon cycle. It is vital for agricultural production, supports biodiversity and provides other ecosystem services to sustain life on earth. Soils are the largest carbon pool in the terrestrial ecosystem and contain over 60 percent of their total C in the form of soil organic carbon (SOC) (Amundson, 2001). Globally, soils contain approximately 1500 Pg of organic carbon (Batjes, 1996); about three times the amount of carbon in vegetation, twice the amount in the atmosphere (IPCC, 2001) and 3.8 times more carbon than in biotic pool (Lal and Kimble, 1997). The global soil C pools far exceed the annual C fluxes to and from the terrestrial biosphere and the pools of C in the atmosphere and vegetations. Soils can therefore regulate atmospheric $CO_2$ concentration through their role as source of carbon emission or net sink for carbon depending upon land-use and management practices (Lal, 2003).

Soil carbon pools are, however, vulnerable to land-use and land cover changes as even small changes in soil C stocks due to human activities might contribute significantly to global climate change, for example, due to negative feedback as a result of global warming

(Cox *et al.,* 2000). The IPCC (2000) estimates that the $CO_2$ emissions from land-use change alone constituted about 1.7 $PgCy^{-1}$ between 1980 and 1989 and 1.6 Pg $Cy^{-1}$ between 1989 and 1998. Deforestation and land-use change from native ecosystems to semi-natural ones such as cropland lead to loss of soil carbon pools and consequent increase in atmospheric pool of $CO_2$ and other GHGs such as methane ($CH_4$) (Shrestha *et al*., 2004). Land-use changes and change in vegetation cover type may also influence soil erosion and soil C dynamics through its effect on SOC contents, $CO_2$ efflux and dissolved organic carbon (DOC) leaching from soils (Bajracharya *et al.*, 1998). Thus land-use or management practice that exerts least soil disturbance contributes to increased SOC accumulation, whilst intensive soil disturbance results in lower C sequestration, SOC stocks and consequent soil degradation. Soils therefore regulate the global C budget from their role as net C sink in the terrestrial ecosystem through C sequestration which transfers atmospheric C pools into permanent storage in the soils. Additional to climate regulation is the contribution of SOC to soil fertility and agricultural productivity. With population growth and surging demand for food and fibre, land-use changes will inevitably increase rapidly in the coming decades implying greater potentials for SOC losses which could affect global climate patterns. Adoption of land-use and management practices that will sequester C on long-term basis will be relevant as part of global efforts to tackle both climate change and rural poverty.

## 1.2 Problem Statement and Justification

Carbon dioxide ($CO_2$) is the most important anthropogenic GHG in terms of quantitative emissions accounting for about 76 percent of total GHG emissions in 2010 (UNEP, 2012). As a result, efforts to reduce the concentration of $CO_2$ in the atmosphere have been an important consideration in studies for informed climate change adaptation and mitigation decisions. Worldwide, grasslands occupy about 40.5 percent of the Earth’s land surface (about 52.5 million km$^2$) and in Africa, grasslands occupy 5 million km$^2$, about 17 percent of the surface area of Africa (Word Resources Institute, 2000). Grassland ecosystems therefore cover a larger area than any forest biome (Prentice *et al*., 2001) and store about 30 percent of the global terrestrial carbon pools. Therefore, grasslands have huge potential to influence global carbon cycling significantly as they could be net or source of carbon depending upon their management.

In developing countries particularly within the Sub-Saharan African (SSA) region, land-use change is rapid, due to biophysical and socioeconomic reasons but current knowledge of Ghana's carbon budget is limited by lack of data on carbon stocks in the various cover (vegetation) types as well as the spatial distribution of these sinks. The savannah ecosystem of northern Ghana is characterized by a great heterogeneity of land-use and management histories. The land is often highly degraded and agricultural productivity is often exhaustive in nature (Le, 2012; Vlek *et al.*, 2008) due to deforestation, over-cultivation, agriculture activities and extensive fuel-wood gathering.

The Vea catchment is a sub-basin of the White Volta basin and falls within the Sudan Savannah Agro-ecological zone of Ghana. The Vea catchment, has a greater portion of its total area (305 km$^2$) located in Bolgatanga in the Upper East Region (UER) of Ghana (295 km$^2$) and only about 10 km$^2$ located in the Nahouri Province in Burkina Faso (Ibrahim *et al.*, 2013). The catchment is important for agricultural production as the Vea dam provides opportunities for farming all year round. As a result, the native savannah of the catchment has been exploited massively for agriculture and other uses resulting in a mosaic of land-uses with consequent deteriorating of soil quality, crop productivity and land degradation which ultimately impact negatively on the global carbon budget through SOC stock losses.

Yet, there is lack of quantitative data to accurately determine the contribution of the Vea catchment and the entire semi-arid Northern Savannah ecosystem to the global carbon budget. The absence of in-situ data limits our ability to predict the effects of climatic and land-use change on SOC pools and net fluxes of $CO_2$ to the atmosphere. Quantifying the global contribution of soils (or ecosystems) to the carbon budget has been burdensome as SOC density can be highly heterogeneously distributed, just like soil horizons and bulk densities (Cambridge Conservation Initiative, 2011). Also scaling from individual measurements to the landholder, project or landscape level is much more onerous. As a result, soil respiration measurements have become widespread in recent times to provide a better insight into the processes underpinning soil carbon dynamics, ecosystems' carbon cycling and climate change (Thomas and Hoon, 2010; Castillo-Monroy *et al*., 2011). Soil respiration or soil surface efflux comprises respiration by roots (autotrophic) and microbial organisms (heterotrophic) and accounts for about 60–90% of total ecosystem respiration (Hanson *et al*., 2000). As the main mechanism by which carbon is transferred from the soil to the atmosphere apart from fossil fuels burning (IPCC, 2001), soil respiration is an important contributor to the SSA and global C budget.

Unfortunately, despite the increasing number of soil respiration studies in recent times, particularly in dry land areas (Brümmer *et al*., 2008; Inglima *et al*., 2009; Thomas and Hoon, 2010) recent reviews by Conant, (2009) suggest there is an incomplete understanding of carbon cycling in arid lands due to poor understanding of the mechanisms of soil respiration. Soil $CO_2$ flux estimates are still highly uncertain due to large spatial and temporal variability, whilst their response to changes in environmental and site conditions including climate, land-use, topography and soil attributes still carries great uncertainty. Predicting SR rates for the Vea catchment through accurate soil $CO_2$ flux measurements will be relevant in deepening knowledge of the soil-plant systems processes and land-atmosphere C fluxes to accurately quantify the contribution of the catchment to global carbon budget, which is essential for national policy makers and organisations assessing strategies for effective reductions in greenhouse gas emissions. Such information will also provide a better insight of the catchment's C dynamics and how C sequestration might change in future particularly for the Savannah ecosystems of West Africa. Additionally, the study may provide a mechanism for monitoring soil carbon pool for improved cropland management to increase long-term carbon storage. This will allow for the development of recommendations concerning sustainable land-use and land management.

## 1.3 Study Objectives

The main objective of the study was to quantify the magnitude of the contribution of soil $CO_2$ flux from predominant land-uses to the global carbon budget as influenced by the variability in environmental and soil conditions in the Sudan savannah catchment.

The specific objectives of the study were to;

i. determine soil $CO_2$ fluxes from predominant land-uses in relation to the underlying soil carbon stocks and estimate the magnitude of the annual carbon contribution of the catchment to the global C budget;
ii. quantify soil $CO_2$ fluxes under common cropping systems and field management practices including (a) mulching (b) fertiliser application (c) compost manuring and (d) land preparation activities in the growing season at the catchment;
iii. assess the patterns of soil $CO_2$ fluxes in relation to soil moisture and soil temperature dynamics;
iv. quantify the effects of topography on soil $CO_2$ flux as influenced by land-uses and

v. assess the seasonal and spatial variations in soil $CO_2$ flux across the study field and identify the major driving factors underlying this variation in the catchment.

## 1.4 Research Questions

The research questions addressed in the study were;

i. How do current land-uses influence soil $CO_2$ flux and soil organic carbon pools and what is magnitude of the annual carbon contribution of the catchment to the global carbon budget?

ii. How do different cropping systems, field management practices and land preparation activities affect soil $CO_2$ flux?

iii. What are the patterns of soil $CO_2$ flux in relation to soil moisture and temperature dynamics?

iv. How does topography affect soil respiration for the different land-uses at the catchment?

v. To what extent is soil respiration influenced by seasonal and spatial variations and what are the major driving factors underlying this variation in the catchment?

## 1.5 Scope and Structure of Thesis

The major land-uses considered in the study were natural savannah woodlands, graze-lands, croplands and wetlands for agricultural use. Other land-uses and land cover types such as dwelling units, roads, footpaths, bare rocks or sand winning areas were not considered as they constitute relatively small proportion of the total land area in the study field and therefore, their contribution to the total soil $CO_2$ fluxes will be insignificant.

The current thesis is divided into five chapters with **Chapter 1** being the introduction. A brief summary of the contents of remaining chapters has been given as follows;

**Chapter 2** presents the underlying concepts and background of soil respiration which forms the backbone of the study and the principles underlying sustenance and decline in SOC stocks due to land-use changes (temporal and spatial). The implications of SOC stocks dynamics on atmospheric $CO_2$ concentration are also highlighted.

**Chapter 3** presents the overall methodology for the thesis with a description of the study area and the procedures used in data collection and analysis. The tools used for the measurement processes are described as well as some limitations of the study approach.

**Chapter 4** presents the major results and discusses the findings of the thesis. Specifically, the relationships between soil $CO_2$ efflux and soil carbon stocks and the effect of common cropping systems and field management practices on soil $CO_2$ efflux are evaluated. The pattern of soil respiration in relation to soil temperature and soil moisture dynamics and the effect of topography on soil respiration at the catchment are discussed. The seasonal and spatial variations of study field conditions on soil respiration are quantified. The annual soil $CO_2$ efflux and soil carbon emissions are quantified from the field data. Additionally, the chapter discusses the findings of the thesis and highlights their implications on the global carbon cycle, particularly, the implications of the annual $CO_2$ emissions and C fluxes on the global carbon budget. The implications of the findings on long-term C storage and agricultural production in semi-arid lands of Sub Saharan Africa are discussed.

The final chapter, **Chapter 5**, summarises the main findings and major conclusions of the study. It also provides recommendations for future research, policy guidance and sustainable land management for soil productivity and climate regulation.

# 2. REVIEW OF LITERATURE

## 2.1 Introduction

This chapter provides all the concepts, processes and background of soil respiration, land-use and land cover changes, and climate change. It also reviews some of the agricultural systems and practices common in the West African sub-region and their effects on carbon sequestration and soil carbon stocks. The chapter further presents the appropriate empirical and theoretical background upon which the results of the study were discussed and grounded.

## 2.2 Soil Respiration, Philosophy and Processes

Soil respiration ($R_s$), below ground respiration or soil $CO_2$ efflux refers to an ecosystem process that releases $CO_2$ from soil via root respiration, microbial decomposition of litter and soil organic matter, and fauna respiration (Luo and Zhou, 2006). It is therefore the sum of respiration by autotrophic organisms ($R_b$) especially plant roots and rhizomes and the decomposition of soil organic matter, plant litter, and root exudates by heterotrophic soil organisms ($R_m$). Soil respiration may also include a small component of $CO_2$ from abiotic reactions among carbonate species (Rochette *et al.*, 1997). Soil respiration accounts for about 60–90% of total ecosystem respiration ($R_e$) (Hanson *et al.*, 2000) which is the respiration from soil, stem and foliar components and affects the Net Primary Productivity (NPP), the overall photosynthetic ecosystem productivity, Gross Primary Productivity (GPP) less autotrophic respiration ($R_b$). The magnitude of both autotrophic and heterotrophic components of soil respiration significantly affects the Net Ecosystem Exchange (NEE), the small difference between carbon uptake by plants in photosynthesis and carbon release through the respiration of plants and soils (Figure 2.1). All of these processes are fundamental ecosystems properties.

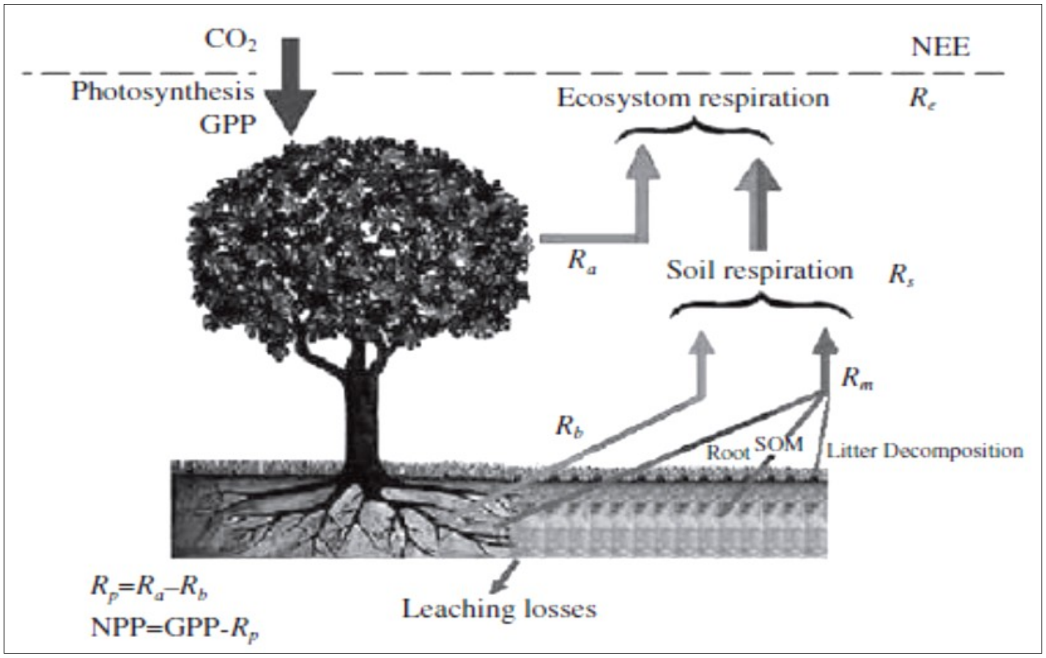


Figure 2.1: Schematic diagram of ecosystem carbon processes Source: Luo and Zhou (2006)

Soil respiration is an important component of ecosystem C exchange with the atmosphere. The net change in terrestrial carbon or the net flux of carbon between land and the atmosphere depends on the rates at which carbon is lost to the atmosphere from decomposition of dead plant material and from oxidation of soil organic matter and the rates at which carbon is removed from the atmosphere through growth of live vegetation and accumulation of organic matter (Houghton *et al*., 1987) in both standing biomass and the soil. Therefore, understanding of ecosystem carbon cycling responses to global climate change hinges on accurate measurements of soil respiration. In consequence, soil respiration measurements have become widespread in recent times in studying soil carbon dynamics and climate change (Thomas and Hoon, 2010; Castillo-Monroy *et al*., 2011) due to the difficulty in quantifying global contribution of soils (or ecosystems) to the carbon budget (Trumbore, 2006). Increasingly, measurements of soil respiration rates are included as inputs to global carbon cycling models to predict global warming effects on soil carbon storage. Extensive research on soil respiration has been done in recent times because it is among the least understood domain in ecosystem ecology.

### 2.2.1 Relevance of soil respiration measurements

Soil respiration is a multidisciplinary subject of concern to ecologists, soil scientists, microbiologists, agronomists, atmospheric scientists, carbon traders and policy-makers. The relevance of soil respiration studies are summarised as follows;

i. Soil respiration measurement is a good indicator of soil quality and microbial activity in the soil. Carbon sequestration rate in soils is a balance between the inputs of carbon from vegetation directly through rhizo-deposition or mycorrhizal fungi, or indirectly through leaf litter decomposition and root turnover and losses due to soil respiration. Thus biologically active soils sequester more carbon with relatively greater respiration than low quality soils;

ii. Soil respiration is related to ecosystem productivity and soil fertility. It may be used to evaluate soil fertility, carbon translocation and soil carbon turnover. Soil respiration is important for agronomic studies as the amounts soil $CO_2$ flux is an indicator of soil fertility for agricultural production. Field studies had confirmed that fertilisation of agricultural soils generally increases soil $CO_2$ flux (Luo and Zhou, 2006);

iii. Respiration measurement is a cost effective approach for assessing the impact of tillage practices, crop and land management on soil carbon turnover and is also relevant for assessing the potential of undisturbed ecosystems and sustainable agro-ecosystems to assimilate carbon dioxide;

iv. Soil respiration is a sensitive indicator of several essential ecosystem processes, including metabolic activity in soil, persistence and decomposition of plant residues in soil, and conversion of soil organic carbon to atmospheric $CO_2$;
v. It represents the critical link in the cycling of elements between autotrophic organisms (e.g. plants) that reduce $CO_2$ to form organic compounds and heterotrophic organisms (e.g. saprophytic fungi in soil) that oxidize organic compounds to release $CO_2$ (Rochette *et al.*, 1997);
vi. Soil $CO_2$ efflux is an important component of total ecosystem carbon exchange and a major contributor to global carbon emissions as well as a key factor in net ecosystem carbon budgets (regional and global) (Luo and Zhou, 2006);
vii. Soil respiration represents a significant source of carbon flux to the atmosphere and a major component in the global carbon cycle. It is the second largest flux of carbon from terrestrial ecosystems to the atmosphere after fossil fuel combustion. They thus are relevant to climate change studies, carbon trading and environmental policy;
viii. Soil respiration measurements are important for monitoring the efficacy of carbon capture and sequestration strategies. For example they are used to monitor soil $CO_2$ flux at surface after $CO_2$ re-injection into the soil and
ix. They are also important for monitoring geological activity. For instance, soil $CO_2$ flux measurements in Masaya volcano, Nicaragua, reported a relatively high soil $CO_2$ emission due to volcanic activity and in seismically active areas (Lewicki *et al.*, 2005).

### 2.2.2 Factors affecting soil respiration

Many factors affect soil respiration. They include photosynthetic supply to roots, quantity and quality of substrates and organic matter in the soil, soil temperature and moisture, soil texture or porosity, soil pH and land-use and management practices. Accurate soil respiration measurement will require thorough understanding of how these factors regulate soil respiration of an ecosystem as well as the processes affecting changes in C storage of the ecosystem and to some extent on the stability of SOC pools under certain conditions such as land-use changes. Some of these factors can be considered as inherent, in connection with soil type whilst others are rather more transient and related to soil the fertility status. Superimposed on these are more fluctuating environmental factors such as soil temperature (Kirschbaum, 1995) and soil moisture content (Davidson *et al.*, 2000), which vary hourly, weekly, seasonally, and annually.

There are many concepts concerning the influence of soil moisture and temperature on soil respiration within different soil types and substrates. They affect microbial growth and substrate utilisation which in turn influence changes in SR derived from decomposing substrates (Larionova *et al.*, 2007). Additionally, complicated biological process which drive soil $CO_2$ exchange are affected by several environmental factors, the major ones being soil temperature and moisture. Previous studies have reported that there exist distinct seasonal pattern for wetland soil-surface $CO_2$ fluxes in line with moisture and temperature variations. Positive correlation between soil temperature and soil $CO_2$ flux in most ecosystems have been observed (Kirschbaum, 1995; Davidson *et al.*, 1998) but the correlation between soil surface $CO_2$ flux and soil moisture is not always significant particularly in wet soils where moisture content exceeds 30% (Savage and Davidson, 2001).

Land and soil management practices may also have an impact on the transient and fluctuating factors. Tillage practices such as no-till, strip-till, and mulch till, application of manure and other organic by products, irrigation and drainage, crop rotation and residue management, use of cover crops or green manure crops may cause SOC increases and can therefore affect soil respiration. This is because these practices create a microclimate on the soil surface layer and this can influence soil temperature and moisture regimes within the field thereby affecting both the temporal and spatial variations in soil respiration rates (Borken and Matzner, 2009). Additionally, management practices might lead to slight changes on C substrate and below ground C supply whilst the plant growth would influence autotrophic and heterotrophic respiration by altering litter production, root exudates and microbial communities of soil (Phillips *et al.,* 2002). Previous studies have demonstrated that due to declining water availability below a certain critical level, soil drying can restrict heterotrophic respiration (Howard and Howard, 1993).

Other factors that can impact and control soil respiration rates include nutrient content (N), soil physical attributes (pH, bulk density, texture, porosity) and soil chemical parameters, and the amount of oxygen in the soil (Cox*, et al.*, 2000) and interaction of these multiple factors (Luo and Zhou, 2006). On the other hand, the spatial and temporal variations in soil respiration may be affected by a host of factors. Diurnal, weekly, seasonal and inter-annual and long term variations in climatic conditions may affect the temporal variability in soil respiration whilst spatial patterns in soil respiration may be affected by scale of measurement (such as stand, landscape or regional level), biomes or vegetation types (forests, grasslands, tundra, savannah/woodlands, deserts, crop fields, or wetlands) and variation along gradients which comprise variations along topography, altitude and latitudes (Luo and Zhou, 2006).

### 2.2.3 Approaches to measure soil respiration

Accurate soil respiration measurement is extraordinarily challenging due to its large temporal and spatial variability and dependence on many environmental and substrate nutrients characteristics (Norman *et al.*, 1997; Lund *et al.*, 1999) and the very properties of $CO_2$ transport in a porous soil medium. Transport of $CO_2$ takes place under the influence of both concentration gradients (diffusion flow) and pressure gradients (mass flow). In general, the $CO_2$ concentration in soil is usually many times greater than that in ambient air with a steep gradient. Thus any measurement method that disturb the soil $CO_2$ concentration and/or distort the gradient would result in serious errors.

Secondly, the $CO_2$ transport from deep soil layers to the surface is driven primarily by diffusion along steep gradients. Since soil is a porous medium, particularly at the soil surface where there is highest porosity, small changes in driving forces or mechanisms of $CO_2$ transport would alter the releases of $CO_2$ from soil. These factors include changes in atmospheric pressure and pressure fluctuation caused by gusts or strong wind. Thirdly, soil respiration is extremely heterogeneous over time and space and therefore highly challenging to sample representative spots at representative times to accurately quantify spatial and temporal variability in soil respiration (Luo and Zhou, 2006).

In this context, several methods are available for soil respiration measurements, each with its own merits and demerits (Davidson *et al.,* 2002; Hutchinson and Livingston, 2002) Broadly, we can distinguish between the direct measurement approaches (chamber measurements and Gas-well [GW] methods) and indirect measurements methods which usually measure ecosystem respiration or net ecosystem exchange (NEE) of carbon, that is the difference between canopy photosynthesis and ecosystem respiration during daytime and the ecosystem respiration at night and from measured NEE or ecosystem respiration, soil respiration may be derived. The commonly used methods of measuring NEE are eddy covariance or micrometeorology and Bowen-ratio/energy balance (BREB). The basic concept of these micrometeorological methods is that gas transport from the soil surface is accomplished by eddies that displace air parcels from the soil to the measurement height. Baldocchi (2003), observed that the eddy-covariance technique ascertains the net exchange rate of $CO_2$ across the interface between the atmosphere and a plant canopy by measuring the covariance between fluctuations in vertical wind velocity and $CO_2$ mixing ratio whilst the BREB method is based on a surface energy balance that assumes similarity between the turbulent exchange coefficients of sensible heat, latent heat, $CO_2$, and momentum to compute net $CO_2$ fluxes from flux-gradient relationships among water vapour, $CO_2$, and heat (Gilmanov *et al.,* 2005). Other micrometeorological methods include the aerodynamic, eddy accumulation, mass balance, dual tracer and surface renewal methods (Luo and Zhou, 2006). Of the direct measurement methods for making soil $CO_2$ flux measurement, the chamber-based method is most common and has two basic system designs: closed chamber systems (also called transient or non-steady-state systems), and open-chamber systems (also called steady-state systems). For closed systems, air is circulated from a chamber to an infrared gas analyser (IRGA) and then returned to the chamber. Soil $CO_2$ flux is estimated from the rate of $CO_2$ concentration increase inside a chamber that has been deployed on the soil surface for a short period of time. For an open system, fresh ambient air is pumped into or pulled from a chamber, and soil $CO_2$ flux is calculated using the air flow rate and the difference in $CO_2$ concentrations between the air entering and leaving the chamber after the air in the chamber headspace has reached a steady state (Madsen *et al.,* 2010). Several modifications of the basic chamber-based principles have been developed with regards to the gas analysers and these include the use of infra red gas analysers (IRGA), gas chromatographs, alkaline or soda lime trapping. Many custom-made closed systems have been described in the literature (Savage and Davidson, 2003; Irvine and Law,

2002) and commercial systems are also available such as the automated closed-chamber system (LI-8100, LI-COR Biosciences, Lincoln, NE USA). Table 2.1 compares the advantages and disadvantages of the various methods whilst Table 2.2 lists and describes the operating principles of the various measurements methods for soil respiration.

Table 2.1: Comparison of the advantages and disadvantages of soil respiration methods

| Method | Advantage | Disadvantage |
|---|---|---|
| Closed Dynamic Chamber (CDC) | 1. Commercially available and easy to use<br>2. IRGA calibration less important due to non-steady state<br>3. Short measurement time and flexible for spatial sampling with a portable system | 1. Builds up $CO_2$ concentration in chamber that distorts the gradient for diffusion.<br>2. Labour intensive with a portable system to sample temporal variation |
| Open Dynamic Chamber (ODC) | 1. High accuracy if artifacts are removed<br>2. Steady-state measurement.<br>3. Allows continuous measurements and high temporal resolution. | 1. Sensitive to pressure differences inside and outside chamber.<br>2. Takes time to reach steady state in chamber.<br>3. Needs power supply.<br>4. Requires differential gas analyser and mass flow controller. |
| Closed static chamber (alkali or soda-lime trapping) – (CSC) | 1. Inexpensive<br>2. Potential to integrate the diurnal change.<br>3. Easy operation in the field and fast laboratory preparation.<br>4. Off-site analysis of samples. | 1. Less accurate due to effects of $CO_2$ building up on diffusion process<br>2. Long enclosure / exposure times cause change in micro-environments in chamber.<br>3. Edge effects, especially in small, shallow chambers. |
| Gas chromatograph (GC) | 1. Parallel analyses of other trace gases and isotopic composition.<br>2. Easy to use and samples can be stored. | 1. Labour-intensive to sample temporal variation.<br>2. Needs a trajectory of headspace CO2 building up to estimate respiration correctly.<br>3. Requires a GC in the laboratory. |
| Gas-well (GW) | Estimation of source depths of $CO_2$ production. | Difficulty in estimation of soil and air diffusivity. |
| Eddy-flux (EF) | 1. Nonintrusive.<br>2. Measured under natural turbulent conditions.<br>3. Sampling a large surface area to represent spatial heterogeneity. | 1. Errors inherent in NEE measurements due to fetch requirements and night time atmospheric inversion.<br>2. Difficult to partition NEE into photosynthesis, above ground and SR |

Source: Redrawn from Luo and Zhou (2006)

Table 2.2: Comparison of soil respiration measurement methods

| Method | Operating Principles | Comments |
|---|---|---|
| Closed Dynamic Chamber (CDC) | Temporal gradient by building up $CO_2$ in chamber | Most of the commercially available systems are based on the principles of this method. |
| Open Dynamic Chamber (ODC) | Differential $CO_2$ at inlet and outlet | Most of the ODCs are homemade and run continuously |
| Closed static chamber (alkali or soda-lime trapping) – (CSC) | Stored or absorbed by base solutions or soda lime | |
| Gas chromatograph (GC) | Discrete temporal gradient by building up $CO_2$ in chamber. | |
| Gas-well (GW) | Spatial gradient by diffusion | |
| Eddy-flux (EF) | $CO_2$ mixing ratio in eddies | Data of NEE are widely available from networks of flux measurements. |

Source: Redrawn from Luo and Zhou (2006)

### 2.2.4 The closed chamber system

Although soil $CO_2$ efflux measurements have being practice for over several it is still very difficult to accurately measure soil respiration due its great temporal and spatial variability and dependence on many environmental and substrate nutrients variables (Luo and Zhou, 2006). Soil $CO_2$ efflux can be measured accurately only by a system that does not alter either soil respiratory activity, the $CO_2$ concentration gradient, the pressure, or air motion near the surface. The concept of chamber-based soil $CO_2$ flux measurements may appear quite simple due to the fewer components needed for making measurements.

However, we must take many factors into account in the process of instrument design and making the measurements to obtain accurate flux data. The fundamental challenge for making accurate soil $CO_2$ flux measurements is how to ensure that the deployment of chambers have minimal or no disturbance to environmental conditions that impact on $CO_2$

production and transport inside the soil profile. In summary, chamber designs must consider the following principles for reliable measurements:

i. Maintaining the chamber-pressure equilibrium with ambient air pressure;
ii. Ensuring good mixing of the air inside the chamber;
iii. Dealing with an altered diffusion gradient inside the chamber;
iv. Minimising the disturbance to the chamber- soil microclimate (Madsen, *et al*., 2010);
v. Ensure that there is no build up or $CO_2$ depletion large enough to cause substantial changes in the gradient of $CO_2$ concentration or leak $CO_2$ into or out of the chamber;
vi. Measure water vapour pressure with a correction factor and
vii. Have relatively stable intake of $CO_2$ concentration for an open dynamic chamber.

In general, two of the most widely used techniques for the measurement of soil $CO_2$ efflux are closed static chamber (Smith *et al*., 1995; Conen and Smith,1998) and the closed dynamic chamber (Norman *et al*., 1997) techniques. Their main difference lies in the presence or absence of air circulation. In dynamic closed chamber systems, air is circulated from the chamber to an IRGA and returned to the chamber. The closed static chambers on the other hand (Figure 2.2), do not use air circulation in their operation but consists of sealing a certain volume of air above the soil surface for a period of time (typically 20-60 minutes) and gas concentration build up is determined by gas chromatography or infrared analysis (Conen and Smith, 1998). Associated with chamber measurements is the so-called “chamber effects”, that have an impact on the flux measurement. Typical example is the soil disturbance from the insertion of the chamber into the soil and release of $CO_2$ from the compacted soil pores which can be overcome by leaving the chambers in place for some time before measurements are taken (Hutchinson and Livingston, 1993).

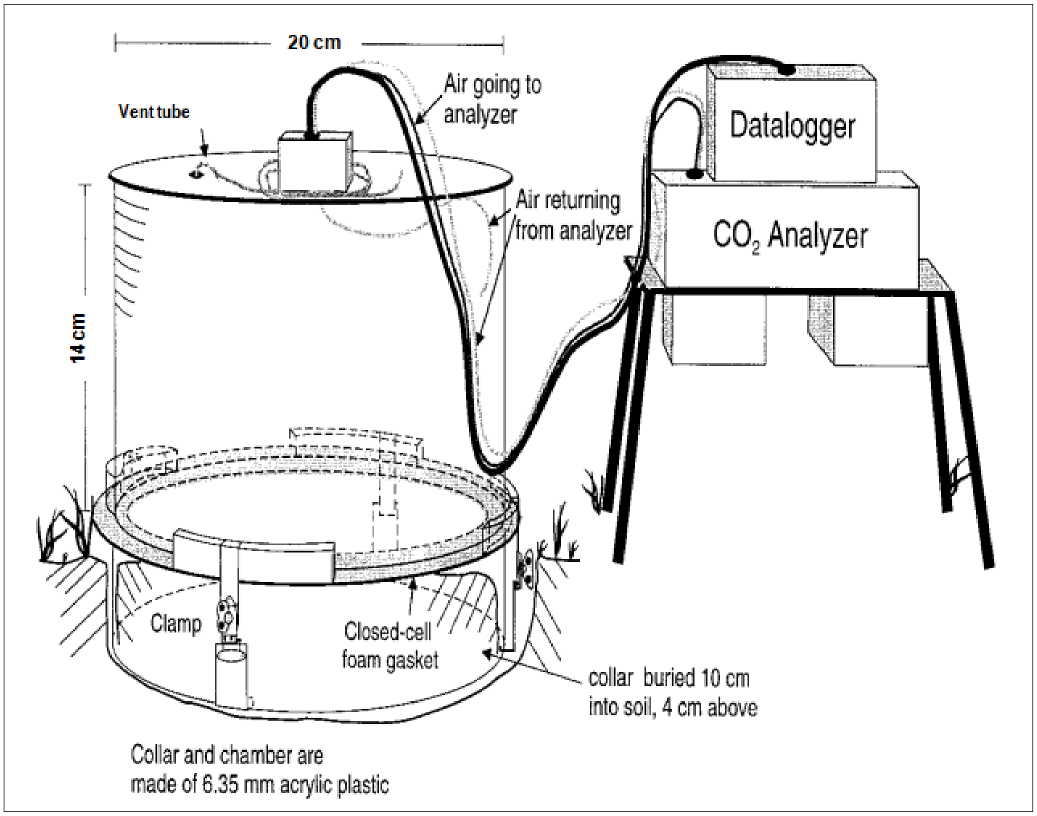


Figure 2.2: Static closed chamber system using a portable $CO_2$ analyser Source: Adapted from Rochette *et al.* (1997)

#### *2.2.4.1 The static chamber technique*

The static chamber technique is applied for quantification of surface fluxes of non-reactive gaseous compounds (e.g. greenhouse gases) at the biosphere-atmosphere interface. Static chambers are also called "closed chambers". Static chambers have been used for several years although not in conjunction with gas chromatography or IRGA methods, but with acid trapping of $CO_2$ and chemical analysis (Luo and Zhou, 2006). They are generally easier to use and less costly to operate than dynamic chambers (Senevirathna *et al.*, 2006). Static chambers have to be sealed gas tight to the atmosphere and to the surrounding environment usually with a rubber gasket to prevent gas leakages during measurement (Drösler, 2005). Normally, frames are placed into the soil (soil collars) onto which the chambers are fixed. Collars provide anchorage for the chambers and ensure repetitive measurements are carried out as required during measurement campaigns. The area that a static chamber can cover can vary; reported sizes range from 0.008 $m^2$ (Ambus *et al*., 1993) to 0.49 $m^2$ (Ambus and Christensen, 1995). Chambers with larger areas exhibit less variability between replicates than smaller ones (Ambus *et al*., 1993).

The principle of the static chamber technique for calculation of flux rates is to monitor changes in concentration over time (enrichment or depletion) often called the mixing ratio. However, chamber closure for the accumulation of gas produces alterations in soil temperature and moisture in the chamber, which can cause changes in the $CO_2$ efflux (Welles *et al*., 2001). The effect can be more pronounced when the chamber closure duration is longer (30 – 60 minutes). Measurements for flux quantification can be operated manually by syringes or IRGA or with use of an automatic sampling system for continuous measurements in high temporal resolution. The static chamber technique can be applied to many environmental in-situ studies in different ecosystems (agriculture, forest, grasslands, and aquatic systems) as well as laboratory experimental setups for simultaneous detection of concentration as well as fluxes of trace gases.

#### *2.2.4.2 Advantages of closed chamber technique*

i. Generally, closed chambers are easy to use and less costly to operate than dynamic chambers. For instance, compared to other techniques for quantification of surface fluxes such as Eddy Covariance, static chamber technique is cost-effective;
ii. They are ideal for determination of spatial heterogeneity as more chambers can be placed in several locations for measurements and this can be coupled with Global Positioning Systems (GPS) measurements for spatial analysis;

iii. The use of closed static chambers can also inhibit pressure fluctuations associated with the turbulence in air movement over the soil surface (Hutchinson and Livingston, 1993);

iv. They are the most commonly used method for the measurement of trace gases such as $CO_2$, nitrous oxide ($N_2O$) and methane ($CH_4$) and

v. Have lower cost of construction, easy installation and removal and are therefore applicable over a wide range of conditions (Smith *et al.*, 1995) making them a popular method.

### *2.2.4.3 Disadvantages of the closed chamber technique*

The main drawbacks of the closed chamber technique include the following;

i. The method has sometimes been criticised for underestimating the soil $CO_2$ efflux at low flux rates and severely underestimating it at high flux rates. Thus closed static chambers tend to be biased in the direction of underestimating the gas fluxes (Senevirathna *et al.*, 2006) compared to the dynamic method. However, Rochette, *et al.* (1997) found little difference in fluxes measured by either the closed dynamic or the static chamber method

ii. The other disadvantage of the static chamber technique is their reduced areal representativeness (about 1 $m^2$ per chamber). Due to large spatial and temporal variability of GHG production and consumption in soils, a large number of replicate chambers are often required making the technique laborious and tedious.

### *2.2.4.4 Considerations for closed chamber technique*

There are some basic factors that need to be considered when operating closed static chamber systems and these are summarised as follows;

i. A proper sealing between the anchor and the chamber is crucial to avoid leaks;

ii. Sufficient mixing of the chamber headspace air is desirable, whilst avoiding pressure effects, which can be achieved by virtue of using vent tube;

iii. On wet soils, soil flux $CO_2$ concentration dilution by water vapour in the chamber will lead to low soil $CO_2$ efflux, thereby underestimating soil $CO_2$ efflux (Welles *et al.,* 2001) which may be accounted for, though this normally causes minor errors;

iv. To achieve adequate measurement resolution whilst working with a closed system the ratio of chamber volume to surface area of the collar should be optimised;

v. Precise placement of a chamber on a collar will avoid pressurisation of the chamber, which otherwise may cause a transient reduction of soil $CO_2$ efflux (Davidson *et al.*, 2002);

vi. There is a size-dependent trade-off between physical and physiological effects of a collar; the diameter of collars will depend on the dimension of the chamber. The larger the collar, the smaller the edge effect in connection with the physical presence of the anchor (Luo and Zhou, 2006);

vii. Additionally, the more compact the collar, the lower the impact on perturbation of the root and accompanying mycorrhisal system, such as severing of roots and reducing assimilate transport to the rhizosphere (Heinemeyer *et al.*, 2007);

viii. To have the least disturbance effects it is desirable to have collars insertion as little as possible within the soil. Chamber legs or collar hooks can help in stabilising even very shallow collars. Collar installation may further disturb the soil structure as well as causing a flush of $CO_2$, and therefore should be done a minimum of 24 hours before starting measurements (Heinemeyer *et al.*, 2007);

ix. Other ways of avoiding soil disturbance is removing above-ground vegetation. This yields soil rather than ecosystem respiration rates in short vegetation such as grassland and annual plants (Raich and Tufekciogul, 2000) and

x. It is advisable to cover soil with water permeable shading cloth after mowing the vegetation to protect the bare soil from heating up and drying out.

### 2.2.5 Manual and automated chamber systems

Apart from the general classification described in subsection 2.2.3, chambers can also be categorised as manual or automated. A comparison of manual and an automated closed dynamic system (i.e. vented chamber in non-steady-state mode with air circulating between IRGA) is made as follows after (Livingston and Hutchinson, 1995) with emphasis on the modifications required to automate the chambers and the advantages afforded by automation; manual chamber measurements are usually made by one person who moves from location to location. Manually based measurements often cannot be sampled frequently due to time constraints of the manual operators. To obtain daily flux for a site, measurement is taken within a time period believed to be representative of the mean daily flux (due to difficulty of sampling continually throughout the day and night). However, the diurnal trend may be variable throughout the year and it may be obscured under very dry or wet conditions. The response of soil respiration to precipitation events can be rapid and often missed due to the infrequency of manually sampled chambers (Merbold *et al.*, 2011). A more frequent measurement schedule is required to capture the diel responses of soil respiration and the rapid responses to precipitation events and to improve models of soil respiration.

Automated systems however, can sample at a much higher temporal frequency without having personal attention and can operate during rain events. The draw backs of the automated soil respiration systems are their high costs more and greater infrastructure (i.e. power, housing) requirement to operate compared manual measurements (Savage and Davidson, 2003). Due to these constraints the automated systems are more poorly spatial distributed than the manual sampling systems. Manual system can more easily address the spatial heterogeneity of an area, whilst the automated system affords greater temporal frequency of sampling. Thus in selecting a chamber system for $CO_2$ flux measurements, there are always trade-offs between the spatially superior manual chamber sampling system and a temporally superior automatic soil respiration sampling system which must be taken into consideration (Savage and Davidson, 2003).

### 2.2.6 Temporal and spatial variation of soil respiration

Soil respiration greatly varies with time and space and information about seasonal and spatial variations in soil $CO_2$ flux are essential to understanding how environmental and biological factors regulate soil $CO_2$ flux of an ecosystem (Luo and Zhou, 2006). The temporal and spatial variation of soil $CO_2$ emission is influenced by several soil attributes related to $CO_2$ production and its diffusion in the soil (Madsen *et al.*, 2007). The spatial and temporal variations in soil respiration result from variations of environmental variables, biochemical processes of respiration, and transport processes of $CO_2$ gas (Luo and Zhou, 2006). A high degree of spatial and temporal variability in soil respiration not only causes measurement errors (Parkin and Kaspar, 2004) but also makes it very difficult to extrapolate point measurements to estimate regional and global carbon budgets (Tang and Baldocchi, 2005).

#### *2.2.6.1 Temporal variation*

According to Xu and Qi (2001) there is strong temporal variation in soil respiration rates over time. In general, the temporal variability can be characterised by four time-scales: diurnal/weekly, seasonal, interannual, and decadal/centennial.

- **Diurnal and weekly variations**

On diurnal basis, Xu and Qi (2001) observed that SR increases in the morning with increase of soil temperature until it reaches a peak at noon to mid-afternoon as the soil temperature keeps increasing, and then declines in the afternoon and throughout the night as the temperature decreases. In most situations the diurnal variation in soil respiration can be explained as a close function of soil temperature, because this is the variable that changes strongly on the diurnal scale (Rayment and Jarvis, 2000). Soil respiration, however, is also correlated with photosynthesis with a time delay by 7 to 12 hours (Tang and Baldocchi, 2005). Thus, substrate supply can be another important factor that regulates diurnal variation of soil respiration. In addition, abrupt increases in soil $CO_2$ efflux can occur in response to rainfall events on a diurnal scale, especially after a long drought (Curtin *et al.,* 2000). Fluctuation in atmospheric pressure and humidity may also affect the diurnal patterns of $CO_2$ emission from soils (Baldocchi *et al.,* 2001). Diurnal variations may not be apparent for soil respiration in heavily shaded forests areas because of the lack of variation in soil temperature (Davidson *et al.,* 2000). Rates of soil respiration at night may be even higher than during the daytime in arid ecosystems, due to high relative humidity at night which favours activities of microorganisms (Luo and Zhou, 2006).

In general, the mid-morning fluxes closely approximate the 24-hour mean efflux (Davidson *et al.,* 1998) such that measurements taken between 0900 and 1100, which have a sampling error of 0.9 to 1.5%, can better represent the daily mean soil respiration compared to the entire daytime measurements, which tend to overestimate the daily mean rates by 4 to 6%. The measurements made at the warmest part of the day can be substantially biased when used to estimate the daily means, weekly or monthly rates of soil respiration (Xu and Qi, 2001). Thus diurnal variation can be a source of errors if it is not accounted for properly especially when point measurements of soil respiration are used to estimate annual soil carbon flux.

On a weekly time-scale, Subke *et al.* (2003) observed that fluctuations in soil $CO_2$ efflux are induced by synoptic weather changes associated with high and low pressure systems, distinct periods of clear sky, overcast, and partly cloudy conditions. All of these conditions alter the amount of available light to an ecosystem and cause changes in air temperature, humidity, and atmospheric pressure available within an ecosystem. The multi-dimensional changes in climatic variables associated with synoptic weather events can directly and interactively influence photosynthesis and respiration (Gu *et al.,* 1999). Changes in photosynthetic assimilation in turn affect root and soil respiration with a time delay on a weekly scale.

- **Seasonal variation**

Seasonal variation in soil $CO_2$ efflux has been observed in almost all ecosystems. Soil respiration rates are usually highest during summer and lowest in winter (Luo and Zhou, 2006). The seasonal variation is driven largely by changes in temperature, moisture, photosynthetic production, and /or a combination of these. The main controlling factors in seasonal variation of soil respiration may depend on the type of ecosystems and climate (Xu and Qi, 2001). For instance in the wet season or spring neither temperature nor moisture is limiting resulting in fast plant growth and high soil respiration. In summer (dry season), moisture becomes limiting, whilst temperature is a limiting factor in winter. As a result, soil respiration declines in summer (dry season) and is low in winter. Borken *et al*., (2002) noted that in ecosystems such as tropical rainforests, temperate forests, and grasslands, soil respiration generally follows seasonal trends in soil temperature and/or radiation whilst in arid and semi-arid ecosystems; soil moisture is the main factor limiting soil respiration. Thus, seasonal patterns of soil respiration closely follow dynamics of soil moisture (Davidson *et al.,* 2000). In the Amazon basin, where the seasonal variation in temperature is not large, whilst variation in soil water content is substantial, soil respiration in pastures and forests correlates significantly with water-filled pore space in soil (Salimon *et al.,* 2004). However, in Mediterranean climate regimes with cold, wet winters and hot, dry summers, water usually constrains biological activity in summer and seasonal patterns of soil respiration are largely determined by soil water availability (Luo *et al.*, 1996).

Globally, soil $CO_2$ efflux reaches the maximum during the season when plant growth is most active in both temperate zones and near- equatorial regions (Raich *et al.,* 2002) as the factors favouring plant growth usually favour soil metabolic activity. Plants also allocate considerable substrate to roots and microbes during active growing seasons, stimulating soil respiration.

Seasonality in soil respiration is also regulated by vegetation types (Grogan and Chapin, 1999). Evergreen and deciduous species show distinct seasonal patterns in productivity, due primarily to plant phonology such as differences in leaf longevity and different timing of root growth, root turnover, and litter fall (Curiel-Yuste *et al.,* 2004) which have important influence on soil respiration. The magnitude of seasonal changes in soil respiration correlates positively with the seasonal changes leaf area index and increases in root production and biomass (Thomas *et al.,* 2000).

### *2.2.6.2 Spatial patterns*

Spatial variability in soil respiration occurs on various scales, from a few square centimetres to several hectares (ha) up to the globe (Rochette *et al*., 1999; Rayment and Jarvis, 2000). Spatial variability poses a challenge in designing appropriate chamber for measurements as well as designing appropriate sampling strategies (such as number of replicates, area covered, and locations of collars or chambers) in order to achieve accurate representation of the field conditions (Rayment and Jarvis, 2000). The spatial variability of soil $CO_2$ efflux has to be understood to derive a representative estimate of regional carbon budget. The pattern of spatial variability in soil respiration at various scales (stands, landscapes, regions, and biomes) can be attributed to different underlying factors.

- **Stand level**

A large spatial variability in soil $CO_2$ efflux occurs at a stand level, even in relatively homogeneous soils such as agricultural fields or mesocosms with homogenised soils. For an of area 3.6 $m^2$ soil respiration rates ranged from 4 to 25 μmol $m^2$ $s^{-1}$ from 150 measurements on over two days (Griffin *et al.,* 1996) for mesocosms with homogenised soils or even in box-lysimeter with homogenised soil and no plants (Nay and Bormann, 2000). Due to the large heterogeneity in natural soil, spatial differences in soil respiration have been observed in various ecosystems (Luo and Zhou, 2006). The high spatial variability in soil respiration may results from large variations in soil physical properties such a soil water content and temperature conditions, porosity, texture, and chemistry, biological conditions such as fine-root biomass, soil animals, fungi, and bacteria and nutrient availability through litter deposition and nitrogen mineralisation (Luo and Zhou, 2006). Management history, site disturbance and weathering also influence spatial variations in soil respiration.

Spatial variability in soil respiration exhibits some patterns along changes in environmental and biological factors. Variation in the moisture content of the litter layer accounts for most of the spatial variation in soil respiration whilst the spatial variation between trees is attributable to parallel gradients in litter mass and fine-root density, given that soil carbon content does not change much along the gradient (Wieser, 2004). To represent the spatial variability of soil respiration over a whole stand, sound sampling strategies, such as random sampling and stratified sampling with adequate replicates, should be employed (Rayment and Jarvis, 2000).

- **Landscape Level**

Large scale variability in soil respiration naturally occurs at landscape level. This is because landscapes are spatially heterogeneous areas with elements of patches, corridors and matrices on scales ranging from hectares to hundreds of square kilometres (Turner, 1989). On the landscape scale, spatial variability in soil respiration is caused largely by variations in climate, topography, soil characteristics, vegetation types, areas and edges of patches, and disturbance history (Luo and Zhou, 2006). Various land-uses have different controlling factors on soil respiration, leading to diverse spatial patterns between land-uses and among land-uses or patch types litter depth is a better predictor of soil respiration than soil temperature and moisture although litter decomposition rates differ substantially among patches (Saunders *et al.*, 2002). For instance, the annual soil respiration rates correlated strongly with SOC content and fine-root biomass for many land-uses along a gradient in central Iowa (Tufekcioglu *et al.,* 2001) whilst soil respiration rates correlated positively with soil microbial biomass and soil physiochemical characteristics including soil carbon content and water-holding capacity across nine landscape regions in the Serengeti National Park, Tanzania (Ruess and Seagle, 1994). Soil respiration rates at the landscape level can also be influenced by mean annual precipitation (McCulley *et al.,* 2005), substrate availability (Campbell *et al.,* 2004), disturbance regimes including land-use changes and climatic changes overtime (Luo and Zhou, 2006). Landscape soil respiration appears to be more sensitive to an increase in minimum temperature than an increase in mean or maximum temperature across this landscape (Luo and Zhou, 2006).

In general, although spatial variability in soil respiration on the landscape scale has been much less studied than on the ecosystem and regional scales

- **Vegetation types**

Soil respiration varies greatly with different ecosystem types, due to variations in biological activities and the inherent characteristics of the ecosystems in the prevailing environments. On a global scale, mean rates of annual soil respiration correlate positively with mean plant productivity among different biomes due to the influence of many confounding factors of climate, soil, and physiological activities. For instance, 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 (Raich and Potter, 1995). Under comparable conditions, soil respiration rates are consistently approximately 20% greater in grasslands than in forests (Raich and Tufekcioglu, 2000) as grasslands usually allocate more photosynthates to below ground than forests which allocate more carbon to wood production. Among forests, soil respiration rates in broad leaf forests are over 10% higher on average than those in coniferous forests located on the same soil types since the two forest biomes have different carbon allocation patterns, litter production rates, litter quality, and relative contributions of root respiration to soil respiration (Weber, 1990).

Generally, rates of annual soil respiration are low in boreal forests, intermediate in temperate forests, and high in tropical forests (Luo and Zhou, 2006). The tropical forests account for an estimated 43% of global NPP and 27% of the carbon storage in soils (Melillo *et al.,* 1993) and this high NPP together with the carbon storage in soils and vegetations lead to high soil respiration rates (Silver, 1998). Tropical moist forests have the highest rates of carbon efflux from soil, whereas soil respiration in tropical dry forests is lower. The main factor in controlling soil respiration in the tropical region is nutrient availability, since high temperature and abundant precipitation occur in tropical forests.

Grasslands account for more than 20% of the terrestrial lands and 10% of the carbon storage on the global scale (Schlesinger, 1997). Recent studies by Luo and Zhou in 2006 report much higher rates of annual soil $CO_2$ efflux, probably due to improved measurements with more intensive, year-round sampling. Savannah and woodlands are potentially a significant carbon sink, because savannah and seasonally dry tropical forest ecosystems contribute 15% of the annual global carbon sink (Taylor and Lloyd, 1992). Soil moisture and fire regimes have overriding influences on soil respiration in savannah and woodlands, particularly during the dry and warm seasons. During the wet seasons, temperature plays a significant role in regulating soil respiration and usually the wooded communities have higher annual soil respiration than the remnant grasslands, probably due to gradients in precipitation and SOC content (McCulley *et al.,* 2004). Grasslands have soil respiration rates about 25% higher than those of the adjacent croplands (Saviozzi *et al.,* 2001).

Globally, croplands occupy about 1.7 billion hectares, with a soil carbon stock of about 170 Pg (Paustian *et al.,* 1997). Compared with natural ecosystems such as grasslands and forests, croplands release a relatively large amount of $CO_2$ from soils due to fertilisation and intensive cultivation. Although many factors affect soil respiration, temperature is likely to be a dominant factor in a given region, because water and nutrients are often supplemented to the optimal levels for crop growth. However, the mean $CO_2$ efflux rate during an irrigation cycle is variable among soils of different field crops due to differences in productivity and rooting systems (Wichern *et al.,* 2004). Croplands have rates of soil respiration approximately 20% higher than those of the adjacent fallow fields (Saviozzi *et al.,* 2001).

Wetlands inhabit a transitional zone between terrestrial and aquatic habitats. They cover only about 3% of the land area (Roehm, 2005) but store nearly 37% of the global terrestrial carbon (Bolin and Sukamar, 2000) and are among the most productive ecosystems (Schlesinger, 1997). The sources of carbon into wetlands are largely from plant photosynthesis and partly from sediments transported through river stream flows which provide both inorganic carbon and organic carbon to wetland ecosystems. Soil moisture controls the rate of oxygen diffusion into the soil and affects $CO_2$ efflux from wetlands. Hence, flooding or prolonged saturation tends to increase the reduction capacity of the soil and decrease decomposition of organic matter and $CO_2$ release rates. Gorham (1995) found that the rate of organic matter decomposition is slow due to anoxic conditions, and carbon tends to accumulate in wetland soils and the carbon stored in wetland soil is a significant component of the terrestrial soil carbon pool.

Wetland soil carbon storage is sensitive to climatic changes, water table fluctuations, and human disturbances and these perturbations can easily shift $CO_2$ sink to source by altering the anoxic conditions. The magnitude of carbon sink or source in wetlands is driven to some degree by latitudinal gradients such that cold ecosystems of the northern latitudes such as peat lands, store great amounts of carbon in the peat due to slow decomposition (Roehm, 2005). The mean rates of $CO_2$ emissions of carbon from freshwater wetlands to the atmosphere range between 1.2 and 7.2 g C m$^{-2}$ d$^{-1}$, with a global total of 11.59 Pg C y$^{-1}$ (Roehm, 2005). Carbon fluxes however, vary widely in different wetlands (Table 2.3) and are estimated to range from 0.13 to 9.12 g C m$^{-2}$ d$^{-1}$ in estuarine studies (Abril and Borges, 2005) and 0.6 to 1.2 Pg C y$^{-1}$ freshwater wetlands (Raich and Potter, 1995). Although $CO_2$ efflux from wetlands is potentially very important in regulating the global carbon cycle, it is poorly understood and usually excluded from global estimates and modelling studies (Trettin *et al.,* 2001).

Table 2.3: Estimated $CO_2$ efflux from freshwater wetlands

| | Boreal Area | | Temperate Area | | Tropical Area | |
|---|---|---|---|---|---|---|
| Type | Area ($10^{22}m^2$) | Efflux ($gCm^{-2}d^{-1}$) | Area ($10^{22}m^2$) | Efflux ($gCm^{-2}d^{-1}$) | Area ($10^{22}m^2$) | Efflux ($gCm^{-2}d^{-1}$) |
| Peat | 3.1 | 4.8 | 0.17 | 7.2 | 3.4 | 2.9 |
| | (2.6 – 3.6) | (0.2 – 31.2) | | (0.1 – 14.4) | (1.7 – 5.1) | (1.6 -18.5) |
| Marsh and | 1.1 | 2.5 | 0.004 | 2.5 | 2.4 | 1.3 |
| swamp | (0.6 – 1.5) | (0.5 – 6.5) | | (0.5 – 6.5) | (0.5 – 0.65) | (0.2 -10.4) |
| Total | | 6.4 | | 0.4 | | 4.7 |
| (TgC y$^{-1}$) | | (0.4 – 44.4) | | (0.01 – 0.9) | | (1.2 -44.7) |

Note: Total global flux 11.6 Pg C y$^{-1}$. Source: Roehm (2005).

Deserts cover about one-fifth of the earth's surface and occur where rainfall is less than 50 cm y$^{-1}$. The extreme environments limit plant production and then soil respiration and soil moisture has an over-riding influence on soil respiration (Raich and Schlesinger, 1992).

Among the biomes, deserts have the lowest rates of soil respiration and fewest studies, probably due to the lesser importance of the deserts in regulating global carbon cycling (Luo and Zhou, 2006).

In general the mean rates of annual soil respiration rates are different among major vegetation types as summarised in Table 2.4.

Table 2.4: Mean soil respiration rates for different vegetation types (g C $m^{-2} y^{-1}$)

| Vegetation type | Soil Respiration Rates | N | Significance |
|---|---|---|---|
| Tundra | 60 ± 6 | 11 | e |
| Boreal forests and Woodlands | 322 ± 31 | 16 | cde |
| Temperate grasslands | 442 ± 78 | 9 | bcd |
| Temperate coniferous forests | 681 ± 78 | 23 | b |
| Temperate deciduous forests | 647 ± 51 | 29 | b |
| Mediterranean woodlands and health | 713 ± 88 | 13 | b |
| Croplands, fields, etc. | 544 ± 80 | 26 | bc |
| Desert scrub | 224 ± 38 | 3 | de |
| Tropical savannas and grasslands | 629 ± 53 | 9 | bc |
| Tropical dry forests | 673 ± 134 | 4 | b |
| Tropical moist forests | 1260 ± 57 | 10 | a |
| Northern bogs and mires | 94 ± 16 | 12 | e |
| Marshes | 413 ± 76 | 7 | bcd |

*including mixed broadleaf and needle leaf forests ± indicates standard error (SE)

Source: Redrawn from Raich and Schlesinger (1992)

### *2.2.6.3 Variation along gradients*

Natural gradients include altitudes, topography, and successional ages. Natural gradients have been found to vary systematically with climatic or other variables and are useful in understanding abiotic and biotic mechanisms which control ecosystem processes and spatial variations in soil respiration (Luo and Zhou, 2006). To clearly examine variations in soil respiration resulting from a primary gradient factor it is recommended that, the primary factor in question is varied whilst all the other variables are kept constant (Rodeghiero and Cescatti, 2005).

- **Altitudes**

Altitudinal gradient influences climate and vegetation for a particular region and therefore variations in soil respiration. Altitudinal gradients often affect climatic (like temperature) and environmental conditions and can therefore regulate soil respiration. The primary factors that regulate soil respiration along an altitudinal gradient may vary at different elevations. With respect to altitude, soil respiration and litterfall varies along an elevation gradient and length of the growing season (Kane *et al.,* 2003). On a whole, the variations in soil respiration with altitudes are due to the combined effects of numerous factor s such as temperature, soil moisture, and length of growing season, frost-free days, and snow-free days along an altitudinal gradient (Luo and Zhou, 2006).

- **Topography**

Topography refers to the description of the physical features of a place and usually describes configuration of the ground surface, its altitude, slope, aspect and exposure. Topographic factors can be classified into configuration of land surface, altitude, slope and aspect and exposure. It affects vegetation type through factors such as climate, soil formation processes, soil nutrients and soil moisture dynamics and together these in turn affect the spatial pattern of soil respiration at a particular site (Luo and Zhou, 2006). The microclimates resulting from different topographic locations can influence soil respiration due to the formation of different micro-site factors, such as soil temperature (Kang *et al.,* 2000), soil water content (Western *et al.,* 1998), incident solar radiation (Kang *et al.*, 2002) and evapo-transpiration (Running *et al.,* 1987).

Generally, there are no consistent patterns of soil respiration along topographic gradients among the current studies, although north-facing and south-facing slopes have significantly different soil temperature, soil moisture, and/or vegetation cover (Hanson *et al.,* 2003). Usually, $CO_2$ efflux rates tend to be high at low-slope positions than at high-slope positions due to variations in soil water, litter mass, and roots (Luo and Zhou, 2006). Table 2.5 shows the spatial distribution of annual $CO_2$ efflux and soil attributes of four topographic locations at a Watershed in Tennessee.

Table 2.5: Estimated annual $CO_2$ efflux and soil attributes of four topographic locations at the Walker Branch Watershed, Tennessee.

| Topographic location | Annual $CO_2$ efflux ($gCm^{-2}y^{-1}$) | Fine Roots ($mgcm^{-3}$) | Soil Carbon (%) | Soil Nitrogen (%) | Forest Litter ($gm^{-2}$) |
|---|---|---|---|---|---|
| Valleys | 736 | 3.7±2.4 | 3.5±1.3 | 0.21±0.07 | 519±180 |
| NE slopes | 818 | 7.7±3.8 | 2.8±0.9 | 0.20±0.06 | 606±193 |
| SW slopes | 845 | 11.9±3.8 | 2.8±0.9 | 0.15±0.06 | 623±229 |
| Ridge tops | 927 | 12.5±7.5 | 2.9±0.8 | 0.16±0.04 | 767±231 |

Source: Redrawn from Hanson *et al.* (1993).

In sum, variations in soil respiration rates are attributable to diverse ecosystems response to interactive effects of climatic and edaphic conditions, biotic factors such as canopy height, LAI, and productivity of different biomes, landscape patterns, natural disturbances, and land-use management histories (Luo and Zhou, 2006). The magnitude of the impact of each of these factors is variable from one scale to another making it essential to investigate the underlying factors of spatial variation of soil respiration at the Vea catchment.

## 2.3 Land-use, Land Cover and Land-use Change

Currently, GHG emissions from land-use and land-use change continue to attract global attention. Land-use and land cover is an important component to understand global land status; it shows present as well as past status of the earth surface. Land-use and land cover are two separate terminologies which are often used interchangeably (Dimyati *et al.,* 1994). Globally, land cover today is altered primarily by direct human use (land-use) and thus any conception of global change must include the pervasive influence of human action on land surface conditions and processes (Yang, 2001). The distinction between land-use and land cover have been the subject of many scientific debates and number of definitions have been proposed. According to Ellis, (2013), land cover refers to the surface cover over land, including vegetation, rock and human-modified surfaces such as buildings. Land cover is a characteristic of the land that can be observed physically, especially by remote sensing techniques and it is different from land-use, because a single land-cover type can be used in various ways by humans. Land-use on the other is a more complicated term. Land-use is defined in terms of syndromes of human activities such as agriculture, forestry and building construction that alter land surface processes including biogeochemistry, hydrology and biodiversity. Social scientists and land managers define land-use more broadly to include the social and economic purposes and contexts for and within which lands are managed (or left unmanaged), such as subsistence versus commercial agriculture, rented versus owned, or private versus public land (Ellis, 2013).

Perhaps the most comprehensive definition of land-use and land cover is the FAO (2000) definition which states that "land cover is the observed (bio) physical cover of the earth's surface" whilst "land-use is the arrangements, activities and input that people undertake on a certain land cover type''. From these definitions it can be seen that land cover is the broad physical conditions on the ground or natural cover of the land such as forest, grassland, land-use refers to the planned human activities (man made things) such as residential areas, industrial areas, and agricultural fields but there is a strong link between land cover and the activities of the people in their environment such that these terminologies are often used interchangeably.

Other closely related terminologies are land-use change and/or land cover change and usually land-use may lead to land cover change. Land-use change denotes a change in the use or management of land by humans, which may lead to a change in land cover (IPCC, 2001). Land cover and land-use change may have an impact on the albedo, evapo-transpiration, sources and sinks of greenhouse gases or other properties of the climate system, and may thus have an impact on climate locally or globally (IUCN, 2011). Put together, Ellis, (2013) refers to land-use and land cover (LULC) as land change, which is a general term for the human modification of Earth's terrestrial surface. Though humans have been modifying land to obtain food and other essentials for thousands of years, current rates, extents and intensities of LULC change are far greater than ever in history and this driving unprecedented changes in ecosystems and environmental processes at local, regional and global scales. Land cover change can be of two types; conversion from one land cover category to another, e.g. from forest to grassland and modification within one category, for example from dense forest to open forest (FAO, 2000).

### 2.3.1 Causes of land cover change

Land-use and/or land cover are dynamic in nature and provide a comprehensive understanding of the interaction and relationship of anthropogenic activities with the environment (Prakasam, 2010). Land cover change is the response of increased use of nature to meet the numerous diverse human survival and development needs. Land cover change can be attributed to natural and / or anthropogenic causes. However, it results more often from human activities than naturally occurring. The natural causes include storms, landslide, and disease and pest of existing vegetation as well as fire which is the most prominent one in most areas. With regards to the human causes, Meyer and Turner II (1992), identified and grouped the main causes of land cover change into technology capacity, socioeconomic organization, level of development and culture. Heilig (1994) added that unprecedented population growth, the growing affluence and changes in lifestyle the worldwide, which may be due to rising per capita income; and the growing influence of geopolitical, economic, and military structures and strategies. Lambin and Ehrlich, (1997) also identified the negative contribution of the rapid human population growth on land resources driving the changes in land cover.

Usually the causes are remote in space and time from the observed changes, and often involve macro-economic transformations, technological effects, socio-political factors and policy changes which are difficult to expect (Geist and Lambin, 2001). This is true for deforestation which stands out among land cover change process in most countries due to the sharp contrast in the transition from forest to cleared land. Lambin and Strahler (1994), summarised impact of the two major causative agents into five categories of causes that influence land-cover change: (a) long-term natural changes in climate conditions, (b) geomorphological and ecological processes such as soil erosion and vegetation succession, (c) human-induced alterations of vegetation cover and landscapes such as deforestation and land degradation, (d) inter-annual climate variability and e) the greenhouse effect caused by human activities.

In Africa and many sub-Saharan countries including Ghana, deforestation from logging, clearing for agriculture, uncontrolled fires, illegal mining and population growth have been the major drivers of land cover change. These drivers are exacerbated by increasing population which tends to put excess pressure on land based resources. Extensive research has been done with the key interest in Ghana forested land being degraded into desert (Ademola *et al.,* 2004) but little has been done on their impacts on GHGs emissions.

### 2.3.2 Impact of land-use / land cover changes on soil carbon dynamics

Land-use changes and modifications are essential for human well-being but also one of the main drivers of the current global warming crisis. Several studies have estimated that emissions from land-use change (particularly $CO_2$ emissions) mostly from developing countries constitute about 20 - 25 % of all anthropogenic GHG emissions (Olander *et al.*, 2008; Skutsch *et al.*, 2007) and this corresponds to about 20 % of $CO_2$ emissions obtained from burning fossil fuels (Brown *et al.*, 1996). Drastic land cover change resulting from forest and land degradation affects carbon sequestration potential of land. The conversion from one land-use to another is largely the contributor to the loss of net carbon stocks, which is a major source of carbon emission into the atmosphere leading to local climate change.

Tropical deforestation is estimated to have released of the order of 1–2 billion tonnes of carbon per year during the 1990s, roughly 15 - 25 % of annual global GHG emissions (Houghton, 2005). Carbon sequestration through forestry can play a significant role in ameliorating global environmental problems such as atmospheric accumulation of GHG's and climate change. Forests ecosystems sequester and store more carbon than any other terrestrial ecosystem and are an important natural ‘brake’ on climate change. When forests are cleared or degraded, their stored carbon is released into the atmosphere as $CO_2$. Combating deforestation and minimising impact of logging are practices that reduce emissions whilst land management practices such as planting trees, changing agricultural tillage or cropping practices, or re-establishing grasslands or degraded land sequester carbon (Pearson *et al.*, 2005). Embarking on reforestation and afforestation projects hold great potential for storing carbon in biomass in tropical regions and also embarking on enrichment planting programmes and Agroforestry interventions enhances carbon storage of forest (Hair *et. al*., 2009). The world therefore need permanent sustainable forests to lock up carbon, to conserve soil and water, to oxygenate the atmosphere, to provide timber, food, medicines and other products and services to preserve and protect biodiversity and wildlife and also provide places for recreation. However, Pearson *et al.* (2005) argued that the effect of changes in land-use on atmospheric $CO_2$ concentration is not only negative but will help sequester more $CO_2$ from the atmosphere into vegetation and the associated soil through primary productivity.

Africa hosts large areas of forests; savannah and grasslands and many populations are relying on woody formations for fuel wood, charcoal and forest fruits, building materials and medicine. These resources are seriously threatened by climate change impacts which main driver is greenhouse gas concentration in the atmosphere deriving from human activities. The sectors of agriculture, land-use, land-use change and forestry are the main sources of emission for African countries. According to Canadell *et al.* (2009), between 2000–2005 Africa's share of global emissions from land-use change was 17 percent. Land-use change and forestry sectors are the most emitting sector in African countries. On average, 55 percent of $CO_2$ (equivalent) emissions are from the land-use change and forestry (LUCF) sector for West and Central African countries (UNDP/GEF, 2004) and these are occurring in areas where uncertainties and data reliability are the most critical. Thus although the energy sector contributes the largest source of greenhouse gases (21.3 %) (Figure 2.3), the combined effect of deforestation, land-use change and biomass burning (10.0 %) and Agriculture (12.5%) has the greatest contribution of GHGs sources (22.5 %).

Agriculture intensification for the provision of food and fibre for the growing human population has been one of the major drivers of land-use changes and deforestation. As a result, the contribution of agricultural activities to GHGs emissions and its impact on the global climate particularly $CO_2$ is highly significant although this sector is often overlooked in most mitigation strategies (Wollenberg *et al*., 2012).

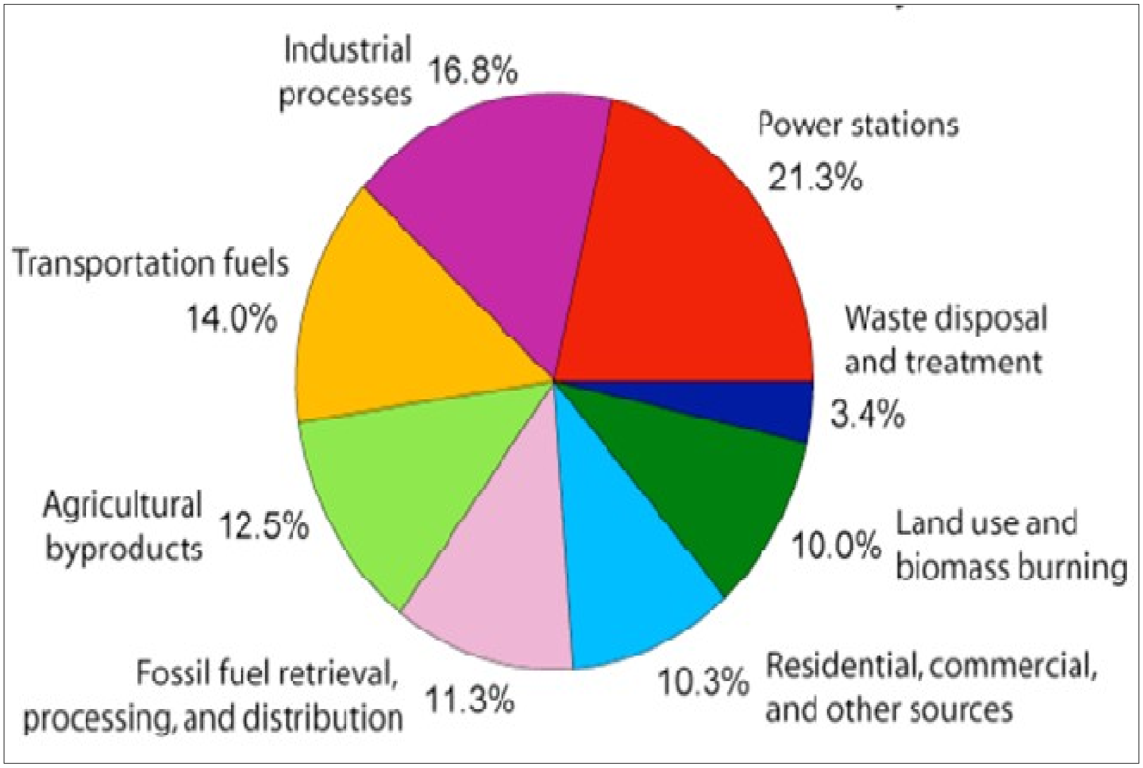


Figure 2.3: Sources of GHGs emissions by sectors Source: IPCC (2007a)

Human influence on the earth's natural climate system is unprecedented (Lambin and Geist, 2006). Disturbance (e.g., vegetation clearing to make way for farms, construction, industries, transport, etc.) of the land can change the global atmospheric concentration of carbon dioxide, the principal heat-trapping gas, as well as affect local, regional, and global climate by changing the energy balance on earth's surface. Consequently, future changes in climate and land-use will affect land-atmosphere exchange and vegetation and soil dynamics, and hence the ability of the land-surface to sequester carbon. It is therefore anticipated that proper management of the terrestrial carbon pools will determine indeed as to whether the land biosphere remains a carbon sink or becomes a source in the late 21st century. Estimates on the contribution of deforestation and land-use change to GHGs emissions vary, but are commonly held to be around 10 % of global emissions and 22.5 % combined with agriculture which is also greater than those emissions produced by the whole of the global transport sector (IPCC, 2007a). The bulk of emissions from deforestation arise when land is converted to agricultural production, particularly if forests are first cleared with burning (WRI-CAIT, 2007).

The effects of land-use change on soil carbon stocks have been of concern in the context of greenhouse gas emissions and climate change mitigation. Soils are the most important component of the terrestrial carbon pools. Globally, soils contain approximately 1500 Pg of organic carbon (Batjes, 1996); about three times the amount of carbon in vegetation and twice the amount in the atmosphere (IPCC, 2001). It is estimated that over 60 Pg C $y^{-1}$ is exchanged between atmosphere and land via net primary productivity (NPP) and vice versa annually via fluxes of carbon dioxide ($CO_2$) (IPCC, 2001) through fossil fuel combustion and soils respiration. Soils therefore have a huge potential to regulate the global carbon budget from respiration (source) or sequestration (sink) through improved land-use and land management. Soil carbon stock is controlled by climate, vegetation, topography, parent material, time and management (Trumbore, 1997). Most of the traditional carbon models explain soil carbon content as a function of vegetation residues returned to soil (Parton et al., 1987), although recently the soil carbon saturation concept emphasises the importance of soil physico-chemical properties to stabilise carbon in soil (Six *et al.*, 2002). Therefore, soil represents the largest carbon sink over which we have control. Groundcover management is the prime determinant of whether agricultural soils act as a source (net loss) or a sink (net gain) for atmospheric carbon.

Soil carbon comprises stocks of carbon in soils as well as additional carbon into soils from active sequestration. Lal, (2009), distinguished between two major pools of carbon in soils; soil organic carbon (SOC) derived from organic matter which is more important for soil fertility and carbon budget and soil inorganic carbon (SIC) which are essentially carbonates derived from weathering of rocks (lithogenic) and direct absorption of carbon dioxide into the soils (pedogenic). Organic carbon (such as humus) has many benefits in soils making effective carbon management the key factor for productive farms, revitalized catchments and a greener planet. Soil organic carbon is likely to change at a slow rate and is also likely to be an expensive pool to measure. However, it should at least be considered, as sequestration of carbon into the soil, or prevention of emissions of carbon from soils can be important – especially in grazing land and cropland systems – and omission of soil carbon is an omission of a source of reductions in atmospheric greenhouse gases.

Soil inorganic carbon (SIC) sequestration rates are generally of lower order of magnitude than those of soil organic carbon (SOC), but this inorganic carbon is still a significant carbon pool and has been estimated to be about 930-1738 Gt C globally, with significant concentrations in arid regions and in degraded ecosystems (Lal, 2009). Unlike SOC, soil inorganic pool is relatively stable, and is thought not to be a net sink or insensitive to land management and therefore not as relevant to climate change mitigation (Walcott *et al.*, 2009). The total soil carbon pools are much larger than carbon sequestered in biomass (Lal, 2004) and the overall fluxes between the atmosphere and soils are of larger magnitudes than anthropogenic emissions (IPCC, 2000) but generally there is poor understanding of soil carbon dynamics and measurement of soil carbon stocks is difficult particularly at a large scale (Trumper *et al*., 2009; Epple, 2012). The accumulation of soil organic carbon is the result of the balance between inputs of carbon to the soil organic matter (SOM) from primary productivity and outputs from soil respiration (De Deyn *et al.,* 2008). Abiotic factors such as temperature and soil moisture are important in determining this balance, but many other factors also influence it, including soil biota diversity and composition (Nielsen *et al.,* 2011).

Carbon sequestration is the pathway through which the carbon dioxide removed from the atmosphere is stored in the terrestrial ecosystems which act as sinks either as organic or inorganic carbon. Biological approaches to sequestration include direct removal of carbon dioxide from the atmosphere through land-use change, afforestation, reforestation, and practices that enhance soil carbon in agriculture whilst physical approaches include separation and disposal of carbon dioxide from flue gases or from processing fossil fuels to produce hydrogen and carbon dioxide-rich fractions and long-term storage in underground in depleted oil and gas reservoirs, coal seams and saline aquifers. As soil is a complex ecosystem, carbon storage and permanence of soil carbon stocks and soil organic matter (SOM) are controlled by both biotic or abiotic factors which regulate the balance between inputs and outputs of carbon to and from the soils in different ecosystems (Schmidt *et al.,* 2011). In this context, organic matter inputs to soils such as fresh plant litter (leaves, stems, roots and rhizosphere), fire residues and inputs from roots and the rhizosphere are significant and this makes soil carbon stocks highly susceptible to land-use or cover changes.

Most changes in land-use therefore affect the amount of carbon held in vegetation and soil, thereby, either releasing $CO_2$ to or removing it from the atmosphere. It is widely believed that land-use conversions from grasslands, forests, or other native ecosystems to croplands or by draining or cultivating organic soils more carbon sequestration occurs from restoring grasslands, forests, or native vegetation on former croplands. According to Yaalon, (2000) soil carbon dynamics has a direct linkage with the climate and biogeochemical systems and it helps us to understand and predict human impacts on the earth. Ellis (2013), observed that soils and vegetation (forests) disturbance through land-use and land cover change **(**LULCC**)** can increase the release of $CO_2$ to the atmosphere especially when followed by agriculture, which causes the further release of soil carbon in response to disturbance by tillage (Ellis, 2013). Changes in land-use and land cover are also behind major changes in terrestrial emissions of other greenhouse gases, especially methane and nitrous oxide from agricultural activities and biomass burning (Ellis, 2013). Deforestation and land-use change from native ecosystems to cultivated ecosystems such as forests to grazing land and agriculture or savannah to agricultural land lead to lose of soil carbon pools and increase atmospheric concentration of GHGs, $CO_2$ and methane ($CH_4$) (Post and Kwon, 2000; Shrestha *et al*., 2004). Studies undertaken by Powers *et al*. (2011) in the tropics revealed that conversion of forest to pasture increased soil carbon stocks in low-activity soils, but decreased soil carbon in high-activity soils, with a confounding effect of mean annual precipitation; whilst pasture to secondary forest increased carbon stocks and forest to cropland decreased carbon stocks, except in high-activity soils.

Another study by Don *et al*. (2011) on soil organic carbon dynamics in response to tropical land-use change reported similar results with greater consideration of depth of soil carbon measurement. The study reported SOC decreases with the following land-use transitions: primary forest to grassland, primary forest to cropland, primary forest to perennial cropland, primary to secondary forest, secondary forest to grassland, and grassland to cropland. However, the following land-use changes increased carbon stocks: grassland to secondary forest, cropland to secondary forest, cropland to grassland, and cropland to fallow. There was however contradictory results of SOC changes from primary forest transition to secondary forest, due to soil depth but clearly, in this transition, whilst upper layers of soil lost carbon; deeper layers were reported to have gained carbon. The greatest magnitude of SOC change involved transitions to and from cropland.

This was confirmed by Guo and Gifford (2002) who concluded that changing from the native or natural vegetation (such as forest or pasture) to semi-natural ones (plantation or cropland) causes decline in soil C stocks whilst soil C stocks increased after land-use changes from cultivated to native vegetation or those dominated by woody perennials (Figure 2.4). The study noted that SOC stocks decreased in the following conversions: pasture to plantation, native forest to plantation, native forest to crop, and pasture to crop whilst following conversions increased soil carbon stocks: forest to pasture, crop to pasture, crop to plantation, and crop to secondary forest. It was further noted that wherever one of the land-use changes decrease soil C, the reverse process usually increases soil carbon and *vice versa* (Guo and Gifford, 2002).

Several other studies have supported the general conclusion that the clearing of forest land for cropland decreases soil carbon stocks (Houghton and Goodale, 2004), but that conversion to pasture does not (Murty *et al.,* 2002). Lal (2008) asserts that conversion of natural ecosystems to agricultural ecosystems depletes soil carbon over a longer period (20 - 50 years) in temperate regions but only 5 to 10 years in the tropics. Averagely, cultivated soils contain on 50 to 70 per cent of the carbon content of undisturbed soils (Lal, 2008) whilst degraded ecosystems and those affected by desertification are widely reported to contain less soil carbon (Olsson and Ard, 2002; Lal, 2009).

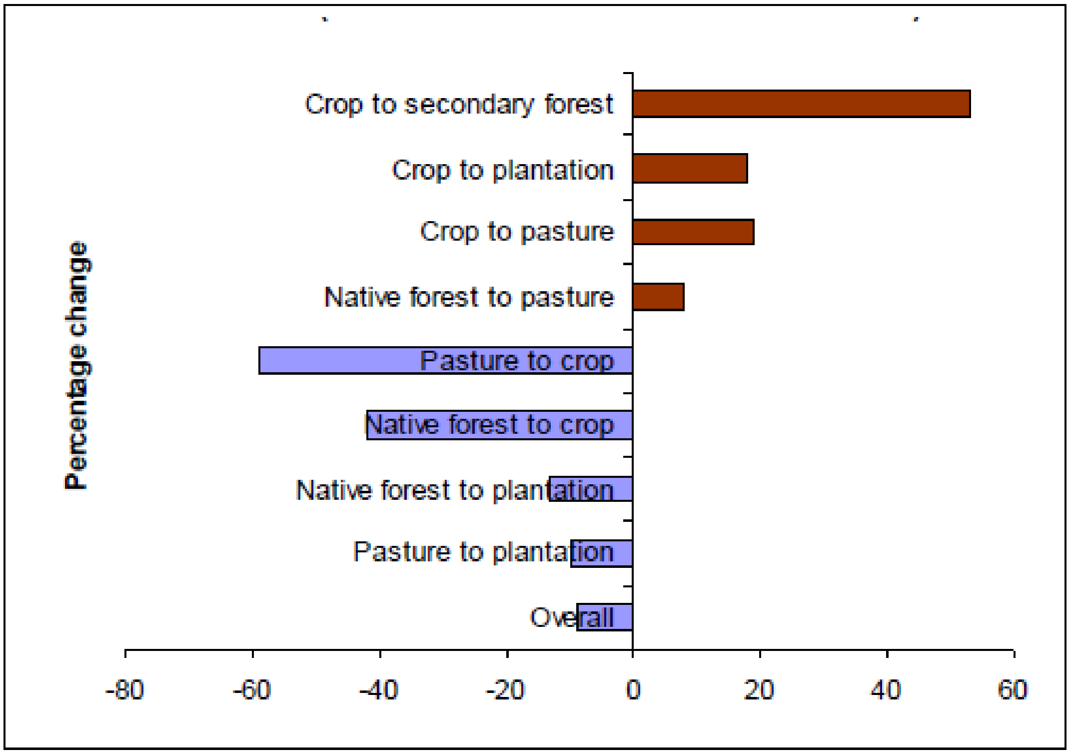


Figure 2.4: Changes in soil carbon stocks in response to land-use change Source: Guo and Gifford (2002)

In West Africa alone substantial amounts of soil organic carbon (SOC) of 4.2 to 4.5 kg C $m^{-2}$ have been estimated and the soils here may have contributed over half of Africa's net emission of C to the atmosphere in 1980 (Houghton *et al.*, 1987). Thus with growing West Africa’s population coupled with increasing demand for food, more land (forested) would be converted into croplands, implying greater potentials for SOC loses and greater carbon emissions.

### 2.3.3 Carbon sequestration potential of grasslands and savannahs in the Tropics

Worldwide, grasslands occupy about 40.5 percent of the Earth’s land surface (52.5 millions of $km^2$) excluding Greenland and Antarctica (WRI, 2000). In the tropics, grasslands and savannahs are broad ecosystem types comprising a continuum of treeless grasslands to open forests (Epple, 2012) located primarily in Africa, South America and Australia (Grace *et* *al*., 2006). The total carbon stocks of global tropical grasslands have been estimated at 285 Gt C, with an average carbon density of 137 t C $ha^{-1}$ (Trumper *et al*., 2009; Epple 2012) whilst Grace *et al.* (2006) reported estimates of 9.4 t C $ha^{-1}$ for above-ground biomass carbon, 19 t C $ha^{-1}$ for below ground biomass carbon and 174 t C $ha^{-1}$ for soil organic carbon. Tropical grasslands experience one or two dry seasons each year and they are frequently burnt (at least once a year) by the farmers. These high constraints have an impact on the dynamic of the vegetation of the grassland and for that matter carbon pools. For the grasslands that grow on poor soils, the constraints are even higher and their mismanagement could make these savannah ecosystems a net carbon source.

In Africa, grasslands occupy 5 millions of $km^2$, i.e. 17 % of the surface area of Africa. This biome is directly affected by climate change that we are facing, in particular through changes in seasonal distribution of rainfall and the increase in temperature (Ojima *et al.* 1993). A recent study of African savannahs reported total soil organic carbon stock of approximately 110 Mg C $ha^{-1}$, although it reported very high spatial heterogeneity and little correlation between soil carbon stocks and vegetation. Savannah ecosystems have total carbon densities that approach those of forests when carbon stocks in vegetation and soils put together (UNEP/CBD, 2012) and thus could have a major influence on the global carbon budget.

However, these ecosystems are highly threatened with degradation and habitat conversion. It is estimated that annually, about 1 per cent of savannah ecosystems are converted to other land-uses and this constitutes a large proportion of converted ecosystems (Grace *et al*., 2006). Land change to croplands or intensive grazing can release large quantities of carbon from biomass and soils but the long-term effect critically depends on soil type and subsequent management practices (Grace *et al*., 2006). In fact, because of high rates of loss and degradation, emission from savannah ecosystems may approach emissions from tropical deforestation (Grace *et al*., 2006).

Fire is an important characteristic of savannah biomes as the main carbon management strategies for savannah ecosystems apart from grazing land management (e.g. reduced stocking densities) is fire management. Whilst fire is a natural component of savannah ecosystems, it releases large quantities of carbon, mostly a short-term basis and this is usually re-accumulated upon regrowth (Ciais *et al*., 2011). However, fire management activities may have negative or positive effects on biological diversity: high suppression regimes typically lead to rare, large fires and related effects on biodiversity whilst controlled dry-season fires may reduce impact on biodiversity whilst maintaining carbon sequestration benefit (Douglass *et al*., 2011). Another characteristic of savannah areas is their high population densities of nomadic people particularly in West Africa where they move together in search of fodder for cattle particularly during the lean season (transhumance), leading to over grazing and land degradation (Conant, 2010).

Notwithstanding, the enormous amount of studies, the tropical savannahs and grassland ecosystems are not fully understood; there are gaps in knowledge making them rarely included into terrestrial ecosystem models and therefore their role in the global carbon cycle difficult to assess (Ciais *et al*., 2011; Epple , 2012).

### 2.3.4. Land-use management to increase soil carbon stocks

Several land management practices are well-known to help in the maintenance of carbon stocks already stored in soils and these include forest management devoid of clearance into open lands, combating land degradation and desertification and conservation of native ecosystems. Beside these, for croplands, rangelands and degraded lands, a range of management options exist with high potential to restore and retain soil carbon stocks. These management practices aim at promoting soil carbon stock by increasing net primary productivity (NPP) through agronomic activities such as irrigation, fertilisers application and re-vegetation or modifications that reduce carbon loss from soils including re-wetting of wetlands whilst reducing soil carbon losses via respiration (UNEP/CBD, 2012).

The success however, of each management practice to improve soils carbon stock depends on the ecosystem, type of soil and soil condition. For instance, among other factors, carbon sequestration rate is faster in cooler soils than in warmer soils whilst wetter soils sequester more carbon as do clayey soils compared to drier, sandier soils (Lal, 2009). Lal (2004) estimated that enhanced management practices had the potential to sequester 0.4-1.2 Gt C $y^{-1}$ whilst simultaneously improving crop yields. There is a finite limit to sequestration potential, and that once a certain amount of carbon has been sequestered in soils, the soils are less able to function as carbon sinks (UNEP/CBD, 2012). It is for this reason that degraded soils and ecosystems are thought to have the highest potential for carbon sequestration since carbon stocks in degraded soils are depleted and Lal (2009) estimates this potential to be approximately 1 Gt C $y^{-1}$ in the global drylands.

Whilst acknowledging the significant global potential for soil carbon sequestration, recent review by Powlson *et al.* (2011) outlined three important caveats to the importance of soil carbon to mitigating climate change. These are; (a) the quantity of carbon stored in soil is finite, (b) the process is reversible; and (c) even if SOC is increased, there may be changes in the fluxes of other greenhouse gases, especially nitrous oxide ($N_2O$) and methane.

In the context of agricultural and rangelands, the adoption of sustainable agro-ecosystems and rangeland management practices to improve soil carbon sequestration is key.

Compared to natural ecosystems, agricultural soils contain relatively less soil carbon however their loss constitutes a major historical carbon emission of about 42-78 Gt C or approximately 20 - 80 t C $ha^{-1}$ (Lal, 2004). Agricultural soils have significant mitigation potential due to their relatively impoverished condition and together their total mitigation potential has been estimated to range between 0.4-0.6 Gt $Cy^{-1}$ to 0.6-1.2 Gt $Cy^{-1}$ worldwide (Lal, 2004).

Lal (2008) identified generic recommended management practices thought to increase soil carbon sequestration in agricultural landscapes and these are enumerated as follows:

i. Development of a positive carbon balance through conversion of plough tillage to conservation tillage or no-till farming along with the use of crop residue mulch and cover cropping;

ii. Improvement in plant-available water resources in the root zone through enhancement of infiltration rate, water harvesting and recycling, supplemental irrigation, and minimising losses due to soil evaporation;

iii. establishment of a positive nutrient budget through integrated nutrient management, manuring, and judicious use of chemical fertilisers;

iv. Adoption of complex cropping systems including Agroforestry; and

v. Selection of appropriate crops and pastoral species most suited for the specific soils and climatic conditions.

Other sustainable agricultural practices include Agroforestry, use of cover crops, crops rotation, mulching, and manuring and together these could sequester an estimated 60,000 t $CO_2$ (~16 363 t C) annually in the Kenya agricultural carbon project (UNEP/CBD, 2012).

Smith *et al.* (2008a) also provided a list of management practices thought to increase soil carbon sequestration in both agro-ecosystems and rangelands and these are as follows:

i. For cropland management, the practices include agronomy, nutrient management, tillage/residue management, water management (such as irrigation, drainage etc), Agroforestry and fallowing and land-use change;

ii. For grazing land management / pasture improvement, the practices include managing grazing intensity, increasing productivity (e.g. fertilisation), nutrient management, fire management and species introduction (e.g. legumes);

iii. For management of organic soils, the recommended practice is to avoid drainage of wetlands whilst erosion control, organic and nutrient amendments are the recommended practices for the restoration of degraded soils.

In general, for all climatic types, restoration of organic soils (wetlands) to their native condition and restoration of degraded lands were the activities with the greatest mitigation potential and these restoration practices could have positive biodiversity outcomes as well (Smith *et al.*, 2008b).

In degraded semi-arid soils in particular, increasing fallow periods and the conversion of degraded croplands to rangelands are seen as options to increase soil carbon sequestration (Olsson and Ard, 2002). Important co-benefits to increasing soil carbon sequestration include increasing soil fertility via increased soil organic matter and resilience to climate change and sometimes biodiversity improvement.

Lal (2004) summarises the carbon sequestration potential of common land-uses as shown in Figure 2.5. A key constraining factor to the implementation of soil carbon sequestration practices is lack of appropriate and cost-effective methodologies to account for soil carbon changes due to land management (UNEP/CBD, 2012).

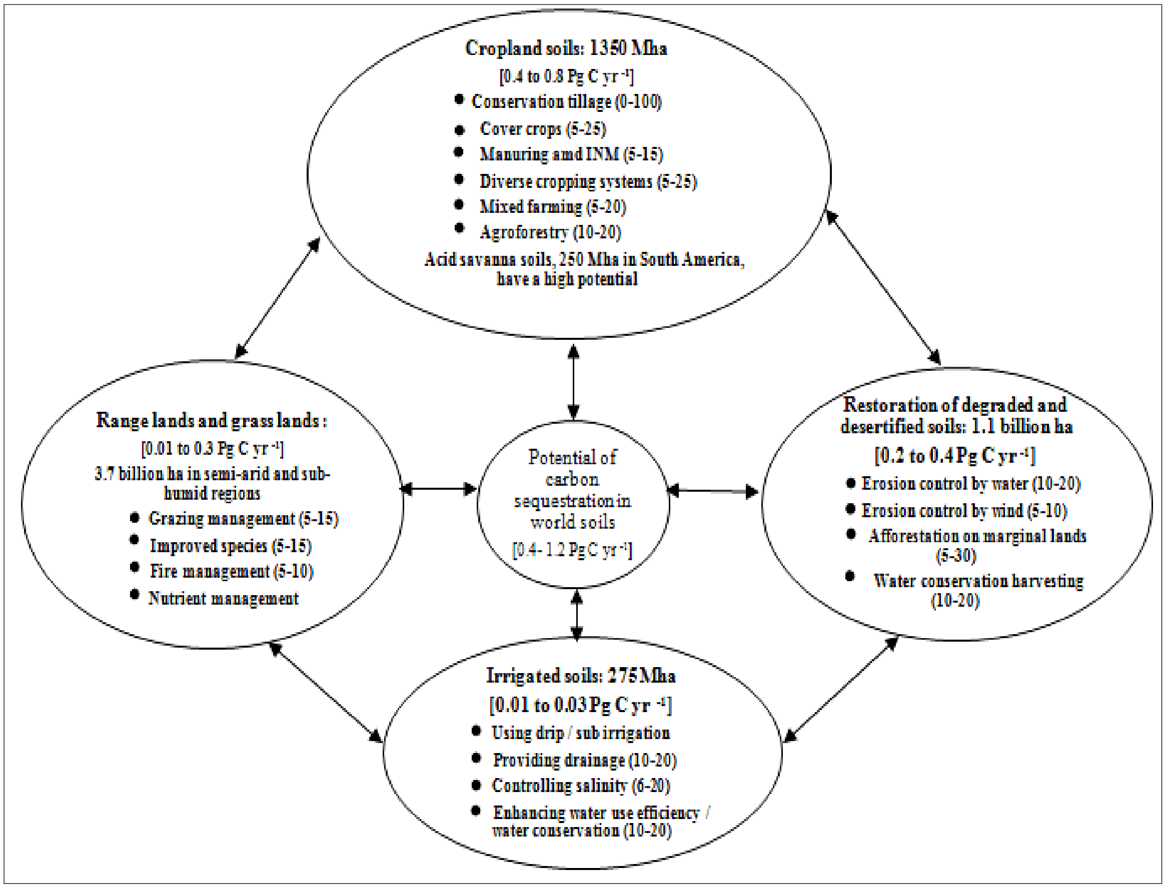


Figure 2.5: Soil carbon sequestration potential of cropland, grazing/rangeland, degraded /desertified and irrigated soils. C sequestration rates (g C m$^{-2}$ y$^{-1}$) Source: Redrawn from Lal (2004).

### 2.3.5 Agricultural systems and practices in West Africa

Agricultural systems refer to the patterns of cultivations which have resulted from man's use of agricultural lands based on environmental limitation. Several methods have been adopted by different groups of people for producing crops and livestock to meet their needs and the primary land resources involved are climate, vegetation, soil, and water.

Noe (1988) asserts that within the tropics the major kinds of cropping practices are driven by rainfall patterns, i.e., arid, semiarid, and humid tropics. In general, there are two distinct agricultural systems; crop production systems based on plant elements and livestock production systems based on animals and generally these are not fully integrated in the sub region except where small animals like sheep and goats are kept by farmers. The systems of agriculture adopted are influenced by land tenure, topography and climatic conditions, social and economic place of farming in the community as well as superstitions and religion custom (Youdeowei *et al.*, 1986).

The major systems of farming prevalent in the humid tropics are traditional, transitional and modern farming systems (Figure 2.6). These systems are in a state of transition; short fallow periods are converting to permanent land-use, low intensity to high intensity; rain fed to irrigated farming whilst natural regeneration of soil fertility through fallowing is now being replaced with intensive manure and fertiliser inputs.

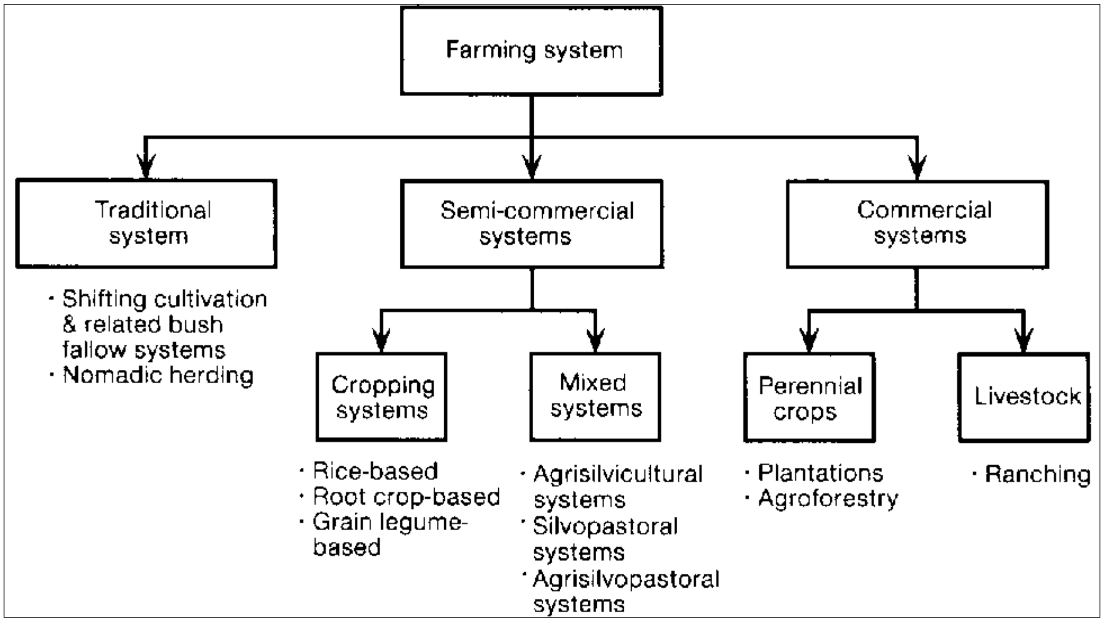


Figure 2.6: Predominant farming systems in the humid tropics Source: Lal (1995)

Although these transitions are gradual, they likely to continue under pressure from human population increase which impose a greater demand for food and other agricultural products. Rapid urbanisation continues to attract labour away from agriculture and encourages intensification whilst technical progress has raised the demand for agricultural raw materials and changed the outlook of farmers from subsistence to commercial production with the aim of maximising income (Youdeowei *et al.*, 1986).

#### *2.3.5.1 Characteristics of agricultural systems in West Africa*

The main characteristics of agricultural systems in West Africa and in the tropics are summarised as follows after Youdeowei *et al*. (1986);

i. Farm size is usually small although large scale group and corporation farms are being developed;
ii. Farm work is mainly done with human labour using simple farm tools.
iii. Use of animal power for farming operations may be limited due to separation of animal and crop husbandry;
iv. Use of fuel-powered implements for farming operations is limited due to small sizes of farms except in few large-scale commercial farms or cooperatives;
v. Permanent cultivation is restricted to homestead farms and tree crops;
vi. Mixed cropping is widespread;
vii. Root, tuber and tree crops dominate wetter forest belts whilst grain crops are associated with the farming systems of the grassland or savannah belts;
viii. Cropping is almost entirely dependent on rainfall or rain fed agriculture;
ix. Burning is widely used as a means of clearing the land;
x. Chemicals are widely used in more progressive crop production because of cost;
xi. Soil fertility is maintained by regular fallowing or application of manure in the form of household and animal refuse on heavily cropped homesteads farms and gardens;

xii. Livestock production is kept on free range. Farm animals are fed on fodder whilst kitchen waste provides food for the farm animals kept in the homestead and

xiii. The level of capital investment is extremely low since the primary objective of most farmers is subsistence.

#### *2.3.5.2 Major cropping systems in West Africa*

Some of the main cropping systems practiced in various parts of West Africa including Ghana are continuous cropping, shifting cultivation, crop rotation, mono cropping, mixed cropping/multiple cropping, mixed farming and pastoral farming. Continuous cropping involves putting a piece of land under cultivation from year to year. Crops planted may be annuals or perennials and the system is common in areas of high population densities where there is land hunger. Farmers may often use fertilisers and organic manure to improve soil nutrient status.

Shifting cultivation refers to a system where a piece of land is cultivated continuously for two to four years or a plot of land large enough to supply the family's needs is cultivated continuous until soil fertility declines. The farmers then move to another plot leaving the first plot to fallow through regeneration of the natural vegetation to restore fertility (Youdeowei *et al.*, 1986). The main advantages of the system include disease and pest control, low expenditure or capital input particularly on subsistence level and erosion control through nutrients cycling. With growing population and increasing land demand, the system is not suitable as fallow periods are short or absent and this may lead to due to loss of fertility or land degradation. This system destroys forests and native ecosystems due to repeated land clearance with negative implications on soil nutrients (carbon sequestration) whilst burning during land preparation may lead to lose of human lives and depletion of soil fertility by continual removal of crop products may lead to soil erosion and degradation. These adverse and negative effects have been the basis of rethinking about continuous cultivation in the humid tropics (Goodland, 1991).

Crop rotation is the system where different crops are grown continually on the same piece of land in such a way that they follow in a definite sequence or cycle for several years without loss of soil fertility or reduced yields. Crop rotation is an art and therefore crops combination on of piece of land follow a particular sequence and principles. In planning a rotation, it is essential to select crops on the basis of their relationship to each other. Relations could be complementary, or supplementary rather than competitive. The main advantages include maintenance of soil moisture and fertility, erosion, pests, weeds and soil-borne diseases control and safety against total crop failure. Perhaps, the possible drawback of the system is the high cost of establishment, stumping for instance can be expensive particularly in the forest zone (Youdeowei *et al.*, 1986).

Mono-cropping is the practice of growing one crop to maturity on a piece of land. The system may apply for both annual crops and perennials. It is not a common practice in the tropics except in plantations of perennial crops such as rubber, oil palm and cocoa or annuals like swampy rice, sugar cane or large scale production of grains (eg. Maize). This system is sometimes called monoculture**,** the practice of growing the same crop on the same piece of land from year to year. This system is common in rice and sugar cane production. Although the system can be mechanised and could lead to specialisation and better yield both in quality and quantity, it is risky especially in the event of crop failure or over production leading to lower prices or soil exhaustion could lead poor yield. Losses in this system may be quite high due to the high investments.

Mixed cropping or multiple cropping refers to the practice of growing two or more crops simultaneously on the same piece of land. Examples include guinea corn, early and late millet, yam and guinea corn intercropping, cotton with guinea corn and millet and okro, plantain and cocoa. Mixed cropping may involve intercropping; planting short-term annuals with long-term annual or biennials and harvesting before the main crop, inter-planting, planting long-term annuals or biennials through short-term annuals, relay planting; following one crop with another immediately before harvesting the former crop or phased planting, which is arranging planting dates systematically to ensure continuous sequence of crop growth and harvesting. The system reduces risk of crop failure and susceptibility to diseases and pests; permits phased harvesting and distribution work involve and suppresses weeds as well as providing a reasonable soil cover to protect the soil against erosion. The system can a suitable adaption against the negative effects of climate change as crops adapt to changes in weather and soil conditions because the demand for water and nutrients differ and the variation in height and spread of crops ensure efficient use of light energy. The system however, can be time consuming and labour intensive.

Other cropping system include mixed farming which is the integration of animal husbandry and crop production on the same farm such that apart from regular income generation, animal feed are obtained cheaply from crop residues and livestock wastes are used as manure, pastoral farming which is a settled form of livestock farming where the major income to the farmer is obtained solely from the keeping of livestock and ley farming, the practice of alternating pasture with arable crop production.

### *2.3.5.3 Common land preparation and management practices*

All cropping activities begin with clearing land of existing vegetation for planting. It is important to distinguish between manual slash and burn land preparation, conservational or no tillage, and mechanical tillage land preparation. The method adopted depends on a host of factors including culture and tradition, size of farm and capital outlay of farmers. The soils in the tropics are extremely prone to intense rains and harsh climate such that soil disturbance through land preparation exposes the soil to climatic elements which degrade the soil structure and accelerate soil erosion. During land preparation and soil turnover, it is important to minimise soil disturbance and keep the soil surface covered to reduce soil exposure and susceptibility to erosion (Lal, 1995).

The slash and burn is a typical manual method of land preparation in the tropics which generally involves clearing herbaceous undergrowth, shrubs and bushes, followed by burning the debris and killing some trees to reduce shade. It is a common practice in shifting cultivation, as it is a practical way of preparing land after long fallow periods accumulates enormous vegetative growth. Usually, it involves no tillage and sowing is done after land clearance by controlled burning (Cerri *et al.*, 2007). This practice has the advantage of addition ash contains nutrients bound in plant tissues which readily available to planted crops. Additionally, the fire destroys harmful pests, disease organisms and seeds of weed and protects planted crops from possible damage. Notwithstanding, the burning destroys organic matter and reduces the potential for soil organic matter accumulation. It also releases volatile nutrients such as sulphur and nitrogen and are lost to planted crops and the ash can usually be blown away by wind or carried away by runoff water.

No-tillage which is a crop production system where soil is left undisturbed from harvest to planting except for fertiliser application is presumed to be the oldest system of soil management. With human improvement and development of more systematic agricultural systems, soil tillage or cultivation of the soil has become an accepted practice as a more suitable means of preparing land for plant growth (Cerri *et al.*, 2007). The common tillage practices include manual or minimum tillage (usually by hoe), animal power ploughing and conventional tillage methods (mechanical tillage) which involve mechanised implements where the land is ploughed and harrowed.

Ploughing slices and buries surface vegetation into the soil using implements such disc plough, mould board plough and rotary hoe and this usually followed by harrowing where large clods of soil resulting from ploughing are broken down with a disc harrow. Usually there is a time lag between ploughing and harrowing to allow vegetation to die and rot. No-tillage practices, however cause less soil disturbance and often result in significant accumulation of soil carbon (Schuman *et al.*, 2002) and consequent reduction of GHGs emissions, especially $CO_2$, to the atmosphere (Paustian *et al.*, 2000) compared to conventional tillage. The use mechanical tillage, such as the mouldboard plough for seedbed preparation or discing for weed control, can promote soil carbon loss by several mechanisms: they disrupt soil aggregates, which protect soil organic matter from decomposition (Soares *et al.*, 2005), they stimulate short-term microbial activity through enhanced aeration, resulting in increased levels of $CO_2$ and other gases released to the atmosphere (Kladivko, 2001) and mix fresh residues into the soil where conditions for decomposition are often more favourable than on the surface (Karlen and Cambardella, 1996). Tillage can also leave soils more prone to erosion, resulting in further loss of soil carbon (Lal, 2006).

Management practices involve practices undertaken to provide an ideal environment for sustainable crop production. Careful management of the soil is essential for crop production, i.e. good-quality produce and high yields. The objective of land management practices is to intervene in the relationship between the crop and its environment (soil) for the purpose of favouring crop growth and yield whilst maintaining the soil moisture and fertility on sustainable basis. Typical land management practices often conserve moisture, control weeds/pests and improve soil fertility. Examples include, use of cover crops, strip cropping, mulching, composting and manuring, fertiliser application, improved fallow and conservational tillage practices (Lal, 1995). Examples of agricultural practices to improve soil productivity and increase soil carbon stocks are summarised in Table 2.6

| Traditional Practice | Recommended Practice |
|---|---|
| Plough till | Conservation till or no-till |
| Residue removal or burning | Residue return as mulch |
| Summer fallow | Growing cover crops |
| Low off-farm input | Judicious use of fertilisers and integrated nutrient management |
| Regular fertiliser use | Soil-site specific management |
| No water control | Water management/conservation, irrigation, water table management |
| Fence-to-fence cultivation | Conversion of marginal lands to nature conservation |
| Monoculture | Improved farming systems with several crop rotations |
| Land-use along poverty lines and political boundaries | Integrated watershed management |
| Draining wetland | Restoring wetlands |

Table 2.6: Agricultural practices to increase soil carbon stocks and improve productivity
Source: FAO (2004)

### *2.3.5.4 Soil carbon measurement*

Whilst the above-ground biomass can be estimated using remote sensing (Goetz *et al.*, 2009), the measurement of soil organic carbon stocks over large areas is much more onerous and scaling from individual measurements to the landholder, project or landscape level is much more difficult. This is because SOC density can be highly heterogeneously distributed, as can soil horizons and bulk densities (soil density) (Cambridge Conservation Initiative, 2011). To obtain an accurate inventory of organic carbon stocks in mineral or organic soil, three types of variables must be measured: (1) depth, (2) bulk density (calculated from the oven-dried weight of soil from a known volume of sampled material), and (3) the concentrations of organic carbon within the sample (Pearson *et al.*, 2005). It is advisable to sample to a constant depth and maintain constant sample volume. This is not only cost-efficiency but also convenient and normally a 30cm probe is an effective measurement tool.

Pearson *et al.* (2005) has recommended the following steps for soil organic carbon determination;

- Undisturbed soil sample is collected by steadily inserting the soil probe to a 30cm depth. A rubber mallet is carefully used to fully insert the probe if soil is hard or compacted;
- Sample is carefully put in a plastic bag (cloth bag) after extracting the probe, making sure that no surface material is included as this can result in a serious overestimation of soil carbon stocks. In some cases samples may be partitioned into three horizons of 0-10cm, 10-20cm and 20-30cm;

- To reduce variability, four samples from each collection point of the sample plot (and sometimes the centre point) for carbon concentration analysis are extracted and bulked to obtain composite sample for the plot;
- At each sampling point, take two additional undisturbed aggregated samples are taken with cores of known volume for bulk density determination. Proper care should be taken to avoid any loss of soil from the cores when taking samples for measurements of bulk density and
- Finally, soil samples are then sent to the laboratory for analysis using standard techniques.

Samples are carefully prepared in the laboratory and analysed for bulk density and carbon concentration by following commonly accepted standard procedures with respect to sample preparation such as mixing and sieving, drying temperatures and carbon analysis methods. For bulk density determination, samples should be oven dried at 105°C for a minimum of 48 hours. If the soil contains coarse, rocky fragments, the coarse fragments must be retained and weighed separately after sieving. For soil carbon determination, the material is sieved through a 2mm sieve and then thoroughly mixed. The well-mixed sample should be air-dried and the total soil carbon is then determined using the Walkley-Black method. The bulk density (BD) is then calculated for the mineral soil core and together with the carbon concentration (C) data obtained from the laboratory (expressed as decimal fraction) and soil sample depth, the amount of carbon (C) per unit area is determined (Pearson *et al.,* 2005).

## 2.4 Concept of Climate, Climate Variability and Climate Change

The IPCC (2007a) defines climate as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO). The relevant quantities are most often surface variables such as temperature, precipitation and wind.

More precisely, climate can be viewed as concerning the status of the entire Earth system, including the atmosphere, land, oceans, snow, ice and living things that serve as the global background conditions that determine weather patterns (Figure 2.7). These elements determine the state and dynamics of the Earth's climate and typically, there are both natural and human factors that influence the climate system, their processes and interactions (IPCC, 2007a). The interactions of the atmospheric systems are so complex that climatic conditions are never exactly the same at any given location from one time to the next. This is due not only to the natural processes in the atmosphere but also anthropogenic activities. Hence, climate is variable and is highly predictable although relatively slow**.**

Climate variability refers to variations of climate conditions over wide range of time scales with an average or mean climate that is stationary usually measured by deviations or departures from the average termed anomalies (Glantz, 2003). Climate change on the other is defined as the long-term major changes in the climate average conditions such as global temperature and precipitation due to natural variability and/or human activities (IPCC, 2007a). This definition differs slightly from the one given by the United Nations Framework Convention on Climate change (UNFCCC, 1992) which is the change in climate attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural variability observed over comparable time periods. Thus the UNFCCC makes a clear distinction between climate change attributed to human activities which alter the atmospheric composition and climate variability attributable to natural processes. The concept of climate change has to do primarily with the alterations in atmospheric and oceanic temperatures, weather patterns and the entire hydrological cycle due to anthropogenic activities. Climate change is a long-term challenge, but one that requires urgent action now given the pace and the scale by which greenhouse gases are accumulating in the atmosphere and the risks of a more than 2°C rise in global temperature.

In fact currently, there is a clear and robust consensus among scientist (95 percent certainty) that human actions are the dominant cause of observed warming of the atmosphere since the mid-20th century leading to climate change (IPCC, 2013). According to the IPCC, (2013), the warming of the climate system is indisputable, with many of the observed changes such as warming of the atmosphere and the ocean, diminishing snow and ice, and rising sea levels being unprecedented over decades to millennia.

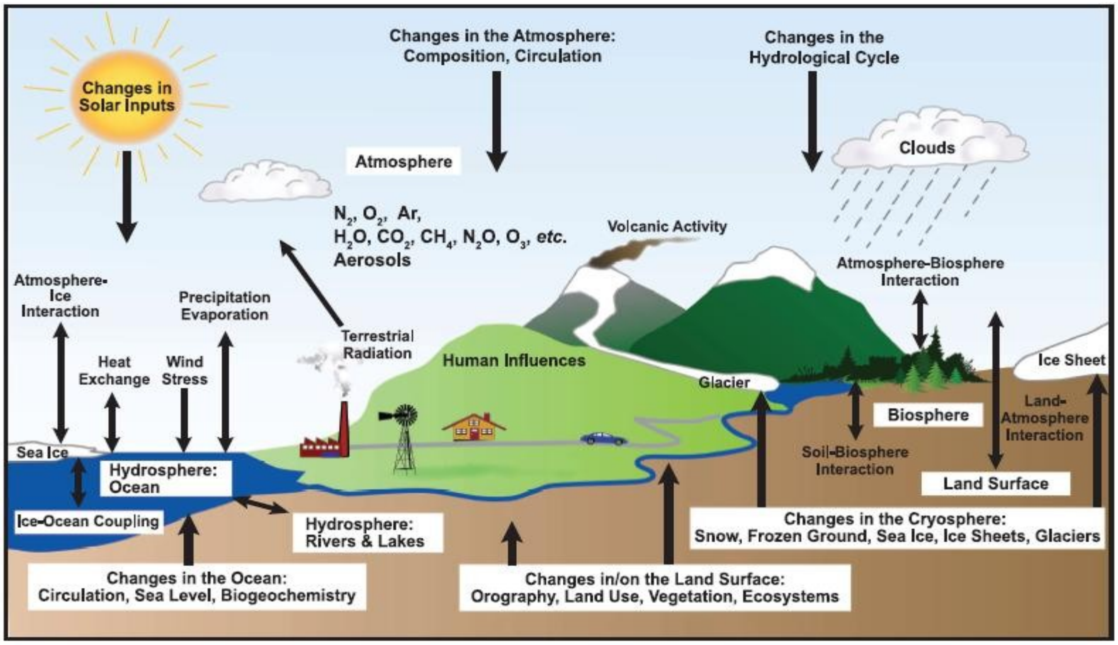


Figure 2.7: Complexity of the global climate system Source: IPCC (2007a)

The observation is that since 1850, each of the last three decades has been successively warmer at the Earth's surface than any preceding decade. With changes in climate, the Earth's average temperature is expected to increase leading to some weather phenomena becoming more frequent and intense (e.g., heat waves and heavy downpours), and others becoming less frequent and intense (e.g., extreme cold events).

### 2.4.1 Climate change and atmospheric greenhouse gases concentration

The variations in climatic conditions can be attributed to the natural and dynamic processes on the earth surface such as biotic processes, plate tectonics and volcanic eruptions and external forces including variations in sunlight radiations received by Earth. However, recent information reveals that climate change is largely human caused through activities which increase the concentration of GHGs in the atmosphere (IPCC, 2013) leading to the observed warming since the mid-20th century. Human-caused climate change has resulted primarily from changes in the amounts of greenhouse gases in the atmosphere, but also from changes in small particles (aerosols), as well as from changes in land-use. These have resulted in recent climate change, often referred to as "global warming".

In fact, from the end of the last Ice age (about 10,000 years ago) till the end of the 18th century, the levels of GHGs in the atmosphere have remained fairly constant and at a level sufficient to sustain life. However, since the industrial revolution (about 200 years ago) human kind has been releasing unprecedented amounts of GHGs into the atmosphere which trap more heat amplifying the natural warming of the earth (IPCC, 2007a). According to Cunningham and Cunningham (2003), the GHGs concentrations are required to regulate atmospheric temperatures through a phenomenon called 'greenhouse effect', which is a natural process by which the Earth's surface temperature is maintained. Through 'green house effect', the GHGs act like a blanket or glass roof around the earth, trapping heat that would have otherwise escaped into space. It is an important mechanism within the climate system and without which the average temperature at Earth's surface would been below the freezing point of water (about -18 °C) making life on earth impossible (IPCC, 2007a). However, human activities, primarily the burning of fossil fuels, clearing of vegetation and land-use change, have greatly intensified the natural greenhouse effect, causing global warming. The most important GHGs are water vapour and carbon dioxide. Others include methane ($CH_4$), nitrous oxide ($NO_2$), Ozone, Chlorofluorocarbons (CFCs) and aerosols which are present in small amounts in the atmosphere (IPCC, 2007a). Table 2.7 provides the major GHG contributing to climate change and their main sources.

Table 2.7: Major greenhouse gases (GHG) contributing to climate change

| Greenhouse Gas | Human Source (Examples) | % of Total Global GHG Emissions (2010) |
|---|---|---|
| Carbon dioxide ($CO_2$) | Fossil fuel combustion, land-use changes, cement production, … | 76% |
| Methane ($CH_4$) | Fossil fuel mining/distribution, livestock, rice agriculture, landfills, | 16% |
| Nitrous oxide ($N_2O$) | Agriculture (fertilisers) and associated land-use change, … | 6% |
| Hydrofluorocarbons (e.g. HFCs) | Liquid coolants, … | < 1% |
| Perfluorocarbons (e.g. PFCs) | Refrigerant, electronics industry and aluminium industry, … | < 1% |
| Sulphur hexafluoride ($SF_6$) | Insulator in electronics and magnesium industry, … | < 1% |
| Nitrogen trifluoride ($NF_3$) | Electronics and photovoltaic industries, … | < 1% |

Source**:** Redrawn from UNEP (2012).

According to UNEP (2012) $CO_2$ is the most important anthropogenic GHG in terms of quantitative emissions, accounting for about 76 percent of total GHG emissions in 2010. In fact, among the many pieces of evidence of climate change is the breakneck rate of carbon dioxide accumulation in the atmosphere, coinciding with measured temperature rise (Figure 2.8). The growing concerns about climate change resulting from increased $CO_2$ concentration in the atmosphere have stimulated discussions about the importance and potential of carbon sequestration particularly from land-use and land management. Clearly, since the turn of the industrial revolution, atmospheric $CO_2$ concentration has risen steadily from 280 ppm during pre-industrial times (around 1750) to about 368 ppm by 2000 (Malhi *et al*, 2002) and to 390 ppm in 2011, with the current figure being almost 400 ppm (Global Carbon Project, 2012). This is largely attributed to emissions from human activities including burning of fossil fuel, cement manufacturing and biomass burning and land-use changes (Malhi *et al*, 2002; Global carbon project, 2012) which release over 8.5 billion metric tons of $CO_2$ (Cunningham and Siago, 1990) annually to the atmosphere.

The increasing atmospheric $CO_2$ concentration had led to an enhanced green house effect (about 40 % rise) and global temperature rise of about 1.1°C (2 °F) since $CO_2$ a recalcitrant polluter and therefore the species has the capacity to trap heat in the atmosphere and has longer atmospheric lifetime of between 5 – 200 years (IPCC, 2001). The report further revealed that the contribution of a trace gas to radiative forcing of climate change depends on a host of factors mainly the molecular radiative properties of the gas, the magnitude of the increase in atmospheric concentration and the atmospheric life-time of the gas once emitted. Table 2.9 provides several examples of GHGs and summarises their concentration between the pre-industrial era (1750) and 1998, their concentrations change during the 1990s and their atmospheric lifetimes.

Apart from industry, the carbon dynamics in terrestrial ecosystems is one major factor affecting $CO_2$ concentration in the atmosphere (Houghton, 1999; IPCC, 2001). Changes in agriculture and other land-uses had greatly influenced $CO_2$ emissions and global warming. These changes can also contribute to local and regional climate change as well as to global climate warming due to deforestation (Houghton, 1999).

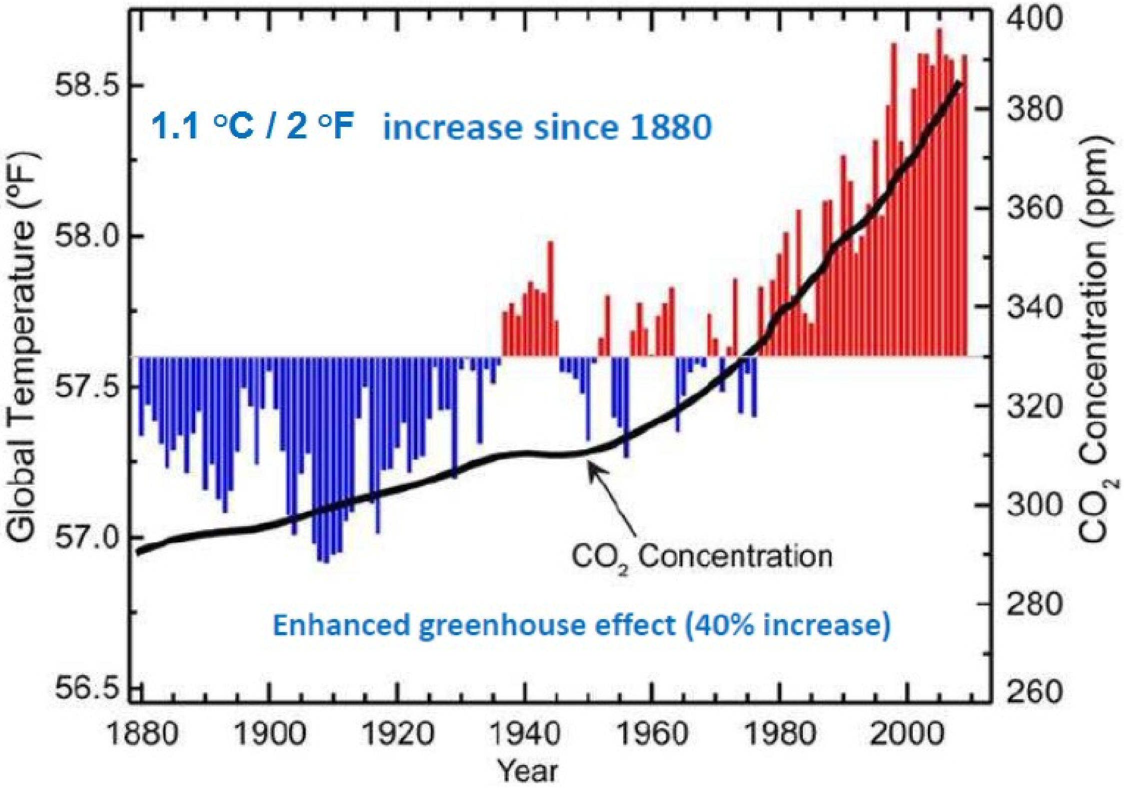


Figure 2.8: Global temperature and atmospheric $CO_2$ concentration
Source: NOAA/NCDC (2009).

According to Stephens *et al.*, (2007) tropical terrestrial ecosystems across the African continent play an increasing role in the global carbon (C) cycle with potentially significant climate change implications. Thus, quantifying carbon stocks in tropical ecosystems is crucial for understanding the global C cycle, formulation and evaluation of climate change mitigation measures, and the management of ecosystems for C sequestration (Sierra *et al.*, 2007).

Consequently, efforts to reduce the concentration of $CO_2$ gas in the atmosphere have been an important consideration in many studies for informed climate change mitigation decisions. Land-use management in international climate change agreements is a viable option to mitigate the build-up of atmospheric GHGs is noteworthy. Land-use based mitigation initiatives such as reducing emission from deforestation and degradation (REDD), clean development mechanisms (CDM) and climate smart agriculture (CSA) should be thoroughly explored for their potential implementation particularly in the tropics as they have the potential to simultaneously contribute to climate change mitigation and development in local communities.

Table 2.8: Atmospheric lifetime of greenhouse gases affected by human activities

| | $CO_2$ (Carbon Dioxide) | $CH_4$ (Methane) | $N_2O$ (Nitrous Oxide) | CFC-11 (Chlorofluoro-carbon) | HFC-23 (Hydrofluoro-carbon-23) | $CF_4$ (Perfluoro-methane) |
|---|---|---|---|---|---|---|
| Pre-industrial concentration | about 280 ppm | about 700 ppb | about 270 ppb | zero | zero | 40 ppt |
| Concentration in 1998 | 365 ppm | 1745 ppb | 314 ppb | 268 ppt | 14 ppt | 80 ppt |
| Rate of concentration change [b] | 1.5 ppm/y [a] | 7.0 ppb/y [a] | 0.8 ppb/y | -1.4 ppt/y | 0.55 ppt/y | 1 ppt/y |
| Atmospheric lifetime | 5 to 200 y [c] | 12 y [d] | 114 y [d] | 45 y | 260 y | >50,000 y |

Source: IPCC (2001)

[a] Rate has fluctuated between 0.9 ppm/y and 2.8 ppm/y for $CO_2$ and between 0 and 13 ppb/y for $CH_4$ over the period 1990 to 1999.

[b] Rate is calculated over the period 1990 to 1999.

[c] No single lifetime can be defined for $CO_2$ because of the different rates of uptake by different removal processes.

[d] This lifetime has been defined as an adjustment time that takes into account the indirect effect of the gas on its own residence time.

### 2.4.2 Climate change and global carbon cycle

Carbon is sometimes considered the element of life, since all living cells and organic molecules contain carbon. Carbon exists in everything that is living or has ever lived. Carbon is stored on the planet in the following major reservoirs: (i) as organic compounds (e.g. sugar, starch) in living and dead organisms in the biosphere; (ii) as the gas carbon dioxide ($CO_2$) mainly with minor amounts present as methane ($CH_4$), carbon monoxide (CO) and other gases in the atmosphere; (iii) as organic matter in soil; (iv) in the lithosphere as fossil fuel and sedimentary rocks such as limestone (including chalk) and dolomite; (v) in the oceans as dissolved hydrocarbons and as calcium carbonate in the shells of marine creatures (e.g. coral).

The carbon cycle is therefore a perpetual cycling of carbon on Earth, in its various forms (such as $CO_2$ and $CH_4$), between the atmosphere, hydrosphere, biosphere, pedosphere and lithosphere. The global carbon cycle shows the stores and fluxes (exchanges) of carbon between them. Through photosynthesis, autotrophic organisms (green plants, algae, and cyanobacteria) absorb carbon dioxide, light and water to produce carbohydrate for energy with oxygen as a by-product. The carbon stored in plant tissues are released to animals and humans when eaten. Carbon is released back to the environment when plants and animals die. Fossil fuels which are formed from remains of dead organic matter also contain carbon. Carbon can therefore, be stored over relatively shorter periods in living organisms (i.e. plants and animals), over thousands of years in the oceans but can be stored over millions of years in rocks or fossils. When fossil fuels and plants are burnt, they release considerable amount of carbon to the atmosphere. Carbon dioxide is also emitted from volcanoes, hot springs, and geysers; and freed from carbonate rocks by dissolution. These activities help to regulate the global carbon cycle and until humans used fossil fuels for energy, the carbon cycle was relatively balanced (i.e. the total amount carbon in the atmosphere stayed constant).

However, humans are affecting the carbon cycle by removing carbon from the long-term storage under-ground (oil, gas, etc.) and putting it into the atmosphere. Humankind is increasingly influencing the carbon cycle through the burning of ever-greater quantities of oil, gasoline and coal and the cutting down of forests. Also removing stored carbon through deforestation and land-use changes have further exacerbates this process (UNEP, 2009).

Humans have therefore, tipped the balance of the carbon cycle, which in turn affects the global climate. It is argued that the human-induced accumulation of $CO_2$ and other GHGs in the atmosphere is driving climate change. Houghton *et al.* (2001) assert that current rates of atmospheric $CO_2$ accumulation are unprecedented and are likely to be 20-million-year high. The perturbation of the global carbon cycle due to anthropogenic activities, averaged globally for the decade 2004–2013 (Gt $CO_2$ $y^{-1}$) is shown in Figure 2.9. Clearly, over 32.6 of $CO_2$ are added to the atmosphere annually from anthropogenic fossil fuel burning and cement manufacturing alone. Land-use changes account for about 3.3 of $CO_2$ compared to annual respective oceanic and land sinks of 10.6 and 9.5 (Gt $CO_2$ $y^{-1}$) of $CO_2$. The result of these perturbations is an atmospheric $CO_2$ concentration build up of 15.8 (Gt $CO_2$ $y^{-1}$) within the last decade (Le Quéré *et al.*, 2014).

The terrestrial ecosystems, in which carbon (C) is retained in the live biomass, decomposing organic matter, and soil, serves as reservoir of carbon and thus plays an important role in the global carbon cycle. It is estimated that the Earth's vegetation and soils currently contain the equivalent of approximately 7500 Gt of $CO_2$ – that is more carbon than is contained in all the remaining oil stocks on the planet and more than double the total amount of carbon currently in the atmosphere. The land biosphere plays an important role in the carbon cycle and climate system such that uptake reduces the rate of atmospheric $CO_2$ build-up and associated climate warming whilst deforestation, fire activity and poor land-use management release $CO_2$ to the atmosphere.

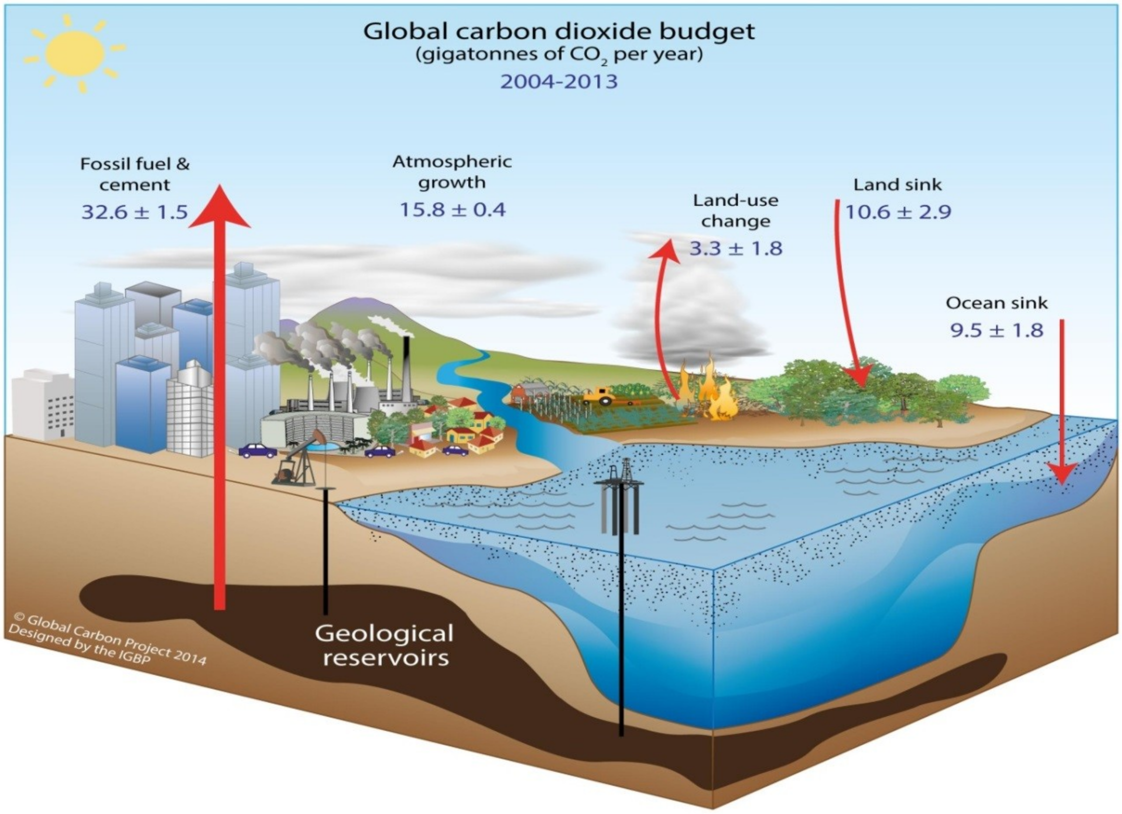


Figure 2.9: Anthropogenic perturbation of the global carbon cycle Source: Le Quéré *et al*. (2014)

For instance, Le Quéré *et al.,* (2012) observes that although the global net $CO_2$ emissions from land-use change, including deforestation, are more difficult to update annually due to data availability, the combined evidences from land cover change data, fire activity in regions undergoing deforestation and models suggest that the net emissions in 2011 were 0.9 ± 0.5 Pg C $y^{-1}$ whilst the global atmospheric $CO_2$ concentration has reached 391.38 ± 0.13 ppm at the end of year 2011, representing an increase of 1.70 ± 0.09 ppm $y^{-1}$ or 3.6 ±

0.2 Pg C $y^{-1}$ in 2011. Again, in 2011 estimates from oceanic $CO_2$ sink was 2.6 ± 0.5 PgC $y^{-1}$, implying that the global residual terrestrial $CO_2$ sink was 4.1 ± 0.9 Pg C $y^{-1}$ (Le Quéré *et al.,* 2012). This implies that the carbon in terrestrial ecosystem exists in dynamic soil and vegetation pools which vary in amounts and cycle with the global atmosphere at varying rates. These stocks and fluxes play important roles in global carbon regulation and in the maintenance of goods and services. Changes in land cover or ecosystems result in increased or decreased fluxes to the atmosphere and play a major role in climate regulation.

The atmosphere, ocean, vegetation and soil on the land surface act as net sinks, but the greater proportion (44 %) of $CO_2$ emissions from anthropogenic sources remains in the atmosphere with negative implications on global climate system (Figure 2.10).

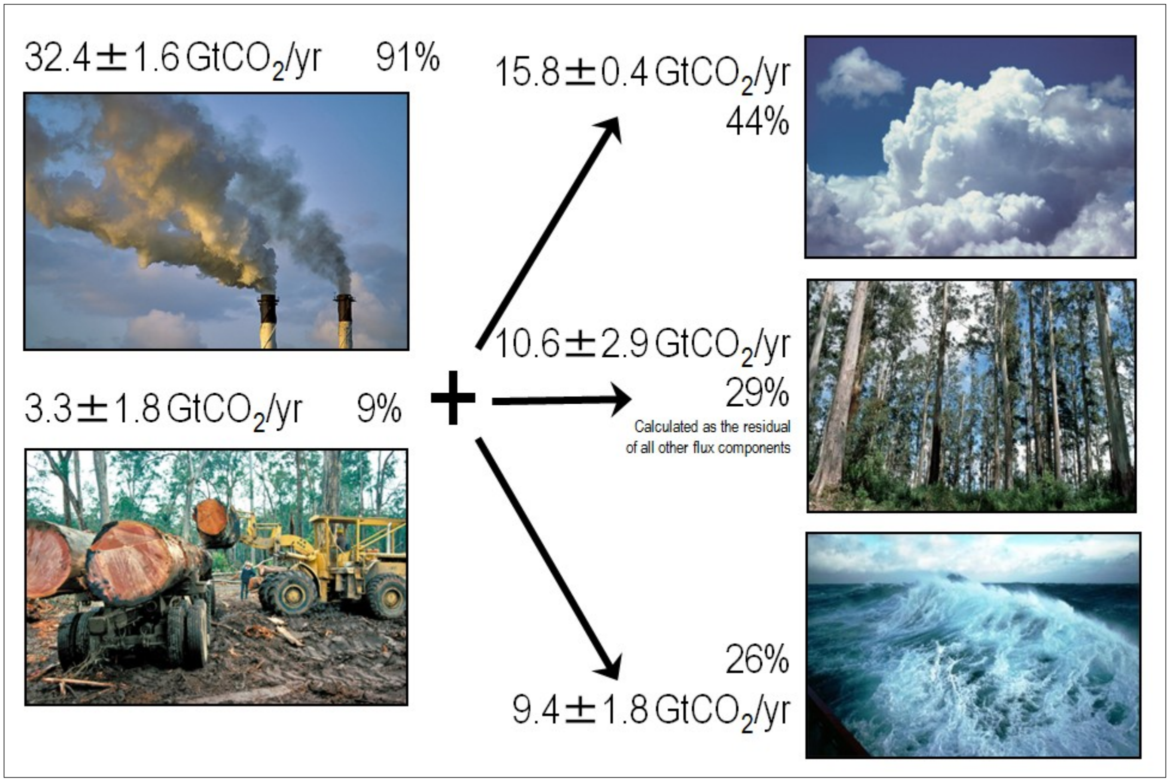


Figure 2.10: Fate of anthropogenic $CO_2$ emissions (2004-2013 average) Source: Le Quéré *et al.* (2014)

Recent studies suggest the C sinks have continued to grow with increasing emissions; but it is uncertain how efficient the sinks will be in the future in the face of the changing climate given the pace and scale by which greenhouse gases are accumulating in the atmosphere and the risks of over 2 °C temperature rise (Le Quéré *et al*., 2012).

### 2.4.3 Impacts of climate change in West Africa

Climate change impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system (IPCC, 2014). Climate change impacts and risks are unevenly distributed and are generally greater for poor and disadvantaged people and communities at all levels of development. Impacts may depend on a number of factors including socio-economic details, technologies available and dependence on natural resources as well as the policies and institutions governing them (Dessler and Parson, 2006). The people and communities in West Africa are particularly vulnerable to the risks of climate change due to the high dependence on natural and environmental resources as well as lack of coherent policy on climate change, and a related lack of monitoring, evaluation and reporting systems (UNEP, 2014). These risks are also exacerbated by population increases which put more pressure on natural resources.

In the West Africa, climate change is predicted to impact directly on human health and lives through thermal stress, death or injury in floods and storms and indirectly through changes in the ranges of disease vectors (e.g. mosquitoes) water-borne pathogens, water quality, air quality and food insecurity (IPCC, 2014). It is also predicted to impact on agriculture and livelihood and land-use systems as well as terrestrial, freshwater ecosystems and freshwater resources availability thereby creating extreme poverty, food insecurity and hotspots of hunger particularly in rural areas (IPCC, 2014). Other impacts includes loss of biodiversity due to invasive alien species, destruction of habitats mainly from deforestation, destruction of protected or conservation areas, land clearance and poaching, overexploitation and unsustainable land-use management. These affect the social fabric of communities in the Sudan and Sahel ecological zones (UNEP, 2014). Increased incidence of land and soil degradation and desertification may result from increases in extreme events, such as flash floods and droughts, inadequate communal land tenure systems and uneven distribution of water, soil erosion and loss of soil fertility and unsustainable farming practices. Contamination of soil, groundwater and surface waters, due to industrialisation, and urbanisation may lead to degradation of land quality (UNEP, 2014).

Predicting the magnitude and occurrence of changed weather patterns resulting in global warming, floods and droughts and developing mitigation and adaptation strategies as well as finding sustainable ways of limiting the growth of GHG emissions whilst pursuing the regions development agenda remains a major challenge confronting the sub-region. Regardless of mitigation and adaptation activities implemented today or in the near future, the planet will still experience a certain degree of change due to historical emissions (e.g. $CO_2$) and inertia in the climate system. Sea level rise, melting of the polar ice caps and increased frequency of severe fires, pests and storms are some of the effects that have already been attributed to changes in climate and its variability (IPCC, 2007a). Some of these phenomena have caused serious social stress and have shown the need to be better prepared for future changes. Because of this, it is essential that individuals, societies and institutions are aware of the likely changes and have strategies in place to adapt to a changing climate.

# 3. MATERIALS AND METHODS

## 3.1 Introduction

This chapter describes the study area including the sites locations, climatic conditions and the biophysical parameters of the sites. It also describes in detail the experimental procedures for data collection and analysis.

## 3.2 Experimental Site Location and Description

The study was conducted at Sumbrungu which is located within the Vea catchment, about 35 km from Bolgatanga, in the Upper East Region (UER) of Ghana (Figure 3.1). It lies on latitude $10^{o}$ 50′N and longitude $00^{o}$ 54′ W. The UER is bounded on the North and East by Burkina Faso and Togo respectively, in the South by the Northern Region, and in the West by the Upper West Region. The other Vea communities are: Vea, Gowrie, Zaare, Yorogo, Yikene, Dindubiisi, Bongo-Nyariga and Bolga-Nyariga.

### 3.2.1 Location and size of Vea catchment

The Vea catchment is a sub-basin of the White Volta basin and it falls within the Sudan Savannah Agro-ecological zone of Ghana. It is located at the border of Ghana and Burkina Faso, extending over an area of about 305 $km^2$ between longitude 0° 45’W to 1° 00’ W and latitude 10°42’30’’N to 11°02’30’’ N (Figure 3.2). The Ghana portion of the Vea experimental site is found in the Upper East Region spanning the Bolgatanga Municipal and Bongo District with average population densities of 156 and 164 persons per square kilometre respectively. The smaller portion of the catchment is located within south central portion of Burkina Faso crossing the Zecco and Zion Districts in the Nahouri province The catchment, highlighted red (Figure 3.2), is a semi-arid agro-climatic domain and spans three agro-ecological zones namely the Sudan and Guinea savannah zones (Northern Ghana) and the Sudanian zone of Burkina Faso (Ibrahim *et al.,* 2013).

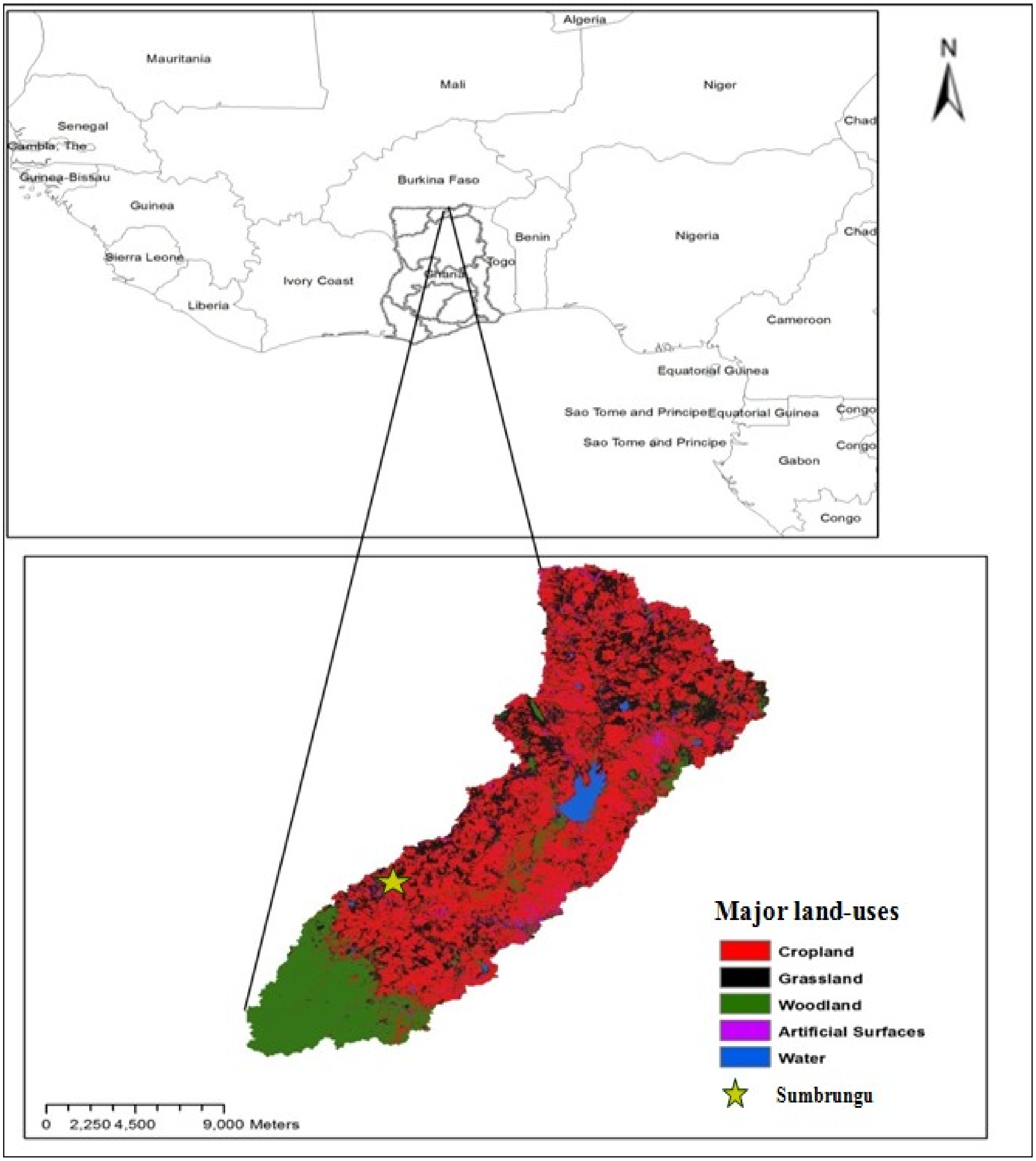


Figure 3.1: Map of Ghana showing the study area, Sumbrungu, in the Vea catchment, Upper East Region

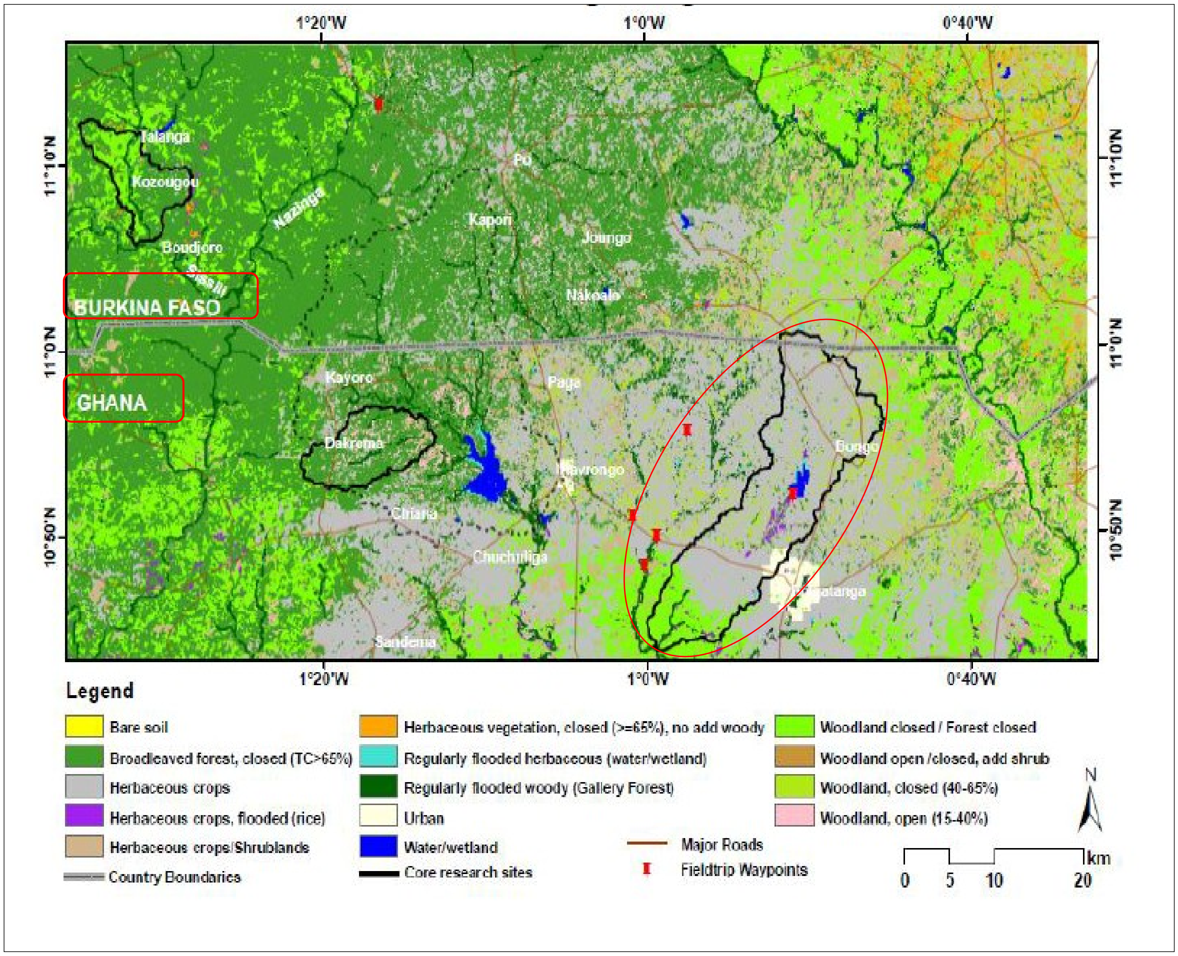


Figure 3.2: Location of Vea catchment site between Ghana and Burkina Faso Source: Ibrahim *et al.* (2013)

### 3.2.2 Climate

The semi-arid northern savannah catchment has tropical continental or interior savannah climate, largely influenced by the tropical continental air mass (Gyasi *et al.,* 2006). It is characterised by drier and hotter weather and longer sunshine duration. The rainfall is uni-modal with mean annual amounts ranging between 950-1000 mm distributed between May-October with prolonged dry season usually from November to April (MoFA, 2011). The entire region is characterised by pronounced wet and dry seasons as monthly rainfall gradually increases during the rainy season, then falls off sharply. Usually, considerable variations exist between successive rainy seasons in time of onset, duration and amount of precipitation and therefore the region has more distribution of small irrigation dams than any other parts in Ghana (MoFA, 2011).

Temperatures are high and fairly uniform throughout the year. The mean annual temperature is about 28-29$^{o}$C, and shows very little variation from year to year (Gyasi *et al,* 2006). Averagely, relative humidity (RH) is fairly moderate, about 54.6 percent. It is high during the rainy season and early mornings but very low, about 20 percent during the dry season. The season of high humidity extends from April to the end of October, during which period the humidity ranges from 69 – 95 percent (Gyasi *et al*, 2006). The region is characterised by daily evapo-transpiration of 4.5 mm (Pan-Man $ET_o$ = 4.5 mm/day), with an annual estimate of between 1652-1720 mm and 0.60 annual aridity index the potential evapo-transpiration (PE) is estimated at 2182 mm (Gyasi *et al.,* 2006). The relatively high temperatures here result in high potential evapo-transpiration and increases mean annual water deficit.

### 3.2.3 Geology and soils

In terms of geology, the entire region belongs to the savannah high plains and is therefore dominated broadly by the Voltaian formation, the Birimian and its associated granite rock formations. The Voltaian formation consists mainly of sandstone, shale, arkose, mudstone, sandy and pebbly beds and limestone. The Birimian formation is part of the basement complex and consists mainly of gneiss, phyllite, schist, migmatite, granite-gneiss and quartzite (Gyasi *et al.,* 2006). Generally, the basin is characterized by wide and almost flat plains in its lower parts and by undulating hills at elevations of between 60 and 80 m in its upper section. The soils here form part of the so-called Bongo soils or Bongo association comprising the Bongo series, Vea series, Yorogo Series, Zoko series, Yaretanga and Akubu series. The soils used to be very productive due to high potash and phosphate content but they are now exhausted from extensive farming, over grazing and mismanagement. Generally, the Bongo soils consist of about three (3) inches of very slightly human stained, crumbly coarse sandy loam overlying reddish brown, fine blocky, very coarse sandy loam which may contain an incompletely weathered feldspar particles (BDA, 2006). Based on the FAO/UNESCO classification (1990), the major soils groups are Lixisols, Leptosols, Luvisols and fluvisols. They were developed either on steep slopes over Bongo granites (Tongo and Bongo series), middle and lower slopes (Vea and Yorogo series) or in bottom of valleys (Yaretanga and Akurubu series). The nature of the soils depends on the geological processes that led to formation of rocks and the subsequent weathering of such rocks. Soils occupying large tracts of land on middle and upper slopes and less frequently on summits are shallow, moderately well-drained and coarse textured those of the valley bottom are usually deep but poorly drained. According to Adu, (1969) soils developed over granites and sandstones have mainly light topsoils varying in texture from coarse sand to loamy and heavier subsoils varying from coarse sandy loams to clays with variable amounts of gravel. However, soils developed over basic rocks and most of those in valleys bottom have heavier topsoils and subsoils which are suitable for rice cultivation.

Typically, these soils have low accumulation of organic matter (about 2 percent) and low inherent fertility, due to the rapid decomposition from high temperatures, erosion and leaching of topsoil nutrients and frequent burning of lands. The soils also have low nitrogen content (Adu, 1969; Boateng and Ayamga, 1992). The dry climatic conditions have also resulted in the hardening of the subsoils to form iron-pans or laterites which are prone to weathering and being non-productive soils, they quickly become incapable of sustaining plant growth when vegetation is removed or burned. Again, as a characteristic of soils in savannah areas of Ghana, the soils in the Vea catchment have lower Cation Exchange Capacity (CEC) and pH values are generally low (about 5.0) whilst available phosphorus and potassium are similarly low - 4.7 and 10.8 mg $kg^{-1}$ respectively (Gyasi *et al.,* 2006). Their poor fertility status coupled with the erratic moisture regime makes the potential productivity of the soils in the area very low. Many soils contain abundant coarse material either gravel and stone, or concretionary materials which affect their physical properties, particularly their water holding capacity. Compaction mainly as a result of livestock trampling causes serious root restriction through the loss of pores and deterioration of structural properties. Consequently, bulk density increases causing delay in seed emergence, decrease in infiltration rate and increases runoff (Benneh *et al.*, 1990). The soil characteristics (chemical and physical) and rainfall pattern combine to influence vegetation cover and land-use pattern over time. The declining soil fertility of northern Ghana is leading to increasing agricultural intensification which has resulted in more exploitation of primary woodlands (Duadze, 2004).

### 3.2.4 Topography and drainage

Topography refers to the description of the physical features of the Vea catchment including the configuration of the ground, altitude, slope and aspect. It affects vegetation through its influence on climate and soil formation processes such as soil moisture and soil nutrient retention. The catchment lies in a relatively flat area with the exception of outcrops of granite and Birimian rocks (inselberg) near Bongo which rises to a height of between 92 and 122 metres above the surrounding area. The catchment area is generally low-lying with undulating areas and isolated gently rolling hills, rising up to 300 metres above sea level (asl) (Gyasi *et al.,* 2006). The land surface has levelled into erosion-plateau or tropical pediplains through chemical and physical weathering. The surface is currently quite flat with slopes less than 2 percent and mean altitude of about 196 m asl. The features of the hills vary but have generally steep rocky slopes and narrow deeply incised valleys (Gyasi *et al.,* 2006).

The main drainage system comprises the Atankuidi, Yaragatanga-Atanure and the Volta River. Basically, the area is drained by both the Red and White Volta basins (BDA, 2006). The Volta River originates from Burkina Faso and flows into the Atlantic Ocean. All the streams in the entire UER area are tributaries of the Volta system. The rivers are flooded during the rainy season but only the main river is permanent throughout the year. Most rivers and springs dry up towards the end of the dry season when they become scarce for those who depend on those sources.

At present the main sources of domestic water supply throughout the area are rivers, streams, ponds, dams, wells, boreholes, and spring or rain water. Boreholes and wells supply water to many towns and villages especially during dry seasons. The main sources of water for agriculture are rain, rivers, wells, and dam/dugout. Water stored in the dams/dugouts/water retaining structures is used to meet livestock and human domestic requirements during the dry season. The VEA provide some relief to people, but only a relatively few of them have access to this source of water (Gyasi *et al.,* 2006).

### 3.2.5 Vegetation, land-use and livelihood

The natural vegetation of the relatively low rainfall semi-arid savannah region is that of the savannah woodland characterised by short scattered drought-resistant trees and grass that gets burnt by bushfire or scorched by the sun during the long dry season and widely scattered shrubs. It is mainly dominated by cropland (herbaceous crops-flooded), woodland (closed and open), and grasses (graze-land). There are also other land cover classes such as broadleaved forest (closed ones), regularly flooded gallery forest and herbaceous water/wetland, bare soil and urban areas or dwelling units with relatively less ground area coverage. Human interference with ecology is significant, resulting in near semi-arid conditions. The dominant tree species are the shea tree (*Vitellaria paradoxa*), dawadawa (*Parkia biglobosa*), boabab (*Adansonia digitata*) kapok (*Ceiba pentandra*) and acacia (*Acacia albida),* whitethorn (*Faidherbia albida*), *Anogeissus leiocarpus, Tamarindus indica, Mangifera indica* with a ground cover of grasses such as *Andropogon gayanus, Brachiaria lata, Sporobolus pyramidialis*, *Pennisetum pedicellatum* and *Stylosanthes erecta*. The tree species appear to have a high rate of regeneration and may be more resistant to the annual bush fires (MoFA, 2011). The few forest reserves include the so called 'gallery forests' along the banks of rivers. There are also number of forest plantations with exotics such as teak, and Cassia spp.

Economically, the inhabitants are poor. The main economic activity in the study area is small holder agriculture which is practiced by about 78% of the population and comprises the cultivation of food staples such as millet (*Pennisetun glaucum*), sorghum /Guinea corn (*Sorghum bicolar*), maize (*Zea mays*), beans (*Phaseolus vulgaris*), groundnuts (*Arachis hypogea*) and rice (*Oryza sativa and Oryza glaberima*) (MoFA, 1998).

Other important economic activities in the study area include livestock rearing, small scale fishing, hunting, charcoal making, handicrafts and basket weaving and gathering (Tripp 1992). The livestock include pigs, cattle, goats, sheep, donkeys, dogs and birds such as guinea fowls, chicken, ducks, turkey and pigeon (Blench, 2006). Laube, (2007) observed that whilst these livelihood activities directly supplement household food requirements, prey, fish and fruits are also sold at local markets. Petty trade, mostly by women, in agricultural produce, processed foodstuffs and beverages, as well as petty industrial commodities, is an additional source of income in most peasant households, whilst some men engage in the profitable long-distance trade of animals (Tripp, 1992).

In general, the Upper East Region is one of the most densely populated areas in the country. The population density within the study area, excluding the mountain areas, could amount to about 200 persons per square kilometre. It has also been observed that a wide array of social institutions, such as norms and values that enhance redistribution, reciprocity and solidarity in times of need, for instance through the sharing of land, labour and food, seed lending, reliance on in-laws and the redistribution of foodstuffs through funerals, have helped local farm households to sustain their subsistence life style even in a difficult environment (Laube, 2007). The catchment is important for agriculture production as the Vea dam provides opportunities for farming all year round. As a result, the catchment has undergone massive land-use conversions with consequent deteriorating soil quality, crop productivity and land degradation.

The land-use pattern at the study sites (communities) in Sumbrungu clearly demonstrates a good understanding of local people about their landscape after several years of cultivation. In general, the entire upland area is dedicated to cropping mainly groundnuts which are sometimes intercropped with ‘bambara beans’. The upland areas left uncultivated are dominated by grasses which are fed by livestock and commonly called graze-lands. A few of such lands are not dedicated grazing sites but sometimes cropping sites which are left to fallow due to a number reasons ranging from fertility decline, lack of farm hands or inadequate planting materials. The mid-slope areas also follow the same trend as the upland areas dedicated entirely to cropping of groundnuts intercropped with beans whilst the fallow areas are dominated by grasses used by grazing animals.

However, the pattern of land-use in the lowland areas is quite different from the upland areas. The fertile areas are dedicated to planting of the main staple crops such as sorghum which is intercropped with millet. There may also be cover crops such as *'sama', local* potatoes or okro mixed with millet and guinea corn. Millets can be early or late depending on variety. Some parts of the lowland areas may be waterlogged (usually wetlands during the rainy season) and the greater portion of these waterlogged areas with poor fertility are dedicated to grazing as they are entirely dominated by grasses of different species. By practice, farmers have learned to leave these poorly-drained areas as permanently graze-lands whilst the fertile areas are dedicated to rice cultivation. Thus the wetlands (seasonally flooded) were also identified as an important land-use at the study site.

Unlike the cropland and graze-lands, the pockets of remnant savannah woodlands are scattered at the entire site irrespective of topographic position. Few of these tree species are unevenly distributed on the cropland and graze-lands whilst the greater proportion are concentrated at burial sites, shrines /religious sites and sacred groves. Often trees species found on croplands are fruit trees or have medicinal value and they include dawadawa (*Parkia biglobosa*), boabab (*Adansonia digitata*), kapok (*Ceiba pentandra*) and *Diaspyros mespiliformis* which can cure mental illness, epilepsy, and convulsion (Abolga, *pers. comm.*). Those species found on graze-lands are often nitrogen-fixing and sometimes used as browse by animals. They include the *acacia* (*Acacia albida),* whitethorn (*Faidherbia albida*) and Ficus species.

## 3.3 Experimental Procedures and Deployment of Soil Collars

The study was conducted in three (3) smaller communities in Sumbrungu. These were Aniabisi (site 1), Agatibisi (site 2) and Atongobisi (site 3) communities which are located downstream of the Vea dam. The experimental sites were located along a topo-sequence with distinct upslope, midslope, downslope and valley bottom positions. For easier classification, spot heights were determined with Differential Global Positioning System (DGPS) and Digital Elevation Model (DEM) and these were used to categorise the various topographic positions. Areas with heights of 180m and above were designated as upslope, whilst locations with heights 160m and below were designated as downslope. The midslope position had heights between 180m and 160m. In order to capture the spatial heterogeneity of the area, for each site, three crop fields, and three graze fields located along the topo-sequence with distinct upslope, midslope and downslope positions were selected. Additionally, three natural woodland fields located upslope, midslope and downslope were selected for the study. These undisturbed sites were pockets of savannah woodlands left for religious, cultural or other purposes. Each of the field (plot) measures 20 m x 20 m. Thus a total of nine (9) plots (20m x 20m) per site and 27 plots for the three selected sites were used for the study. With the help of the Global Positioning System (GPS), Garmin GPSMAP 62sc (Garmin, Inc., USA), the locations of plots were determined (location accuracy, ± 1 - 2 m).

In each plot, three separate subplots (5m x 5m) were selected within an apparently homogeneous area and three (3) soil respiration polyvinyl chloride (PVC) collars of diameter 20 cm and height 8 cm, (Figure 3.3) representing three replications were randomly placed within each subplot. Collars were carefully inserted up to 5cm deep into the mineral soil and the tops were almost flushing with the soil surface (about 3cm) to ensure least disturbance to soil as possible (Heinemeyer *et al*., 2007). According to Rochette *et al.* (1997) the recommended depth for soil collars to provide firm anchorage, solid foundation for the chambers and prevent gas seepage ranges from 4 cm for small chambers (up to 5 L) to about 10 cm for larger chambers.

A: Placement of PVC Collar on a plot B: Checking the level of PVC collars

C: Collars deployed at experimental site D: Static chamber system for measurement

Figure 3.3: PVC Collar placement procedure and static chamber system at experimental site

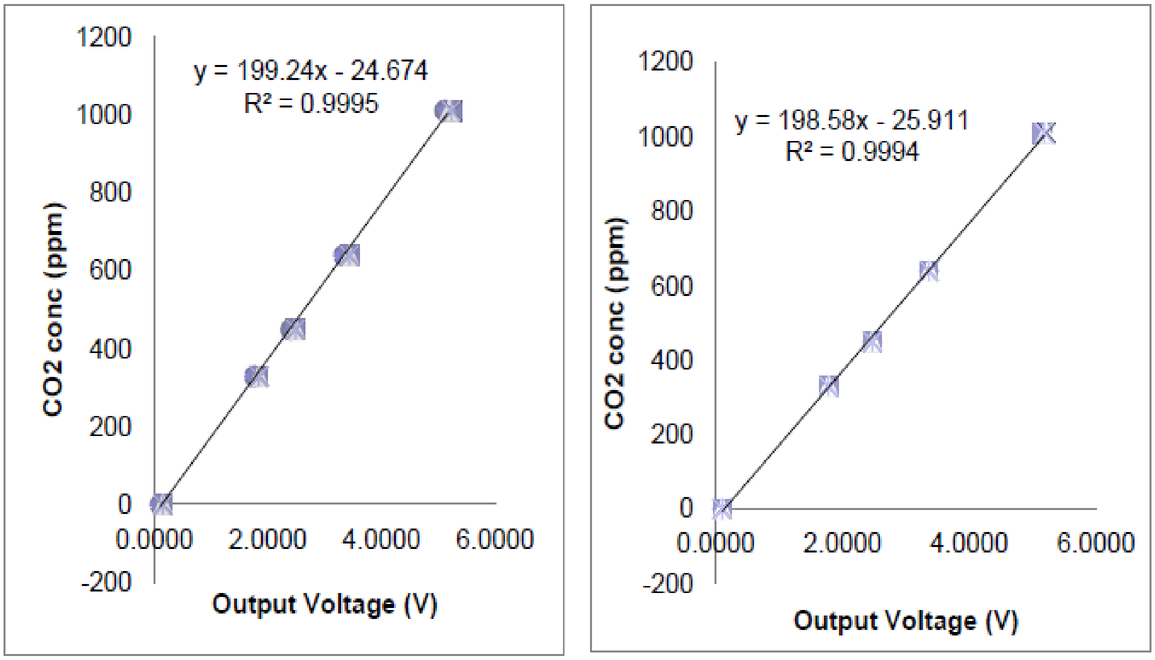
Apart from providing anchorage for soil respiration chambers during flux measurements, soil collars also help to trap the gases emitted from the soil and prevent gas leakages. Collars also provide spatial establishment for the measurement plots such that repeated measurements can be undertaken at the same site (Chojnicki *et al.*, 2010). Collar depths and locations were monitored continuously to prevent build up of microbes which could alter the microclimate of the soil collar environment and hence introduce biases into measurements. Additionally, to avoid disturbance to the soil entrapped in the chamber, collars were inspected at least 24 hours before measurements were taken. This is necessary to minimise disturbance to the soil structure as well as causing a flush of carbon dioxide (Heinemeyer *et al.*, 2007). The locations of collars placed at the centre of each subplot were also determined by GPS for geo-statistical analysis in Geographic information System (GIS). This approach will guarantee high representativeness whilst accounting for rare areas which may be potential hot spots.

### 3.3.1 Instrument description and calibration

Static chambers have been used for many years although not exactly by means of gas chromatography or infra red gas analysers (IRGA) methods, but with acid trapping of $CO_2$ and chemical analysis. The custom-made closed static chamber systems used for the study were constructed as described by Irvine and Law, (2002) and Savage and Davidson, (2003). The custom-made closed static chambers were however mounted with the Vaisala's GMD20 (Vaisala Inc. Helsinki, Finland) which is a portable non-dispersive infrared gas analyser (IRGA) instead of chemical traps. The construction of GMD20 (Vaisala Inc. Helsinki, Finland) transmitters was based on silicon CARBOCAP® sensor technology and therefore it provides excellent stability and reliability and it has a measurement range of 0 - 2000 ppmv which corresponds to output voltage range of 0 - 10 V after manufacturer's calibration. The GMD20 transmitter is designed to monitor $CO_2$ levels in the air inside the static chamber. They are duct mountable and the distance between the probe and the duct wall can be easily adjusted by using the mounting plate. The GMD20 transmitters require almost no maintenance within the recommended calibration interval of five years (www.vaisala.com). Apart from direct measurement of $CO_2$ fluxes which eliminates the cumbersome nature of chamber systems with chemical traps, the GMD20 (Vaisala Inc. Helsinki, Finland) sensors offer additional advantage of being relatively easy to deploy as they require less infrastructural support and therefore more suited to remote experimental sites. They give precise measurements of $CO_2$ fluxes and potentially; they are capable of minimising the problem of $CO_2$ flux underestimation usually associated with the use of chambers. The usefulness of enclosing an IRGA (e.g. GMD20) in a soil chamber to determine the $CO_2$ flux rates was demonstrated by Nobuhiro *et al*. (2003) using the static chamber method and the results almost equalled those measured by the closed-flow method with an LI-800 (Li-COR Inc. Nabraska, USA ) device over a wide range. The Vaisala INTERCAP Humidity and Temperature Transmitter, HMD53 (Vaisala Inc. Helsinki, Finland), was used to measure the chamber temperature and humidity concurrently as the $CO_2$ fluxes were being measured. The HMD53 humidity and temperature transmitter is a three-wired transmitter, duct mounted and the electronics can be disconnected without dismantling the installation. The $CO_2$ sensors in the chambers were connected to a four-channel VERITEQ universal input datalogger (SP 4000, Vaisala Inc. Helsinki, Finland) and using a handheld notebook computer, the data stored were downloaded after each measurement campaign. The entire measurement system was powered by 24V direct current (DC) provided by two 12V LICOR batteries (LICOR Inc. NE, USA) connected in series which were charged fully after every measurement campaign.

For full accuracy, the GMD20 transmitters were calibrated against accurate and traceable $CO_2$ gas at standardised concentrations (0, 325, 450, 650 and 1000 ppmv) in May, 2013 at the IBG-3 laboratory at Forschungszentrum Jülich (FZJ) Jülich-Germany. The laboratory provided a stable environmental condition with respect to temperature and pressure corrections. Using laboratory standardised $CO_2$ gas concentrations and an airtight acrylic glass chamber of volume of 2.57 L (diameter 12.2 cm, height 22 cm). The GMD 20 sensors were calibrated as follows;

A known $CO_2$ gas concentration was injected inside the calibration glass chamber mounted with the $CO_2$ duct transmitter. The initial voltage reading at ambient concentration (about 395ppm) was noted and the output voltage from the datalogger (SP 4000, Vaisala Inc. Helsinki, Finland) was monitored using a digital voltmeter (UT 61A-E, Reichelt Electronics, Germany) at two-minute intervals until chamber saturation was reached. The $CO_2$ gas flow through the chamber system was controlled by a digital mass flow controller (GF40, Brooks Instrument, Hatfield, USA) and the gas flow rate was simply adjusted via Excel (macros). The datalogger converts the output voltage signals from the $CO_2$ transmitters to $CO_2$ concentration values (ppmv) using a simple relationship based on the measurement range of 0 – 2000 ppmv corresponding to 0 – 10 V (i.e. measured output voltage over the maximum output voltage of 10 multiplied by 2000 ppmv). The procedure was repeated three times for all the five sensors at each standardised $CO_2$ gas concentration and the mean voltages at every two minutes was determined in addition to gas concentrations outputs recorded by the datalogger. Based on the relationship between voltage (V) and gas concentration (ppmv), each GMD20 transmitter was uniquely calibrated for the field measurements. The calibration output plots (Figure 3.4) clearly indicated that measuring output voltages from the GMD20 transmitter can be sufficiently used to obtain soil $CO_2$ concentration (ppmv) as the coefficient of determination was almost one ($R^2 = 0.999$). The results implied that soil $CO_2$ flux measurements in the field using static chambers and the GMD20 transmitter can be undertaken rapidly with simple digital voltmeter instead of a relatively sophisticated and costly dataloggers and palmtop computers. As the calibration aims at providing error estimates for static chambers, the calibration demonstrated the feasibility of using the chamber-sensor technique for soil $CO_2$ flux measurements from a wide range of locations including rural communities in West Africa where electricity power supply is unreliable.



**GMD 20 Sensor 2** **GMD 20 Sensor 6**

Figure 3.4: Output voltages of the GMD 20 Sensors for different $CO_2$ gas concentrations

### 3.3.2 Determination of optimum chamber closure duration

Knowledge of chamber closure duration is important in field measurements of soil $CO_2$ fluxes (or trace gases) particularly in manual chambers. It helps to minimise flux underestimation (Healy *et al*., 1996; Senevirathna *et al.,* 2006) and maximise time spent for the field work and ensures that the spatial heterogeneity of the site is adequately captured.

The optimum chamber closure duration for soil respiration chambers (manual or automated) are variable and dependent on a number of factors including the volume of chamber (litres), sensitivity of the $CO_2$ gas transmission sensors (other infrared gas analyser -IRGA), soil quality and other external factors such as atmospheric pressure, ambient and soil temperature (Lloyd and Taylor, 1994; Kirschbaum, 1995) and soil moisture content (Davidson *et al.,* 2000), which vary hourly, weekly, seasonally, and annually (Savage and Davidson, 2003). For many automated chambers, such as the LICOR chambers (LI-COR Inc., Nebraska, USA) a closure duration of two minutes is often sufficient to obtain the minimum number of concentration points to estimate fluxes  the manual chambers may be closed for up to one hour depending on the methods used to measure the soil respiration (gas chromatography, IRGA, or acid traps).

For the GMD20 $CO_2$ sensors used for the study, a combination of laboratory testing and field trials were used to establish the optimum closure period. Closure duration less than this optimum underestimates the fluxes but beyond it the chamber becomes saturated. Using laboratory testing with standardised $CO_2$ gas concentrations and an airtight acrylic glass chamber of volume of 2.57 L (diameter 12.2 cm, height 22 cm) optimum closure duration of between 6 - 8 minutes was obtained for the GMD20 sensors (Figure 3.5). The detailed description of procedure is found in subsection 3.1.1. The closure time obtained (about 8 minutes) was then used as a guide for the field trials using the static soil respiration chambers of almost double the volume 4.40 litres (diameter 20cm, height of 14cm) under field conditions.

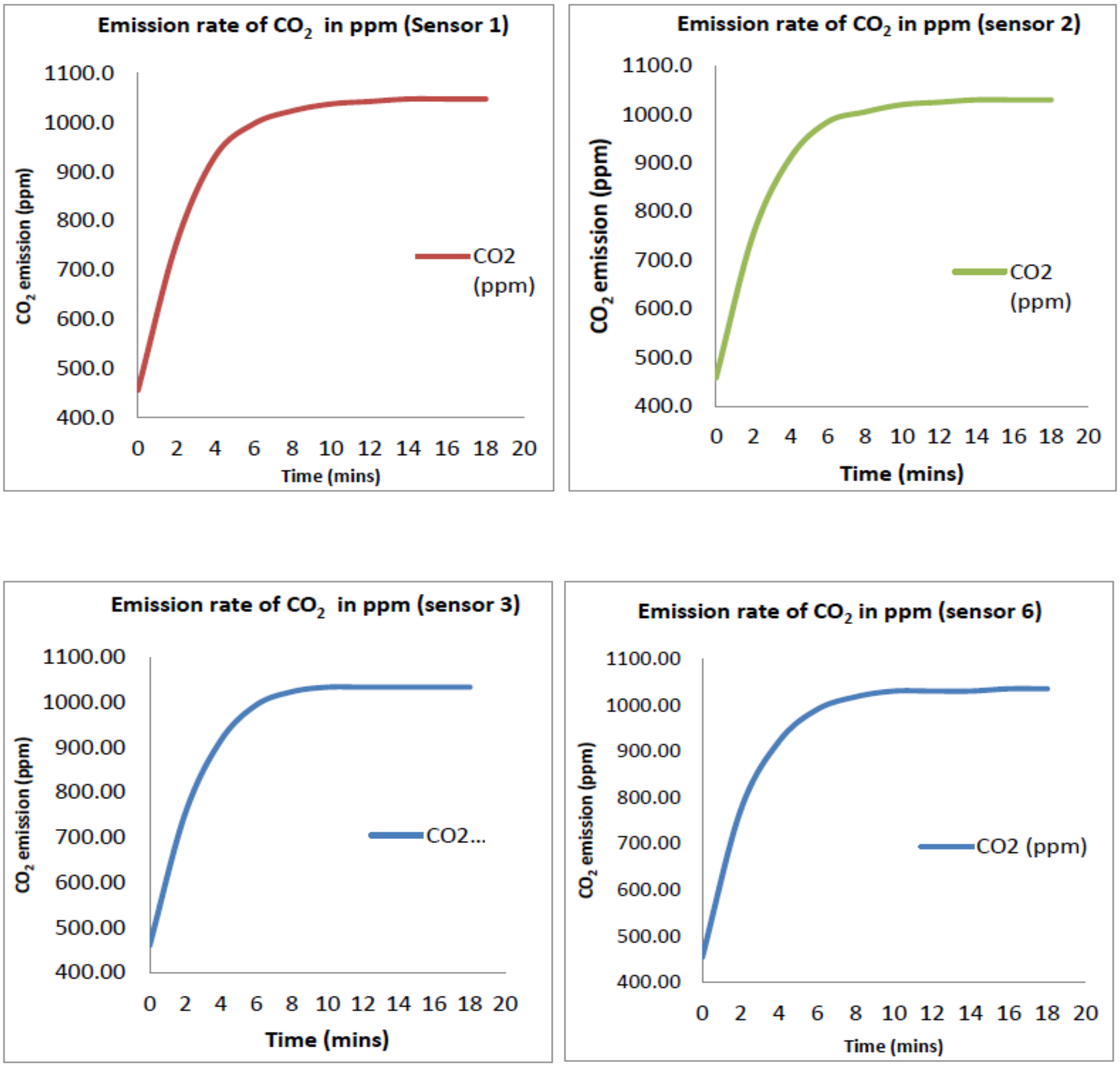


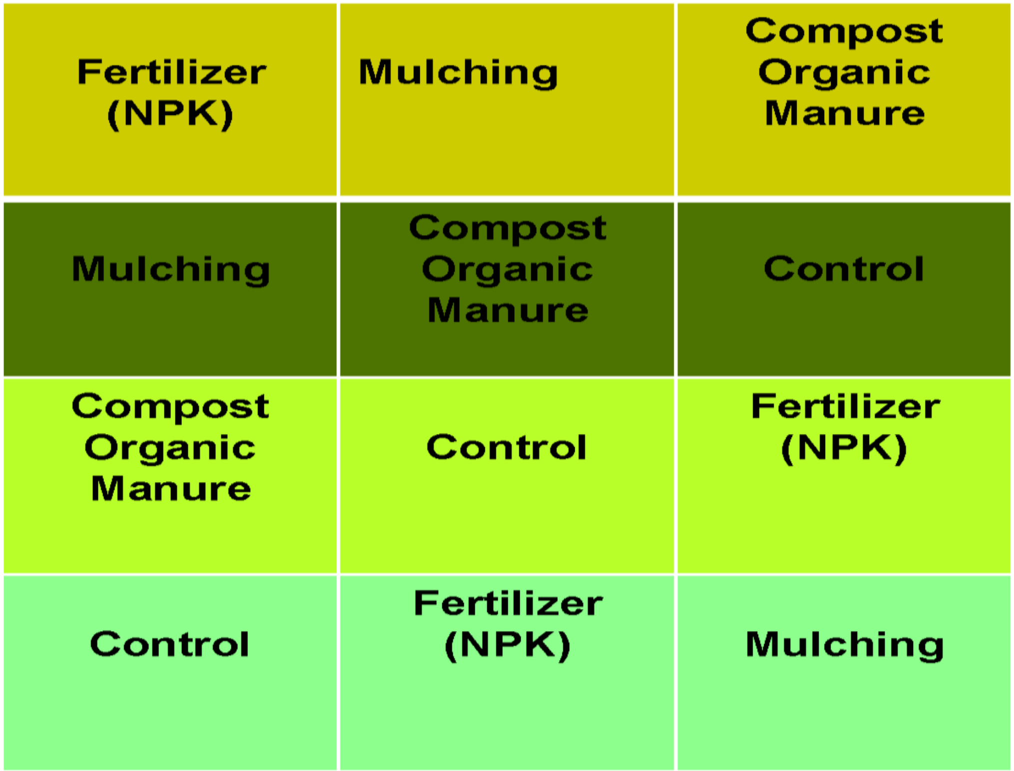
Figure 3.5: Estimated chamber closure duration for Vaisala GMD 20 sensors

During field trials, soil chambers were timed immediately after closure (zero time) and monitored at one-minute intervals using datalogger (SP 4000, Vasaila Inc. Helsinki, Finland) until the peak concentration of $CO_2$ was reached (saturation). The procedure was repeated under several different site and environmental conditions and the average closure duration determined for the site and sensor to be 20 minutes. Thus using the GMD 20 sensors (Vaisala Inc. Helsinki, Finland) and a chamber volume of 4.40 litres, chamber closure duration of 20 minutes was optimum for the study site such that chambers become saturated after 20 minutes and further closure becomes time wasting.

### 3.3.3 Design of field management practices experimentation

The experiment was conducted in a rice field which was initially ploughed with a disc plough to a depth of 30cm to breakdown the lumps of soil in the relatively heavy and compacted clayey loam soils and bounds were then made. Using an average planting distance of about 20cm by 20cm, about 5-6 seeds of local rice variety (*oryza glaberima*) were drill sown per planting hole within and between rows on 02/07/2013. Plots of size 10m x 10m were laid out in a Randomised Complete Block Design (RCBD) for the field management practices (Figure 3.6). To minimise the heterogeneity within the plots, each main plot was subdivided into two subplots of 5mx10m and two soil collars were deployed on the two subplots respectively. Collars were placed in between the rows of crops for soil $CO_2$ flux measurements. The management practices were fertiliser application, compost manure application, mulching and control. Each treatment was replicated three times.

For fertiliser application, the recommended rate of chemical fertiliser ($N-P_2O_5-K_2O$) for adequate levels of P and N for the rice variety was N90-P60-K60 kg/ha with Urea as N source. The N levels application were split into two; the first split was applied at first tiller initiation after germination and the second at the panicle initiation stage using the bunding method to all plots. The compost manure used was composted cow dung at rate of about 7 t/ha (or 70 kg) whilst sufficient quantities of guinea corn husks, stover of crops, rice husks and straws were used for the mulching treatment. The control experiment had no pre-treatment. Thinning and refilling of plants was done a week after full germination. Hand weeding was done twice within the growing season, the first hand weeding was done two weeks after germination and the second hand weeding was done when weeds were observed to be present in the plots. Soil $CO_2$ flux and associated environmental parameters measurements were done weekly from the date of sowing (July) till end of the season (November). At physiological maturity stage, 1m x 1m area of each treatment was randomly harvested for biological yield analysis (biomass). Fresh weight of shoots was determined with Satorious balance of sensitivity 0.01g. The shoots were dried in a Memmert air-circulated oven for 36 hours at 80°C until a constant weight was achieved through intermittent drying and weighing until the same biomass weight is maintained.



| | | |
|---|---|---|
| Fertilizer (NPK) | Mulching | Compost Organic Manure |
| Mulching | Compost Organic Manure | Control |
| Compost Organic Manure | Control | Fertilizer (NPK) |
| Control | Fertilizer (NPK) | Mulching |

Figure 3.6: The RCBD field layout for field management practices experiment

### 3.3.4 Field survey and measurements of soil respiration

In this study, one measurement cycle consisted of a 20-minute measuring period and a 5-minute rest period where the chamber was well ventilated to make sure that the initial $CO_2$ concentration (zero time) in the chamber headspace was close to ambient concentration.

Measurements were taken in sufficient spatial locations from the different land-use systems within the experimental catchment (Figure 3.7) which represent a range of (agro) ecosystems and soil conditions using a custom-made static chamber system described in detail in subsection 3.3.1. For easy spatial integration of space and time, at least once weekly measurements frequency was undertaken (Savage and Davidson, 2003) but in line with Merbold *et al*. (2011) observation, more than once measurements per week were done during rain events in order to capture the perturbations as result of the precipitation. Pressure changes within the chamber and ambient were minimised during measurements by a vent tube (Ø 6 mm and 50 cm long) that was inserted downwards into the chamber headspace.

During measurements, the static chambers of volume 4.40 litres (diameter 20cm, height of 14cm) were lowered onto the preinstalled PVC collars and fastened by bolts and nuts system connecting the base of the chambers and the top frame of the collars. A rubber gasket was installed on the chamber's lower edge to ensure the tightness of the chamber and avoid gas leakages during measurements (Drösler, 2005). Three chamber systems representing triple replicates of soil respiration were measured at vegetation-free spots at all sites where collars were prefixed usually about 24 hours before measurements. Chambers were closed for 20 minutes but the initial $CO_2$ concentration (zero time) was taken soon after the chamber was lowered.

Subsequently, the $CO_2$ mixing ratio in the chamber headspace was determined every 5 minutes by measuring the output voltage signals from the portable $CO_2$ sensor (GMD20, Vaisala, Helsinki, Finland) which was connected to a datalogger (SP 4000, Vasaila Inc. Helsinki, Finland) of 30 seconds sampling frequency which was installed in a portable control box. The logger was connected to a palmtop so that all measured parameters and system performance were easily checked during measurements.

A: Soil respiration measurement in cropland

B: Soil respiration measurement in graze-land

C: Soil respiration measurement in rice field

D: Data collection by field staff

Figure 3.7: Soil respiration measurements with static chamber system at experimental site

Additionally, the output voltage signals from the portable $CO_2$ sensor were measured using a digital voltmeter (UT 61A-E, Reichelt Electronics, Germany) and they served to provide backup measurements in the unlikely event of data logger malfunctioning. After each day's campaign the logged data was downloaded using a portable palm top computer. The entire field work covered 13 months from beginning of June 2013 till end of June, 2014 and measurement were taken between 7 am – 4 pm since this period was observed to give accurate and highly representative mean daily flux for the site.

### 3.3.5 Measurement of environmental factors

Chamber temperature and relative humidity were measured concurrently along the soil collars as the $CO_2$ efflux was being measured using the solid-state INTERCAP® Humidity and Temperature Transmitter, HMD53 (Vaisala Inc. Helsinki, Finland). Volumetric soil moisture content was measured continuously in the field at 5cm depth (the zone where the bulk of the roots were located) in the soil with a Theta Probe ML2-X moisture meter (Delta-T Devices, Cambridge, UK) calibrated using the gravimetric method. Additionally, ambient temperature was measured at breast height (1.3 m above terrain) whilst the soil temperature measurements at 5cm depth were undertaken using the OMEGAETTE ® HH306 thermometer and datalogger (Omega Eng. Stamford, United States) at all locations where $CO_2$ effluxes were measured.

### 3.3.6 Soil sampling and analysis

The PVC collar locations were used as reference points for soil sample collection. Undisturbed soil samples were collected at a depth of 0 to 30 cm and partitioned into three horizons as 0-10cm, 10-20cm and 20-30cm. Samples were air-dried, ground and sieved using a 2mm sieve, thoroughly mixed and stored for further analysis of particle size distribution, pH, organic carbon and organic matter (OM), nitrogen (N), available phosphorus (P) and potassium (K) and exchangeable bases, in the laboratory following standardised procedures. Mechanical analysis of particle size and soil texture was determined using the Bouyoucos hydrometer method. Samples' pH were determined by a glass electrode / pH meter, and 1:2.5 soil - water suspension; the percentage organic carbon in soils was determined by the Walkley-Black method and subsequently converted into percentage organic matter by multiplying the percent organic carbon by the Van Bemmelen factor (1.724).

The percent total nitrogen (N) was determined by micro-Kjeldahl digestion method, available phosphorus (P) was determined by the Bray 1 method the available potassium (K) in the soil sample was estimated with the help of a flame photometer. The concentrations of P and K (ppm) were then obtained by extrapolation from standard P and K curves and finally the ammonium acetate method of Hanway and Heidel was used for exchangeable bases. Additionally core samplers (Ø 48 mm and height 50 mm) were used to collect undisturbed samples from these respective horizons for bulk density measurements using the core method whilst soil moisture content was determined by gravimetric method after oven drying of samples at 105°C for 24 hours.

### 3.3.7 Determination of soil carbon stock under predominant land-uses

Soil carbon stocks under all the predominant land-uses at the catchment were determined by following two main steps; bulk density determination from the core samples followed by the carbon stock determination. Equations (3.1) and (3.2) were the relationships used for the determination (Pearson *et al.*, 2005). The soil carbon stock for each land-use was determined to a depth of 30 cm in line with the IPCC Good Practices Guidelines (2003). The required parameters, bulk density and carbon concentration percentage were obtained from the laboratory analysis of soil samples following commonly accepted standard procedures with respect to sample preparation such as mixing and sieving, drying temperatures and carbon analysis methods. For bulk density determination, samples were oven-dried at 105°C for at least 48 hours. The coarse, rocky fragments were retained and weighed separately after sieving. The portion of soil used for carbon determination was sieved through a 2mm sieve and then mixed thoroughly. Samples were air-dried and the total soil carbon was determined using the Walkley-Black method.

The bulk density (BD) was then calculated for the mineral soil core using the expression;

$$\mathrm{BD} = \frac{\mathrm{M}}{\mathrm{V} - \frac{\mathrm{m}}{\mathrm{d}}} \tag{3.1}$$

where BD is the bulk density for the < 2mm fraction (Mg $m^{-3}$), M is the oven dry mass (Mg $m^{-3}$), V is the core volume ($m^3$), m is the mass of coarse fragments (> 2mm fraction), (Mg) and d is density of rock fragments (Mg $m^{-3}$).

Using the carbon concentration (C) data obtained from the laboratory (expressed as decimal fraction), the amount of carbon (C) per unit area was determined by the following relation after Pearson *et al.* (2005):

$$\mathrm{C} = \mathrm{BD} \times \mathrm{h_s} \times \mathrm{C_c} \times 100 \tag{3.2}$$

where C is the amount of carbon (Mg $ha^{-1}$), BD is the bulk density of soil (Mg $m^{-3}$), $h_s$ is the soil depth (0.10 m) and $C_c$ is the carbon concentration in samples (%).

The total carbon pool for each of the eligible land-use was obtained by summing the carbon stocks (Mg $ha^{-1}$) for each of the three horizons 0 - 0.10 m, 0.10 – 0.20 m and 0.20 – 0.30 cm to give the carbon stock for the 0 - 0.30 m soil depth (IPCC, Good Practices Guidelines, 2003) and this was followed by the standard error (SE) determination.

### 3.3.8 Estimation of soil carbon stocks related to land-use conversions

The SOC stock determined for the land-uses; woodland, graze-land and cropland based on the field measurements were used at the reference soil carbon stock. Then, using this SOC stock as the base year (2013) and assuming the business as usual (BAU) scenario, the IPCC default values and SOC tool (IPCC, 2003) were used to estimate the decadal historical SOC stock dynamics for the predominant land-uses for a 30-year period (2003, 1993 and 1983) and based on that, a short-term prediction of the SOC stock dynamics was made for a 60-year period. The IPCC SOC tool estimates changes in SOC stocks associated with management changes in croplands and graze-lands and it is based on the following IPCC default data;

i. Management factor which represents type of tillage (no, reduced or full tillage) in cropland or for graze-land, it is level of management improvement or degradation
ii. Input factor which represents amount of crop residue and/or external organic amendments whilst for graze-land it represents the level of improvement that affects primary productivity and hence carbon inputs to soil;
iii. Land-use factor which represents the nominal soil carbon stock relative to the native reference condition for broad-classes of different land-uses. The land-use factor for all native (unmanaged) ecosystems is set equal to 1 and
iv. Reference carbon stock which refers to the default reference (under native vegetation) soil organic carbon stocks (t C ha$^{-1}$) for the 0 - 30 cm depth. It was based on soil profile data from Bernoux *et al.* (2002) and Jobbagy and Jackson (2000).

The soil carbon stock from one ecosystem to another (usually after 20 years) is calculated as follows:

$$\text{Soil carbon stock (Mg/ha)} = \text{RCS} \times \text{LUF} \times \text{MF} \times \text{IF} \qquad (3.3)$$

Where RCS is the reference or initial carbon stock, LUF is the land-use factor which is dependent on the ecosystem, MF is the management factor and IF is the inputs factor.

The annualised carbon stock change rate is calculated as follows:

$$\text{Annual soil carbon stock} = \frac{\text{Estimated carbon stock} - \text{Initial carbon stock}}{20\ \text{years}} \tag{3.4}$$

For cropland, the IPCC (2003) default values for the management factor was 1.1, inputs factor was 1.1 and the land-use factor was 0.69 resulting in the annual change in SOC of 0.33 whilst for graze-land the default value management factor was 0.97, input factor was 1.0 and land-use factor was 1.0, resulting in an annual SOC change value of 0.05.

On benchmarking the natural savannah woodland, the impact of internal land-use trading or land-use conversions on SOC density was additionally estimated. Thus the impact of the following land-use conversions on SOC density were estimated; transition from woodland to graze-land, woodland to cropland; conversion from graze-land to cropland or graze-land to woodland and transitions from cropland to graze-land and cropland to woodland.

### 3.3.9 Flux computations and data analyses

The collected time series data of $CO_2$ concentration build up in the chamber headspace were summed for every 5 minutes and validated in terms of temporal linearity of $CO_2$ concentration. The correlation coefficient ($R^2$) was calculated for each series and if $R^2 > 0.95$ then $CO_2$ flux rate ($FCO_2$) was calculated using the following equation after Flessa *et al.* (1998);

$$\mathrm{FCO_2} = \mathrm{kCO_2} \frac{\Delta c}{\Delta t} \times \frac{273.15}{T_{air}} \times \frac{V}{A} \tag{3.5}$$

where $FCO_2$ is $CO_2$ flux density (µg $CO_2$ C $m^{-2}$ $h^{-1}$), $kCO_2$ is gas constant at 273.15 K = 0.536 (µg C $\mu l^{-1}$), $T_{air}$ is air temperature in chamber (K), V is the chamber volume ($m^3$), A is the collar surface area ($m^2$), $\Delta c$ is the change in concentration of $CO_2$ ($ppms^{-1}$) and $\Delta t$ is the time interval (s).

Data on $CO_2$ flux ($FCO_2$) computed were analysed by comparing time series of soil respiration amongst land-uses, cropping systems and management practices and across slopes using the statistical software package SPSS version 21.0 (IBM Inc.) and Minitab version 17.1 (MINITAB® Minitab Inc.). Preliminary data preparation and cleaning was undertaken with Microsoft Office Spreadsheet, 2007 (MICROSOFT Corp.). Analysis of variance (ANOVA) was undertaken to determine whether the differences between the mean fluxes of soil $CO_2$ from the different land-uses and experimental treatments were significant at 95 percent level of confidence ($\alpha = 0.05$). Pearson paired correlation matrix was used to determine the relationship between the soil $CO_2$ fluxes from predominant land-uses and the underlying soil organic carbon stocks.

The soil $CO_2$ efflux measurements were also correlated with soil temperature to estimate the dependency of soil respiration variability on soil temperature using the simple exponential relationship:

$$\mathrm{R_{soil}} = \mathrm{Ae^{BT_{soil}}} \tag{3.6}$$

where $\mathrm{R_{soil}}$ is soil respiration (mg $CO_2$ C $m^{-2}$ $h^{-1}$), $\mathrm{T_{soil}}$ is soil temperature (°C) at 5cm depth and A and B are coefficients (Davidson *et al.*, 1998).

Hence, the temperature response of soil respiration ($Q_{10}$) was determined with the formula:

$$\mathrm{Q_{10}} = \mathrm{e^{B10}} \tag{3.7}$$

The averaged soil respiration for each categorised subplot (represented by three collars and each measured four times on monthly cycles) was fitted to soil water content data captured and recorded as volumetric water content (VWC [%]) with a linear function:

$$\mathrm{R_{soil}} = \mathrm{A}\theta + \mathrm{B} \tag{3.8}$$

Where $\mathrm{R_{soil}}$ is the soil respiration, (mg$CO_2$ C $m^{-2}$ $h^{-1}$), $\theta$ is the volumetric soil moisture content (%), at 5cm (the zone where the bulk of the roots were located), *A* and *B* are constants derived from curve fitting (Merbold *et al.*, 2011).

For spatial variation of soil $CO_2$ flux across the study field, the averaged soil respiration for each categorised subplot represented by three collars and each measured four times per month on weekly measurement cycles for the 13-month measurement campaign were interpolated. The point measurements of the soil $CO_2$ fluxes from the predominant land-uses were interpolated using the Inverse Distance Weighting (IDW) algorithm of the Geostatistical analyst extension of ArcGIS software version 9.3 (ESRI, Inc. Redlands, USA) which provided an extensive set of tools for performing the interpolation to determine the spatial variability of soil $CO_2$ fluxes across the catchment. The IDW estimates values at unsampled points by the weighted average of observed data at surrounding points. It is a distance reverse function of each point from neighbouring points where the weights are defined by the opposite of the distance and normalised so that their sum equals one. Thus as the distance increases, their weights decrease and by using a linear combination of values at a known sampled point, values at un-sampled points can be calculated (Teegavarapu and Chandramouli, 2005). The IDW is a commonly used interpolation method and it minimises the interpolation errors if the correct power value is used (Dirks *et al.,* 1998). Goovaerts (1999) recommended a power value of 2 for daily and monthly time steps, 3 for hourly and 1 for yearly time steps and in line with this, a power value of 2 was adopted for the IDW in the current study. Moreover, the corresponding averaged soil temperature and soil moisture content (at 5 cm) for the same measurement campaign period were also interpolated to determine the spatial inter-relation between soil respiration, soil temperature and soil moisture content.

The major driving factors underlying the spatial variations of soil $CO_2$ fluxes in the catchment were identified through a series of statistical analyses and interpretation. As the soil $CO_2$ fluxes are influenced by many soil-plant environment and climatic independent factors (Xu and Qi, 2001), several explanatory parameters including soil moisture, soil temperature, air temperature, pH, porosity, bulk density, land-use types and topography were concurrently determined with soil $CO_2$ flux measurements across the study field. To avoid the complication of using all these measured independent variables to determine the underlying drivers of the spatial variation of soil $CO_2$ as well as the high multi-collinearity effect between some explanatory variables, an integrative summary of the overall set of explanatory variables was necessary. The Principal Component Analysis (PCA) was thus used to reduce the dimensions of the explanatory variables.

The PCA is a multivariate statistic method that is often used to condense information in a large number of original variables into a smaller set of new composite dimensions, with a minimal loss of information (Campbell *et al.*, 2001). The basic assumption of the technique is that it is possible to explain the correlation pattern between two or more variables in terms of a few underlying factors, called principal components. The principal component is a linear combination of the original variables that accounts for the maximum possible information in the original set of variables. The meaning of each principal component is interpreted in terms of those original variables with higher weights/loadings, i.e., the most important variables. The first principal component (PC1) directs along the greatest variation whilst the second principal component (PC2) has the direction with maximum variation in the remaining data, which is orthogonal to the PC1, and so forth. Since the extracted principal components are independent from each other, the use of component scores for subsequent analysis will help to avoid the multi-collinearity problem. Thus PCA was initially run with Varimax rotation and Kaiser normalisation and the components with Eigen values over 1.0 were interpreted and used for subsequent analyses. In order to preserve the relationships among the data values (Manikandan *et al.,* 2013), the component scores produced in PCA were saved and standardised. The PCA extracted two (2) principal components (PC) that accounted for 80.6 % of the total variance of the original independent variables. Accordingly, PC1 and PC2 were able to explain 61.3 % and 19.3 % of the total information. The standardised component scores were used for the subsequent K-Mean Cluster Analyses (K-CAs) to derive land-use groups. The K-CA is a non-hierarchical, divisive clustering technique that attempts to reduce the intra-cluster variances while maximising the inter-cluster distances (Kintigh and Ammerman, 1982). The K-CA method works by searching for cluster formations that minimise the global Sum of the Squared Error (SSE). The SSE is defined as the total of the squared distances between the cluster's centre and each of its members (measured in Euclidean distance). Unlike hierarchical methods such as nearest neighbour and average linkage, non-hierarchical methods avoid problems of "chaining" and artificial boundaries and work on the original input data rather than on a similarity matrix (Kintigh and Ammerman, 1982).

Four land-use groups were identified based on the K-CA. Based on the weighted parameters in the rotated component matrix, the variables with high loading under each PC were selected as key categorising variables and they represent the major drivers of spatial variation. A radar diagram was finally drawn to prioritise the major driving factors underlying the spatial variations of soil $CO_2$ fluxes in the catchment.

## 3.4 Limitations of the Study

In this study, fluxes of $CO_2$ were based on day time measurements only. Typically, chamber measurements are done during day time, due partly to the practicability of undertaking measurements during day time hours and also the difficulty in ventilating chambers after one measurement cycle at night time campaigns. The observation is that at night-times, the relatively stable atmospheric conditions makes the ventilation process much more difficult and takes longer time to be achieved.

Again, the study computed the total fluxes of soil $CO_2$ derived from both heterotrophic and autotrophic respiration and it was impossible with available measurement tools to separate the respiration into autotrophic and heterotrophic components which are required to estimate the net ecosystem exchange (NEE).

Also, the study used custom-made manual chambers for in situ $CO_2$ soil flux measurements which unlike the automated systems cannot undertake continuous long-term measurements. Thus due to the relatively low frequency of measurements, soil respiration due to very short-term variability in diurnal weather conditions could be overlooked. Diurnal weather conditions may be variable throughout the year, such as the influence of precipitation events on soil respiration and this may be obscured under very wet or dry conditions.

# 4. RESULTS AND DISCUSSION

## 4.1 Introduction

This chapter focuses on the effects of the predominant land-uses and agronomic practices on soil respiration and soil carbon stock density at the catchment. The remaining part of the chapter focuses on the impact of topography, soil temperature and moisture content dynamics on soil respiration. Temporal and spatial variations of soil $CO_2$ efflux across field and annual carbon flux density from the catchment via soil respiration were quantified.

## 4.2 Effect of Predominant Land-uses at the Catchment on Soil Respiration

The mean monthly flux of $CO_2$ for cropland, graze-land and woodland (Table 4.1) were summed together to obtain the annual flux of $CO_2$ for each land-use. Analysis of variance (ANOVA) revealed that the differences between the mean annual soil $CO_2$ fluxes were significantly different ($P< 0.05$). The results (Figure 4.1) showed that savannah woodland had the highest soil $CO_2$ flux of 12.97 ± 0.89, followed by graze-land with mean total, 9.10 ± 0.42 whilst cropland had the least, 5.61 ± 0.29 t $CO_2$ C $ha^{-1}$ $y^{-1}$. The differences in soil carbon efflux could be due to the biological activities in the soil as soil respiration measurement is considered a suitable index for decomposition and other biological activities in the soil.

Generally, the basal soil respiration rate is a measure of overall soil microbial activity, soil microbial biomass and edaphic conditions such as total N, C, CEC, and pH (Gray, 1990). The croplands are subjected to continuous cropping with very little soil inputs occasionally in the form of animal droppings. Even where leguminous crops like groundnuts and peas are planted, the whole plant is harvested leaving virtually no plant residues to the soil. The few left over crop residues on the field are grazed by livestock during the dry season. The practice depletes the soils of organic matter leading to less decomposition activities compared to the woodland which has litter fall throughout the year. The low organic matter inputs to the cropland soils from plant residues (leaves, stems, roots and rhizosphere) and inputs from roots such as rhizosphere reduces both autotrophic and heterotrophic soil respiration. High microbial biomass and significant underground litter promote higher decomposition and high soil $CO_2$ efflux as $CO_2$ is a major product of decomposition (Schmidt *et al.*, 2011). Compared to cropland, graze-land has relatively high underground storage in the form of roots which usually remain dormant during the dry season but regenerate shoots from the underground storage when the rainy season begins. Thus the amount of SOC in the soils under each land-use may be the determining factor controlling soil respiration.

Table 4.1: Mean monthly soil $CO_2$ fluxes from the predominant land-uses in the Vea catchment (Fluxes are in g $CO_2$ C $m^{-2}$ $month^{-1}$)

| Year | Month | Cropland | Graze-land | Woodland |
|---|---|---|---|---|
| 2013 | July | 60.92 | 109.71 | 119.14 |
| 2013 | August | 82.55 | 144.72 | 90.11 |
| 2013 | September | 109.98 | 112.93 | 98.16 |
| 2013 | October | 66.89 | 100.12 | 89.89 |
| 2013 | November | 24.60 | 65.31 | 73.52 |
| 2013 | December | 8.02 | 11.54 | 84.50 |
| 2014 | January | 9.84 | 10.32 | 104.93 |
| 2014 | February | 11.76 | 12.71 | 110.38 |
| 2014 | March | 30.14 | 46.40 | 131.77 |
| 2014 | April | 53.10 | 102.58 | 146.05 |
| 2014 | May | 60.44 | 126.07 | 141.61 |
| 2014 | June | 42.88 | 67.95 | 106.63 |
| Mean annual (g $CO_2$ C $m^{-2}$ $y^{-1}$) | | 561.13 | 910.36 | 1296.69 |
| Mean annual (t $CO_2$ C $ha^{-1}$ $y^{-1}$) | | 5.61 | 9.10 | 12.97 |

Generally, Guo and Gifford (2002) observed that land-use conversions from native vegetation, either savannah woodland or herbaceous grasses to semi-natural ones such as cropland lead to reduction in SOC. As SOC accumulation in the soil is partly due to the soil's decomposition rates, soils under cropland with less decomposition will have relatively low SOC stocks. Thus typically, the woodlands would have high annual soil respiration than the graze-lands, due to variations in soil moisture and SOC content (McCulley *et al.,* 2004) as well as root biomass. The findings agree with the observation by Saviozzi *et al.* (2001) that graze-lands have soil respiration rates about 25% higher than those of the adjacent croplands. Similarly, results from Brümmer *et al*. (2009) at Southwest Burkina Faso, revealed that the mean annual soil respiration for cropland was lower (3.51 t $CO_2$ C $ha^{-1}$ $y^{-1}$) than that of savannah or grassland (4.84 t$CO_2$ C $ha^{-1}$ $y^{-1}$).

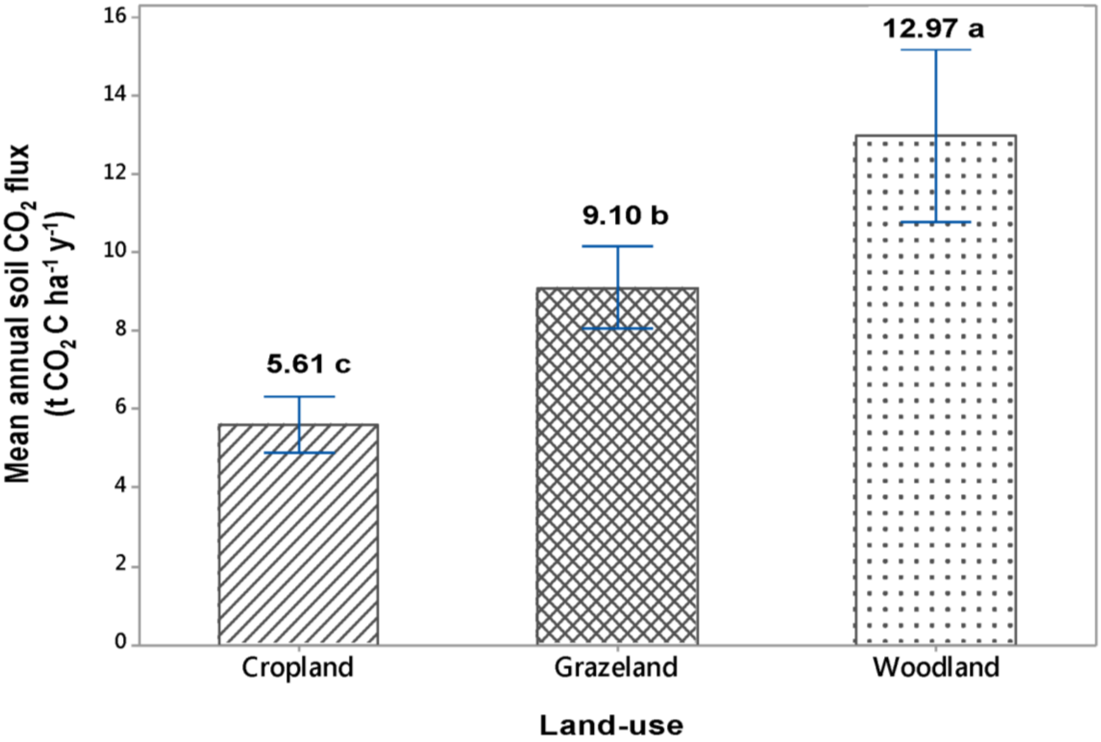


Figure 4.1: Comparison of mean annual soil $CO_2$ flux from the major land-uses in the Vea catchment.

***Land-use systems with different alphabet(s) are significantly different at α=5% (0.05) by Fisher's LSD multiple comparison tests at P = 0.000, DF = 2 and F-ratio = 117.34.***

Conversely, Raich and Tufekcioglu (2000) reported that under comparable conditions, soil respiration rates are consistently greater in graze-lands than in forests as grasslands tend to allocate more photosynthetic products to below ground portions than forests which allocate more carbon to wood production. For tropical savannas in general, Raich and Schlesinger (1992) estimated the soil C turnover rates from a ten-year data and revealed that annually, tropical savannah and grassland $CO_2$ efflux was 6.3 t $CO_2$ C $ha^{-1}$ $y^{-1}$.

### 4.3 Effects of land-use dynamics on soil organic carbon (SOC)

The total SOC density (0 – 30 cm soil depth) under the predominant land-use systems in the catchment were respectively 37.91 ± 1.29, 29.31 ± 1.74 and 27.36 ± 1.70 Mg C $ha^{-1}$ for the woodland, graze-land and cropland (Table 4.2). Using the current (2013) SOC stock as the base year and assuming the business as usual scenario, the IPCC SOC tool was used to estimate the decadal historical SOC dynamics of the predominant uses for a 30-year period (2003, 1993 and 1983) as well as a short-term prediction of the SOC stock dynamics was made for a 60-year period.

Using the woodland SOC stock estimates from the base year (2013) as a benchmark, the impact of internal land-use conversion on SOC stock was determined. A carbon loss on the conversion of woodland to cropland was more pronounced than conversion from woodland to graze-land, which is relatively, a poorly-managed native vegetation. On the other hand, conversion from cropland to graze-land or woodland or from graze-land to woodland increases SOC stock. Within the land-use systems, the C losses were in the increasing order of cropland followed by graze-lands whilst woodland SOC stock was maintained constant. Soil carbon stocks largely comprise stocks of carbon in soils as well as additional carbon into soils from active sequestration. Unfortunately, the current agricultural management regimes in the study area provide few opportunities for organic matter returns to the soil. The results confirm the observation by Le (2012) that agricultural production in the region is exhaustive in nature and could eventually lead to land degradation if not checked.

Table 4.2: Total soil carbon stocks under predominant land-uses in the Vea catchment at 0 – 30 cm depth

| Year | Land-use | SOC (Mg C $ha^{-1}$) |
|---|---|---|
| | | (Mean ± SE) |
| 2013-Base year | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 29.31 ± 1.74 |
| | Cropland | 27.36 ± 1.70 |
| 2003* | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 29.76 ± 1.74 |
| | Cropland | 30.64 ± 1.70 |
| 1993* | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 30.22 ± 1.74 |
| | Cropland | 33.92 ± 1.70 |
| 1983* | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 30.67 ± 1.74 |
| | Cropland | 37.20 ± 1.70 |

* denotes estimates based on IPCC (2003) defaults values.
± precedes the standard error (SE) values

Paired correlation matrix was used to determine inter-relationship between the soil $CO_2$ fluxes and the estimated SOC stocks under the predominant land-uses (cropland, graze-land and woodland) at the catchment (Table 4.3). Soil $CO_2$ fluxes correlated highly with SOC stocks for all the major land-uses (p=0.74) at 1% level of significance (99 percent confidence), signifying that measurements of soil $CO_2$ fluxes can easily be used as a suitable indicator of SOC stocks and soil carbon turnover for agricultural production. Thus soil respiration measurements could be essential in agronomic studies to evaluate soil fertility, carbon translocation and soil carbon turnover (Luo and Zhou, 2006) and may be as well useful in policies regarding carbon trading and payment for on-farms carbon sequestration which is an important ecosystem service to enhance soil productivity and mitigate climate change.

Table 4.3: Correlation between soil $CO_2$ flux, SOC, SOM and selected soil physical parameters under predominant land-uses in the Vea catchment

| Correlations | Overall Parameters | | | | | |
|---|---|---|---|---|---|---|
| | Soil $CO_2$ flux | SOC (Mg/ha) | SOM (%) | VMC (%) | pH | Porosity |
| Soil $CO_2$ flux | 1 | | | | | |
| SOC (Mg/ha) | 0.74** | 1 | 0.95** | 0.58** | | |
| SOM (%) | 0.69** | | 1 | 0.54** | | |
| VMC (%) | 0.58** | | | 1 | | |
| pH | 0.65** | 0.47** | 0.45** | 0.16 | 1 | |
| Porosity | 0.64** | 0.65** | 0.74** | 0.57** | 0.52** | 1 |

** Correlation is significant at the 0.01 level (2-tailed).

Table 4.4 shows the 60-year SOC stock density predictions for the major land-uses. It clearly shows that the current agricultural practices will deplete SOC stocks within the next 30 years. De Deyn *et al.* (2008) observed that SOC accumulation is the result of the balance between inputs of carbon to the soil organic matter (SOM) from primary productivity and outputs from soil respiration. Thus if this process of arable land SOC loss continues, food supply will be at stake (Mackenzie and Mackenzie, 1995) as in the long run, carbon mineralisation would have a significant impact on soil fertility and food security through SOC depreciation and on GHG emissions and the net ecosystem carbon balance. As soil is a complex ecosystem, carbon storage and permanence of soil carbon stocks and soil organic matter (SOM) are controlled by both biotic or abiotic factors which regulate the balance between inputs and outputs of carbon to and from the soils in different ecosystems (Schmidt *et al.,* 2011). Thus the combination of high temperature, moisture stress and lower SOC input to soil due to poor land management practices will make soils in the area prone to land degradation. Good land-use or management practices that encourage high organic matter returns to the soil should be recommended to help stem this threat of land degradation. Examples of such practices include, use of cover crops, strip cropping, mulching, composting and manuring, fertiliser application, improved fallow and conservation tillage practices (Lal, 1995).

Table 4.4: Predicted total soil carbon stock under predominant land-uses in the Vea catchment based on IPCC (2003) default values

| Year | Land-use | SOC (Mg C ha$^{-1}$)<br>(Mean ± SE) |
|---|---|---|
| 2013-Base year | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 29.31 ± 1.74 |
| | Cropland | 27.36 ± 1.70 |
| 2023 | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 28.85 ± 1.74 |
| | Cropland | 24.08 ± 1.70 |
| 2033 | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 28.40 ± 1.74 |
| | Cropland | 20.80 ± 1.70 |
| 2043 | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 27.94 ± 1.74 |
| | Cropland | 17.52 ± 1.70 |
| 2053 | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 27.49 ± 1.74 |
| | Cropland | 14.24 ± 1.70 |
| 2063 | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 27.03 ± 1.74 |
| | Cropland | 10.96 ± 1.70 |
| 2073 | Savannah woodland | 37.91 ± 1.29 |
| | Graze-land | 26.58 ± 1.74 |
| | Cropland | 7.68 ± 1.70 |

Soil depth at 0 – 30 cm, ± indicates the standard error

## 4.4 Effect of Major Cropping Systems on Soil Respiration

The effects of the agricultural land-uses (cropping systems) in the growing season on soil respiration were computed. Essentially the growing season starts from June till October, but soil respiration measurements were extended to November. The common cropping systems at the catchment were monoculture (rice and groundnut) and mixed cropping of the major staple crops; early millet intercropped with sorghum and late millet. Figure 4.2 illustrates a plot of the mean total soil respiration rates for rice and groundnut monocultures and that of early and late millet and sorghum intercropping for the entire growing season. Soil respiration rate under mixed cropping system was highest with mean total $CO_2$ flux of 114.67 ± 3.51 followed by rice monoculture 108.08 ± 2.82 and lastly groundnut monoculture, with 83.17 ± 2.85 mg $CO_2$ C $m^{-2}$ $h^{-1}$. Statistically, each of these soil $CO_2$ flux estimates were significantly different ($p<0.05$) based on Fisher's multiple tests at 95 percent level of confidence ($\alpha=0.05$)**.**

The pattern of cropping at the catchment is that by experience, farmers cultivate the main crops (sorghum and millet) on relatively fertile soils whilst the poor soils are dedicated to groundnut cultivation and the waterlogged sites are dedicated to rice farming. Thus early millet, sorghum and late millet are intercropped but harvesting is done in phases such that there remain significant amount of soil cover which tends to conserve moisture and protect the soil from erosion. Again, the intercropping system tends to increase root biomass. All these factors lead to relatively high soil $CO_2$ flux under this cropping system compared to the monocultures as the high soil fertility, optimum soil moisture and temperature and high root biomass favour decomposition and other biological activities which release $CO_2$.

On the other hand, groundnut cultivation could have improved soil nitrogen through fixation by bacteria and residues addition but unfortunately, the crops are dedicated to poorer sandy soils on quite steep slopes and harvesting is done wholly such that there are virtually no returns to the soil. This could account for the lowest respiration rates. The dry soil conditions also affect decomposition and activities of soil organisms which result in low soil $CO_2$ efflux as optimum amount of soil moisture normally increases the bio-activity in the soil (Uusimaa, 2003) and hence $CO_2$ production.

Rice cultivation is dedicated to waterlogged areas in the catchment. As rice is moisture demanding, it tends to maximise the relatively high soil moisture for its growth and productivity and these activities eventually release $CO_2$ onto the soil-plant environment leading to slightly higher $CO_2$ flux compared to groundnut fields. However, at high levels of soil water content (particularly in the wet season) limitations on oxygen diffusion tends suppress soil $CO_2$ flux whilst the simultaneous dissolution the soil $CO_2$ within the chambers also minimises the $CO_2$ flux. Thus although, soils in the rice fields can retain more moisture which tend to favour the plants physiological activities and high soil $CO_2$ efflux compared to the relatively poor sandy soils at groundnut cultivated areas, moisture content at certain threshold tends to inhibit aerobic respiration due to oxygen deficiency. This eventually suppresses the rate of $CO_2$ diffusion within the soil profile (Davidson and Trumbore, 1995) and reduces the overall soil $CO_2$ flux. Thus total soil $CO_2$ flux was reduced in rice fields because of limited diffusion of oxygen and subsequent suppression of $CO_2$ emissions (Tang *et al.*, 2003).

Notwithstanding, the cropping practices at the catchment are typically exhaustive (Le, 2012) with very minimal returns to the soil in terms of organic matter. The SOC density predictions (Table 4.2) indicated that soil carbon stocks will be depleted in the next three decades if good management practices are not adopted by farmers. The SOC density is expected to fall to 17.52 ± 1.70 Mg C ha$^{-1}$ compared to expected value of 28.8 Mg C ha$^{-1}$ estimated for the area by IPCC (2003). Farmers must embrace good soil management practices if they want to sustain their livelihood in the next few decades as they risks degrading the soil and climate change is likely to exacerbate the situation.

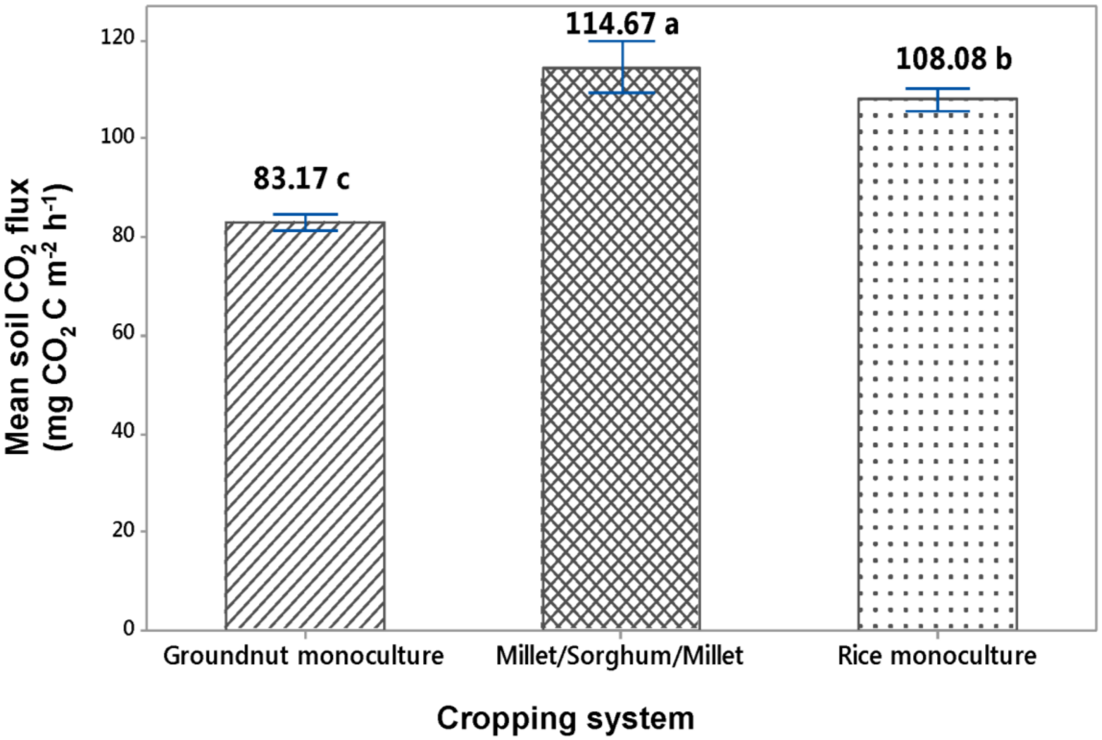


Figure 4.2: Effects of common cropping systems on mean soil $CO_2$ flux in the growing season (June - October) at the catchment

***Cropping systems with different alphabet(s) are significantly different at α=5% (0.05) by Fisher's LSD multiple comparison tests at P-value of 0.000, DF =2 and F-ratio of 434.***

### 4.5 Effect of Field Management Practices on Soil Respiration

Comparison of soil respiration on rice field under different field management practices (fertiliser application, mulching, compost manuring and control) is shown in Figure 4.3. Soil $CO_2$ efflux obtained from the four different management practices were significantly different at F (3) =13.67 and p = 0.002. The mean soil $CO_2$ flux from mulched soils was the highest (127.03 ± 7.61 mg $CO_2$ C $m^{-2}$ $h^{-1}$) followed by fertiliser application (114.05 ± 8.68 mg $CO_2$ C $m^{-2}$ $h^{-1}$), with the control obtaining slightly higher soil $CO_2$ flux (107.40 ± 4.60 mg $CO_2$ C $m^{-2}$ $h^{-1}$) than the flux from soil under the composted organic manure application (93.36 ± 5.82 mg$CO_2$C $m^{-2}$ $h^{-1}$). Soil $CO_2$ flux from mulched soils were significantly different ($p<0.05$) from all the other practices due to high decomposition rates from substrates and moisture availability. There were also significant difference ($P<0.05$) between $CO_2$ fluxes from fertiliser and compost organic manure application and those from control experiment, but between fertiliser application and control field, fluxes were not significantly different ($p>0.05$). The relatively high soil $CO_2$ flux from fertilisation may be due to the increased physiological activities of plants including photosynthesis, LAI and root biomass increment. Field studies had confirmed that fertilisation of agricultural soils generally increases soil $CO_2$ flux (Luo and Zhou, 2006). The low soil $CO_2$ flux from compost organic manuring may be due the composting method used by farmers in the area such that greater amount of the $CO_2$ are given off during the passive composting of the fresh cow dung (Hao *et al.*, 2001). Thus on application to the soil, only limited amount of $CO_2$ and other GHGs are emitted.

In general, during the decomposition of SOM, organic nutrients contained in organic matter (e.g., organic phosphorus, nitrogen, and sulphur) are converted to inorganic forms that are available for plant uptake. This conversion is known as mineralisation. As a result soil respiration can sometimes be referred to as carbon mineralisation. The reduced soil respiration rates indicate that there is little or no SOM or aerobic microbial activity, an indication of less input from the management practices of farming system. Soil respiration reflects the capacity of soil to support soil life including crops, soil animals, and microorganisms and describes the level of microbial activity, SOM content and its decomposition.

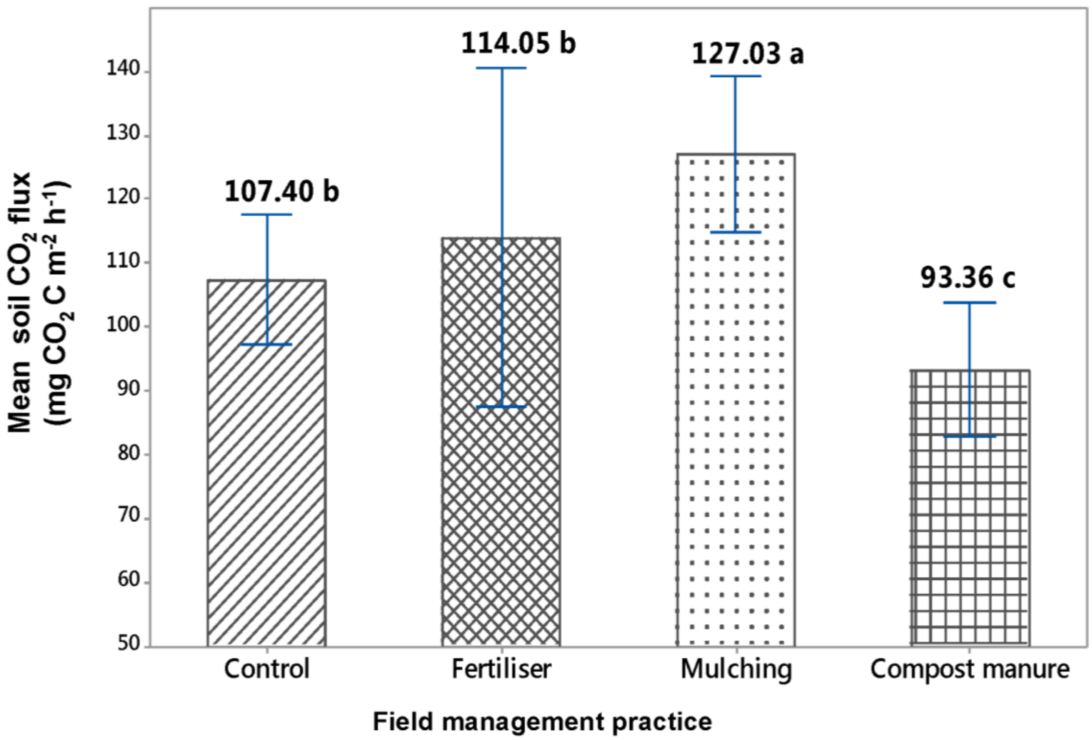


Figure 4.3: Effects of field management practices on mean soil $CO_2$ flux from rice field in the growing season (July – November, 2013)

***Management systems with different alphabet(s) are significantly different at α=5% (0.05) by Fisher's LSD multiple comparison tests at P-value of 0.002, DF of 3 and F-ratio = 13.67***

Lal (2004) recommends the adoption of cropping systems and management practices that add crop residues to soil to help improve SOC quantities and enhance the soil productivity. Such practices have a dual advantage of adding SOC and helping in their eventual sequestration to lock carbon in permanent storage as well as reducing C flux in the atmosphere which will affect the global carbon budget. Examples of such practices include, use of cover crops and crop rotation, strip cropping, mulching, composting and manuring, fertiliser application, improved fallow and conservational or no tillage practices. The success however, of each management practice to improve soils carbon stock depends on many factors such as the ecosystem type, type of soil and soil condition (Lal, 2009).

## 4.6 Effect of land preparation activities at the catchment on soil respiration

The effect of different land preparation activities on soil $CO_2$ flux is shown in Figure 4.4. The common land preparation activities at the catchment include manual hoeing which affects just some few centimetres of the topsoil (4 – 6 cm), bullock ploughing (about 7 – 9 cm of topsoil) and conventional tillage methods (mechanical tillage) which affects up to 10 – 12 cm of the soil or beyond and involve mechanised implements where the land is ploughed and harrowed. The mean soil $CO_2$ flux from manual hoeing was highest (108.78), followed closely by conventional tillage (107.40) whilst bullock ploughing had the least (106.89 mg $CO_2$ C $m^{-2}$ $h^{-1}$). However, Fisher's LSD multiple comparison tests indicated that the mean soil $CO_2$ flux from the land preparation activities were not significantly different ($p > 0.05$). The observation made from the study was that farm lands are usually prepared soon after the first few rain events in waiting for the onset of the full rainy season before seeds are sown. Thus during this period of waiting, soil disturbances resulting from land preparation could have been minimised drastically before crops are sown at the start of the growing season. This might have accounted for the relatively no differences in the mean soil $CO_2$ flux from the land preparation activities. Again, it was impossible to undertake the $CO_2$ flux measurements concurrently with the land preparation activities as the activities were not done at the same time. The less endowed farmers usually wait for the relatively rich farmers to finish preparing their lands before they could borrow their implements to prepare their lands.

In general, unlike no tillage, reduced or conservation tillage, conventional tillage practices in land preparation activities typically cause more soil disturbances. This often results in significant soil carbon loss (Schuman *et al.*, 2002) and increases GHGs emissions, especially $CO_2$ to the atmosphere (Paustian *et al.*, 2000). Again, the use of mechanical tillage disrupt soil aggregates, which leads to decomposition of soil organic matter and $CO_2$ efflux (Soares *et al.*, 2005) and stimulates short-term microbial activity through enhanced aeration, resulting in increased levels of $CO_2$ and other gases released to the atmosphere (Kladivko, 2001).

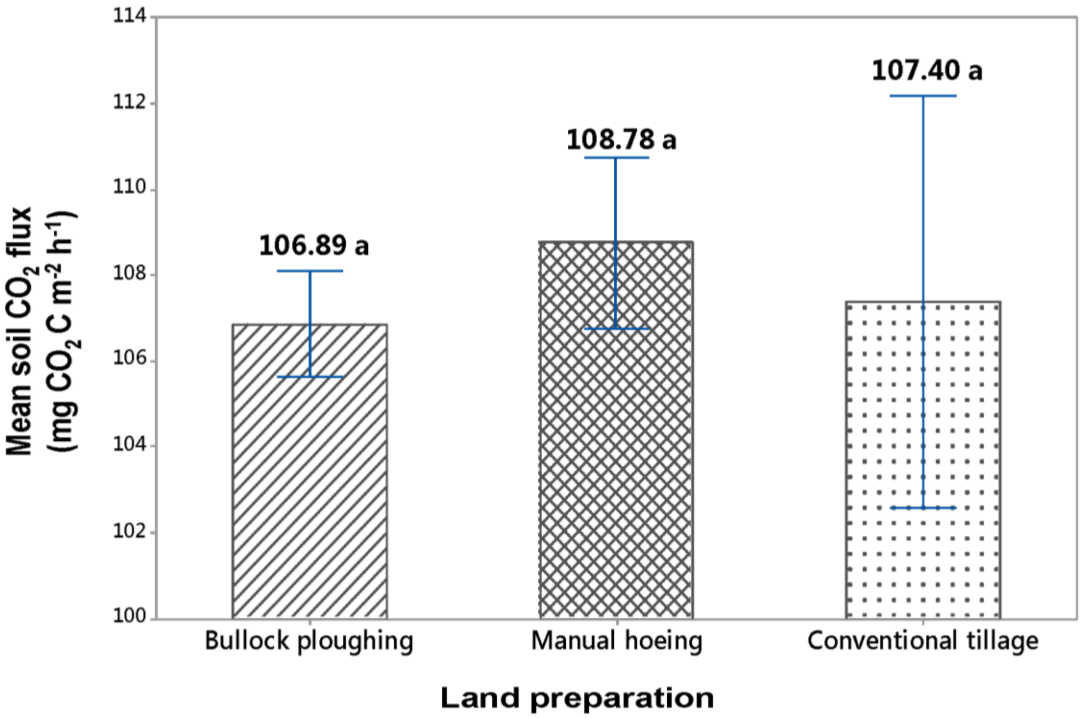


Figure 4.4: Effects of land preparation on mean soil $CO_2$ flux from rice field in the growing season (June- October)

***Field practices with same alphabet(s) are not significantly different at α=5% (0.05) by Fisher's LSD multiple comparison tests at P-value of 0.236, DF of 2 and F-ratio of 1.86***

Contrary to these findings, the mean soil $CO_2$ fluxes from the land preparation activities were almost similar and the slight differences could result from diversity in soil constituents rather than tillage or land preparation effect. However, conventional tillage practice coupled with poor residue management may accelerate soil erosion making the soil less productive and eventually leading to soil degradation as tillage can leave soils more prone to erosion and degradation, resulting in further loss of soil carbon (Lal, 2006).

## 4.7 Effects of Soil Temperature and Moisture on Pattern of Soil Respiration

Soil temperature and soil water content, or the interaction between both, are the main controlling factors of the variability of soil respiration (Kang *et al.,* 2003). In many previous studies in the tropical savannah on soil-atmosphere exchange of trace gases measurements are usually limited to only few weeks of either the dry or wet season or the transition period between the two seasons (Castaldi *et al*., 2004; Sanhueza and Donoso, 2006). As a result, measurements may not be representative of the true conditions pertaining on the field. In line with Rayment and Jarvis (2000), measurements for the present study were undertaken continuously for 13 months spanning the growing season of first year of investigation (2013), the dry season through the transition period (dry to wet season) to the beginning of the growing season of the second year of investigation (2014).

### 4.7.1 Effect of soil temperature on pattern of soil respiration

In many ecosystems, soil temperature is the main environmental factor affecting soil $CO_2$ efflux due to its influence on decomposition activities. Soil temperature at 5 cm depth near each soil collar was measured for each chamber during soil respiration measurement. Figure 4.5 shows the response of soil respiration (SR) to change in soil temperature (Tsoil) at the depth of 5cm for wet season (a), dry season (b) and combined seasons (c). The dots represent mean soil $CO_2$ flux data whilst the solid lines represent the exponential regressive curves *a, b*, and *c* for the wet, dry and combined seasons for the study site respectively. For the entire study period, no soil temperature below 10 °C were recorded at any of the sampling sites, the lowest soil temperature recorded was about 28 °C. The results show that soil respiration was quite sensitive to soil temperature. The highest mean soil $CO_2$ fluxes (280 - 300 mg $CO_2$ C $m^{-2}$ $h^{-1}$) were measured in the wet period (Figure 4.5a), when the mean soil temperature was between 30 °C and 33 °C whilst the least soil $CO_2$ fluxes (3-6 mg $CO_2$ C $m^{-2}$ $h^{-1}$) were measured in the dry season (Figure 4.5b) when the mean soil temperature was beyond 35°C despite the different temperature sensitivities ($Q_{10}$). The results of correlation analysis indicated that there were obvious negative correlations between soil temperature and soil $CO_2$ flux for all the land-uses apart from woodland (Table 4.5). Thus since the climate of the study area is generally characterised by high temperatures (annual average 29 °C), soil temperature increases beyond a certain threshold (about 30°C) tends to negatively affect the soil respiration rates such that there was no correlation between soil respiration and soil temperature beyond this threshold value.

Table 4.5: Correlation between soil respiration, soil moisture and soil temperature under cropland, graze-land and woodland in the Vea catchment

| | CROPLAND | | | GRAZE-LAND | | | WOODLAND | | |
|---|---|---|---|---|---|---|---|---|---|
| | SR | SM | ST | SR | SM | ST | SR | SM | ST |
| SR | 1 | | | 1 | | | 1 | | |
| SM | 0.955* | 1 | | 0.911* | 1 | | 0.232* | 1 | |
| ST | -0.606* | -0.760* | 1 | -0.624* | -0.759* | 1 | 0.372* | -0.612* | 1 |

**Correlation is significant at 1% level (α=0.01) (2-tailed)*

SR = Mean soil $CO_2$ flux (mg $CO_2$ C $m^{-2}$ $h^{-1}$),
SM = Volumetric soil moisture content (%) at 5cm depth
ST = Soil Temperature (°C) at 5cm depth

In general soil temperature is one of the most dominant factors affecting the soil respiration rate and many previous studies on many different sites at different time scales have reported that soil respiration is strongly temperature-dependent such that typically, increasing soil temperature also increases the soil respiration rate (Kirschbaum, 1995; Davidson *et al*., 1998). Soil $CO_2$ efflux usually increases exponentially with increasing temperature and this relationship can be described with exponential or Arrhenius type equations, which have different theoretical bases (Lloyd and Taylor, 1994).

However, a totally opposite response has also been recorded at certain climatic conditions as observed by the current study. This may be due to the fact that soil environment is a complex system with a community of soil organisms and total activity is determined by the combined activity of a range of different organisms that may have different individual temperature sensitivities (Kirschbaum, 1995). The $Q_{10}$ which is commonly used as a convenient indicator to summarise the temperature sensitivity of soil $CO_2$ efflux, has been found to be conceptually constant in most commonly used models (Kirschbaum, 1995) or variable in the other models with temperature (Lloyd and Taylor, 1994). The temperature sensitivity ($Q_{10}$) values obtained in the currently were extremely low. The wet period had 0.54, the dry period obtained 0.51 whilst 0.33 was determined was for soil $CO_2$ fluxes for the combined seasons. Consequently, for ecosystems in areas where soil temperatures are low (< 35 °C), soil $CO_2$ efflux tend to be more sensitive to changes in soil temperature whilst in areas where soil temperatures are high as in current study, soil $CO_2$ efflux tends to be less sensitive to changes in soil temperature.

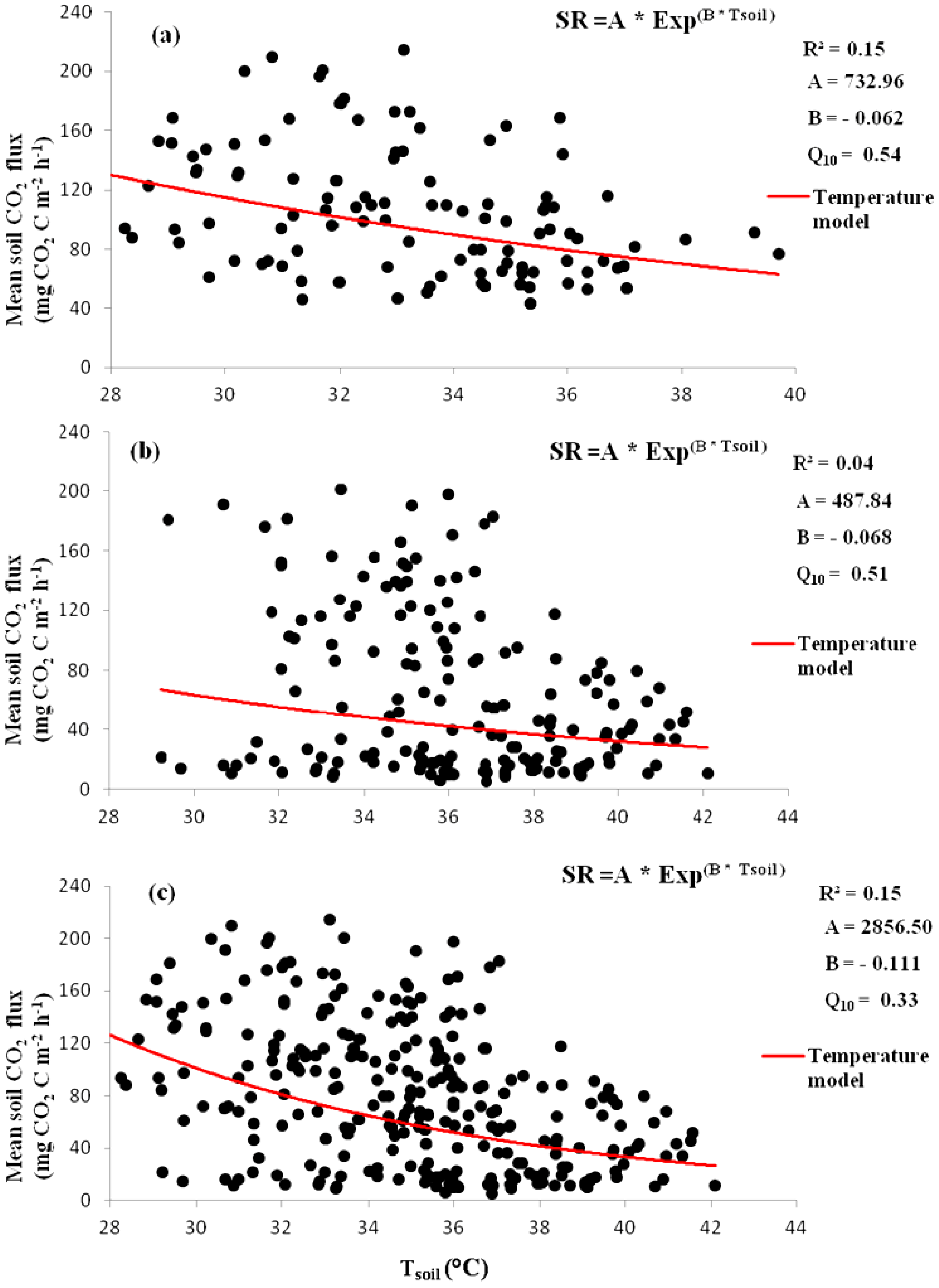


Figure 4.5: Response of soil respiration (SR) to change in soil temperature (Tsoil) at the depth of 5cm for wet season (a), dry season (b) and combined seasons (c)

### 4.7.2 Effect of soil moisture content on pattern of soil respiration

Soil moisture is another important factor influencing soil respiration. Soil volumetric water content (VWC [%]) at 5 cm depth near each soil collar was measured for each chamber during soil respiration measurement. The response of soil respiration (SR) to changes in soil water content (VWC) at the depth of 5cm for wet season (a), dry season (b) and combined seasons (c) at the study sites is shown in Figure 4.6. The dots represent mean soil $CO_2$ flux data whilst the solid lines are the linear regression relationships *a, b*, and *c* for the wet, dry and combined seasons for the study site respectively. The results show that for all seasons, SR was sensitive to soil moisture with SR increasing linearly with increase in soil moisture although SR was more sensitive to changes in soil moisture in the dry period (Figure 4.6b, $R^2 = 0.40$) than in the wet period (Figure 4.6a, $R^2 = 0.30$). During the dry period, the soil is subject to a combination of high temperatures and water stress, which tend to control the fluxes of soil $CO_2$. Thus the occurrence of small amount of rain event increases the soil moisture content and hence the SR rates, however, at high levels of soil water content (particularly in the wet season) limitations on oxygen diffusion tends to suppress soil $CO_2$ efflux whilst the simultaneous dissolution the soil $CO_2$ within the chambers also minimises the soil $CO_2$ flux.

Figure 4.7 shows relationship between soil respiration (SR) and soil moisture VWC (%) across four land-uses on the landscape. It clearly shows that VWC is unevenly distributed across the land-uses on the landscape. Consequently the SR rates will be controlled by the VWC distribution. Soils under cropland had the least VWC (5-10 %) and least SR (50-90 mg $CO_2$ C $m^{-2}$ $h^{-1}$) whilst those under woodland with relatively high VWC (12 %) had the highest SR (190 mg $CO_2$ C $m^{-2}$ $h^{-1}$). The SR rates of the waterlogged soils (wetland) were also low (80-120 mg $CO_2$ C $m^{-2}$ $h^{-1}$) although it had the highest VWC (13 %) among the land-uses, signifying the suppressing effect of soil water on $CO_2$ flux due to limitations on oxygen diffusion and $CO_2$ dissolution within the measurement chamber (Welles *et al.,* 2001).

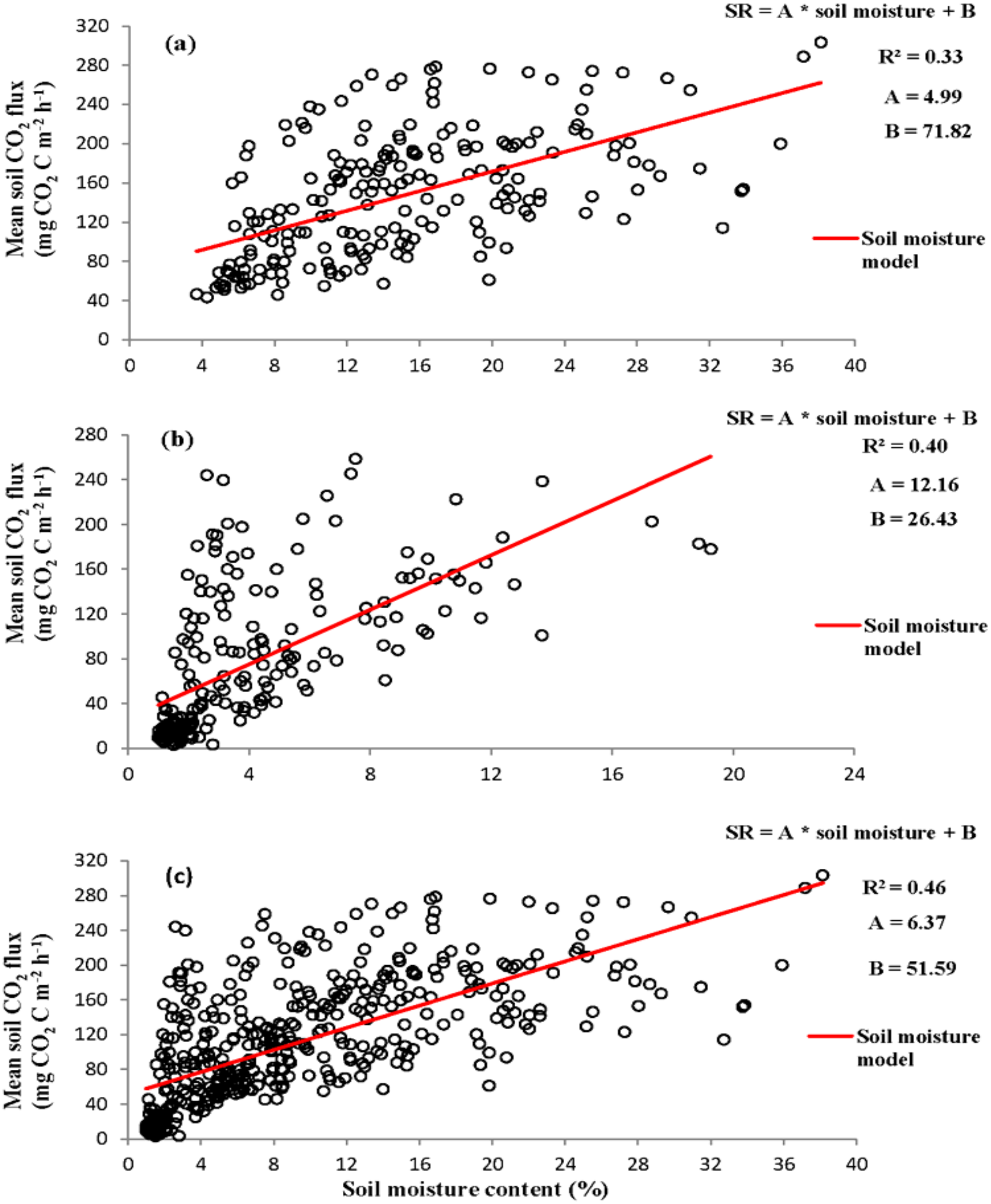


Figure 4.6: Response of soil respiration (SR) to change in soil moisture content (SMC) depth of 5cm for wet season (a), dry season (b) and combined seasons (c)

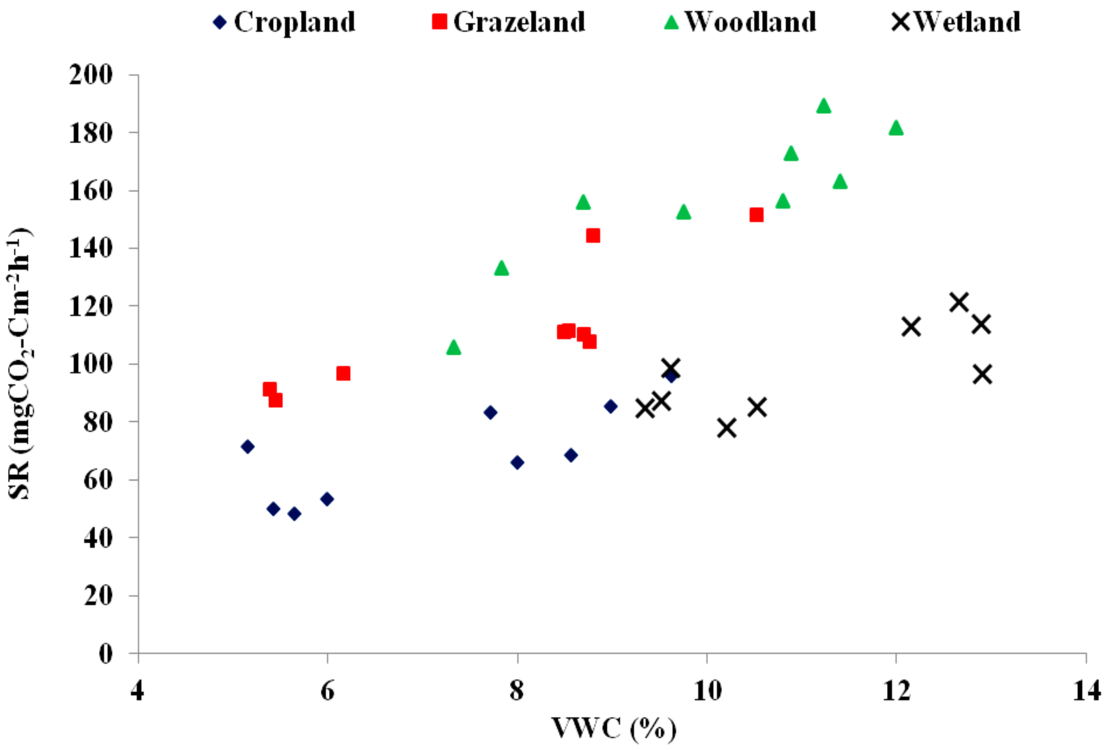


Figure 4.7: Relationship between soil respiration (SR) and soil moisture VWC (%) across four land-uses on the landscape

Figure 4.8 (a, b and c) shows the influence of the major land-uses on the pattern of soil respiration (SR), soil moisture (SM) and soil temperature (ST) dynamics for the entire study period. It was observed that SR increased steadily between June and September and started decreasing sharply between September and November for all land-uses except woodland. Thus the highest rate of SR (about 220 mg $CO_2$ C m$^{-2}$ h$^{-1}$) occurred in the wetter months (July-September, 2013 and March-May, 2014) whilst the least rate of SR (30 mg $CO_2$ C m$^{-2}$ h$^{-1}$) was observed in the drier months (November - January) for all land-uses. Similarly, for all land-uses, SM followed the pattern of respiration as described; the highest moisture percentage (about 30 %) were recorded in the wet months (July-September, 2013 and March-May, 2014) and the lowest percentage (about 3% ) were recorded in the drier months (November – February) (Figure 4.8b). The pattern of ST however, was quite opposite to observation for soil respiration and soil moisture (Figure 4.8c). The coldest soil temperatures (about 28 °C) occurred in March – May (2014) and hottest (about 40°C) occurred between October and February. This observation affirms the high dependence of soil respiration on soil temperature and moisture such that the two factors must be considered together to predict accurately the level of respiration as they affect soil microbial activity (Tang *et al.*, 2003).

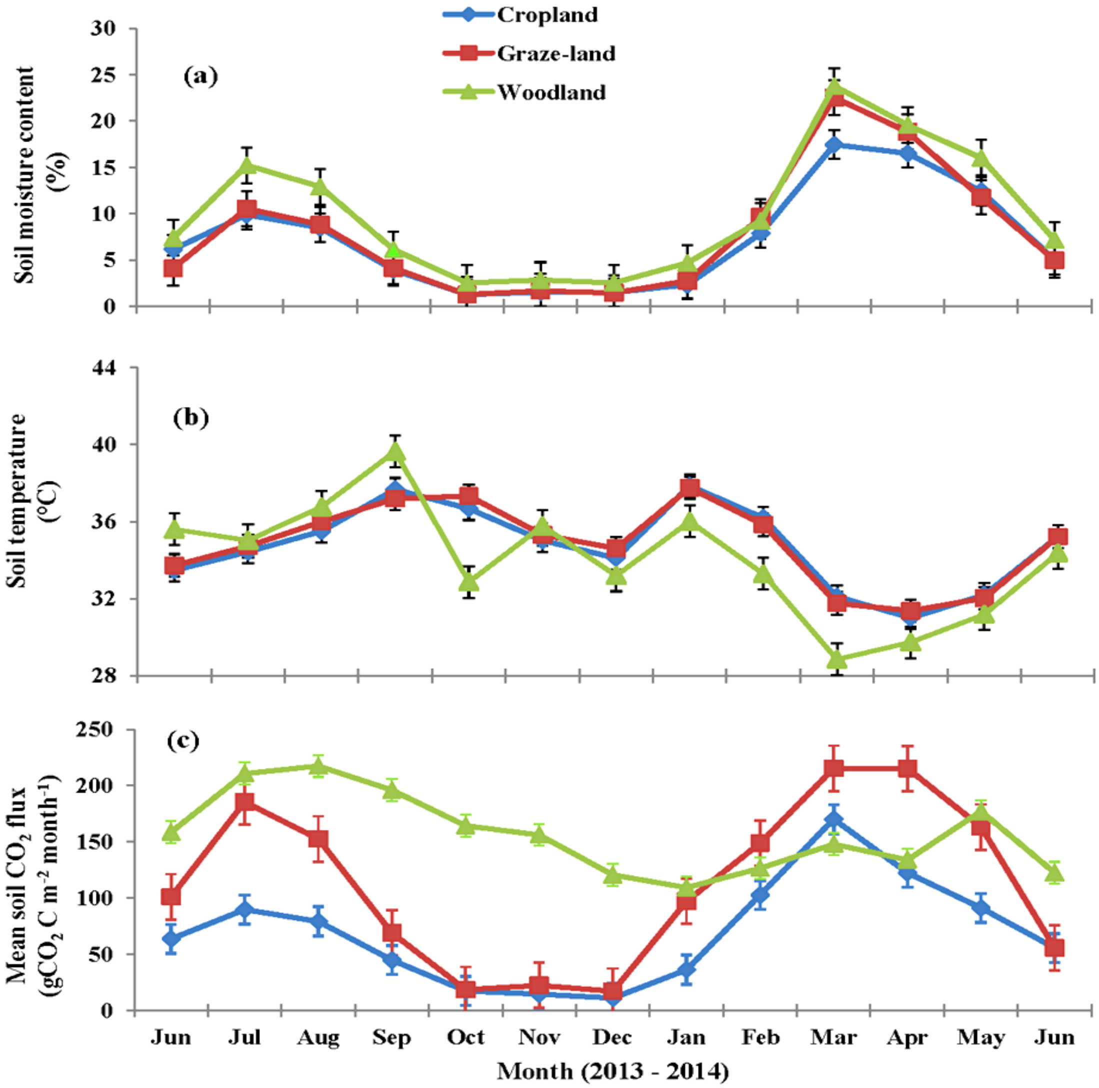


Figure 4.8: Pattern of soil $CO_2$ flux (c) with variations in soil moisture (b) and soil temperature (a) at 5 cm depth for the major land-uses

Generally, water content is an important abiotic factor affecting soil $CO_2$ efflux and often interacts with soil temperature to affect soil respiration, making it difficult to separate the two factors due to their influence on soil microbial activities. Hence, accurate prediction of soil respiration level will demand that the influence of soil temperature and moisture on soil respiration be considered together (Raich and Potter, 1995; Davidson *et al*., 1998). Usually dry soils exhibit lower $CO_2$ flux than wet soils (Davidson *et al*. 2000; Reichstein *et al*. 2003) but at low temperatures (<5 ºC) (Tang *et al*., 2003) the soil $CO_2$ efflux is insensitive to water content until about 10-20 ºC (Howard and Howard, 1993).

In the current study, for instance, the combined effect of soil temperature and moisture on soil respiration rates for the major land-uses (Table 4.6a, b and c) revealed that for cropland, the mean soil $CO_2$ flux was low (69.21 mg $CO_2$ C $m^{-2}h^{-1}$) at high optimum soil temperature (34.72 °C) and low soil moisture content (7.24 %). However, the mean soil $CO_2$ flux for woodland was high (157.06 mg $CO_2$ C $m^{-2}$ $h^{-1}$) at high optimum soil temperature (34.02 °C) and relatively high soil moisture content (9.99 %) whilst the mean soil $CO_2$ flux for graze-land was 112.50 mg $CO_2$ C $m^{-2}$ $h^{-1}$ when the soil temperature and soil moisture content were 34.83 °C and 7.87 % respectively.

Thus soil respiration is usually driven by the optimum soil water content which is somewhere near field capacity as this volume facilitates $O_2$ diffusion., and where the micropore spaces are mostly water filled to facilitate diffusion of soluble substrates (Davidson *et al*., 2000). Extremely wet soils on the other hand, inhibit aerobic respiration due to oxygen deficiency (Skopp *et al*., 1990) and affect rate of $CO_2$ diffusion within the soil profile (Davidson and Trumbore, 1995). Thus total soil $CO_2$ efflux is reduced in soils with high water content, because of limited diffusion of oxygen and subsequent suppression of $CO_2$ emissions (Tang *et al.*, 2003). Drier soil conditions, on the other hand, affect root and micro-organism activity resulting in low soil $CO_2$ efflux. Thus increasing the soil moisture normally increases the bio-activity in the soil (Uusimaa, 2003) and hence $CO_2$ production.

Table 4.6a: Combined effects of soil temperature and soil moisture on the mean soil $CO_2$ flux in croplands in the Vea catchment

| | | Cropland | | | | | |
|---|---|---|---|---|---|---|---|
| Month | Year | SR (mg $CO_2$ C $m^{-2}$ $h^{-1}$) | | Soil Temperature (°C) | | Soil Moisture Content (%) | |
| | | Mean | SE | Mean | SE | Mean | SE |
| June | 2013 | 55.68 | 3.12 | 35.21 | 0.46 | 4.96 | 0.24 |
| July | 2013 | 91.24 | 11.91 | 32.19 | 0.46 | 12.42 | 1.22 |
| August | 2013 | 122.53 | 18.68 | 31.00 | 0.61 | 16.49 | 1.42 |
| September | 2013 | 170.14 | 16.78 | 32.10 | 0.63 | 17.43 | 2.24 |
| October | 2013 | 102.75 | 15.05 | 36.18 | 0.50 | 7.87 | 0.88 |
| November | 2013 | 36.31 | 4.11 | 37.87 | 0.75 | 2.31 | 0.12 |
| December | 2013 | 11.01 | 1.71 | 34.10 | 0.84 | 1.47 | 0.11 |
| January | 2014 | 14.69 | 1.22 | 35.01 | 1.30 | 1.50 | 0.10 |
| February | 2014 | 17.51 | 3.68 | 36.67 | 0.98 | 1.24 | 0.05 |
| March | 2014 | 44.90 | 5.88 | 37.67 | 1.22 | 3.91 | 0.17 |
| April | 2014 | 79.38 | 5.20 | 35.50 | 0.86 | 8.48 | 0.72 |
| May | 2014 | 89.84 | 12.14 | 34.43 | 1.12 | 9.86 | 1.10 |
| June | 2014 | 63.74 | 6.93 | 33.47 | 0.98 | 6.12 | 0.39 |
| Mean | | 69.21 | 8.19 | 34.72 | 0.82 | 7.24 | 0.67 |
| Min | | 11.01 | - | 31.00 | - | 1.24 | - |
| Max | | 170.14 | - | 37.87 | - | 17.43 | - |
| P-value | | 0.000 | - | 0.000 | | 0.000 | |

Table 4.6b: Combined effects of soil temperature and soil moisture on the mean soil $CO_2$ flux in graze-lands in the Vea catchment.

| Month | Year | Graze-land<br>SR ($mg\ CO_2\ C\ m^{-2}\ h^{-1}$) Mean | SE | Soil Temperature (°C) Mean | SE | Soil Moisture Content (%) Mean | SE |
|---|---|---|---|---|---|---|---|
| June | 2013 | 55.68 | 3.12 | 35.21 | 0.46 | 4.96 | 0.24 |
| July | 2013 | 163.20 | 14.15 | 32.02 | 0.33 | 11.76 | 0.78 |
| August | 2013 | 215.27 | 15.30 | 31.36 | 0.37 | 18.81 | 1.20 |
| September | 2013 | 215.37 | 16.25 | 31.75 | 0.52 | 22.51 | 2.35 |
| October | 2013 | 148.95 | 17.05 | 35.84 | 0.36 | 9.65 | 1.15 |
| November | 2013 | 97.17 | 15.78 | 37.75 | 0.60 | 2.73 | 0.25 |
| December | 2013 | 17.17 | 4.55 | 34.61 | 0.70 | 1.42 | 0.14 |
| January | 2014 | 22.47 | 2.85 | 35.31 | 1.16 | 1.66 | 0.12 |
| February | 2014 | 18.70 | 3.24 | 37.33 | 1.52 | 1.26 | 0.03 |
| March | 2014 | 69.12 | 8.47 | 37.19 | 0.96 | 4.12 | 0.26 |
| April | 2014 | 152.65 | 14.78 | 35.99 | 0.73 | 8.81 | 0.86 |
| May | 2014 | 185.6 | 12.58 | 34.71 | 1.07 | 10.52 | 1.07 |
| June | 2014 | 101.11 | 8.31 | 33.72 | 0.92 | 4.09 | 0.50 |
| Mean | | 112.50 | 10.49 | 34.83 | 0.75 | 7.87 | 0.69 |
| Min | | 17.14 | - | 31.36 | - | 1.26 | - |
| Max | | 215.37 | - | 37.75 | - | 22.51 | - |
| P-value | | 0.000 | - | 0.000 | | 0.000 | |

Table 4.6c: Combined effects of soil temperature and soil moisture on the mean soil $CO_2$ flux in woodlands in the Vea catchment.

| Month | Year | SR ($mg CO_2 C m^{-2} h^{-1}$) |  | Soil Temperature (°C) |  | Soil Moisture Content (%) |  |
|---|---|---|---|---|---|---|---|
|  |  | Woodland |  |  |  |  |  |
|  |  | Mean | SE | Mean | SE | Mean | SE |
| June | 2013 | 122.47 | 6.39 | 34.36 | 0.19 | 7.16 | 0.22 |
| July | 2013 | 177.21 | 16.18 | 31.18 | 0.11 | 16.01 | 1.23 |
| August | 2013 | 134.11 | 7.10 | 29.73 | 0.16 | 19.56 | 1.41 |
| September | 2013 | 148.01 | 17.47 | 28.85 | 0.19 | 23.77 | 2.36 |
| October | 2013 | 126.54 | 15.44 | 33.28 | 0.31 | 9.21 | 0.35 |
| November | 2013 | 109.45 | 8.98 | 36.00 | 0.42 | 4.67 | 0.52 |
| December | 2013 | 120.56 | 11.33 | 33.19 | 0.38 | 2.52 | 0.19 |
| January | 2014 | 156.14 | 16.54 | 35.77 | 0.18 | 2.82 | 0.22 |
| February | 2014 | 164.32 | 16.37 | 32.86 | 0.82 | 2.50 | 0.20 |
| March | 2014 | 196.14 | 14.12 | 39.64 | 0.21 | 6.11 | 0.37 |
| April | 2014 | 217.45 | 16.46 | 36.76 | 0.36 | 12.89 | 0.67 |
| May | 2014 | 210.75 | 14.70 | 35.02 | 0.37 | 15.22 | 0.98 |
| June | 2014 | 158.67 | 14.43 | 35.59 | 0.35 | 7.37 | 0.74 |
| Mean |  | 157.06 | 13.50 | 34.02 | 0.31 | 9.99 | 0.73 |
| Min |  | 109.45 | - | 28.85 | - | 2.50 | - |
| Max |  | 217.45 | - | 39.64 | - | 23.77 | - |
| P-value |  | 0.000 | - | 0.000 |  | 0.000 |  |

### 4.8 Effects of Topography on Soil Respiration for the Different Land-uses

Topography refers to the description of the physical features of a place and usually describes configuration of the ground surface, its altitude, slope, aspect and exposure. To determine the effect of topography, average monthly flux measurements for the 13 months (June, 2013 – June, 2014) observation were used. Figure 4.9 clearly illustrates the effect of topography on soil $CO_2$ flux for the three land-uses (a, b and c). Paired sample T-test shows that the overall effect of topography on soil respiration was highly significant ($p = 0.00$) with mean soil $CO_2$ flux at downslope (86.27 ± 9.12 [g $CO_2$ C $m^{-2}$ $month^{-1}$]) being over 30 percent higher than that at upslope position (64.81 ± 7.23 [g $CO_2$ C $m^{-2}$ $month^{-1}$]). Although the extent is variable, similar results were obtained on comparison of the effect of topographic positions on soil $CO_2$ flux for all the predominant land-uses considered for the study; cropland, graze-land and woodland. For cropland, the upslope was 52.57 ± 0.67 whilst the down slope was 72.83 ± 1.02, ($p= 0.009$), upslope graze-land was 90.31 ± 0.66 compared to 125.40 ± 4.34 at down slope ($p=0.042$). The upslope woodland soil $CO_2$ flux (117.44 ± 6.59) significantly differed from that at downslope (118.49 ± 6.40 [g$CO_2$C $m^{-2}$ $month^{-1}$]) ($p=0.000$). Table 4.7 shows the statistical comparisons for the major land-uses.

The effect of topography is widely driven by runoff which carries sediments and nutrients including SOC from upslope positions and deposit them downslope during rainy events which eventually creates micro-sites within the landscape with different environmental conditions and hence soil $CO_2$ effluxes. The findings agree with that of Risch and Frank (2006) on effect of slope position. In general, changes in soil $CO_2$ emissions and soil properties have been reported to be related to a host of topographic factors including micro-topography (Jia *et al.*, 2003), slope length and exposition (Kang *et al.*, 2006), slope angle (Silva *et al.*, 2004) and relief form (Souza *et al.*, 2006). Such topographic aspects can affect sub surface water redistribution and underground water flows, constituting the major cause of spatial variability of soil characteristics (Daniels and Hammer, 1992).

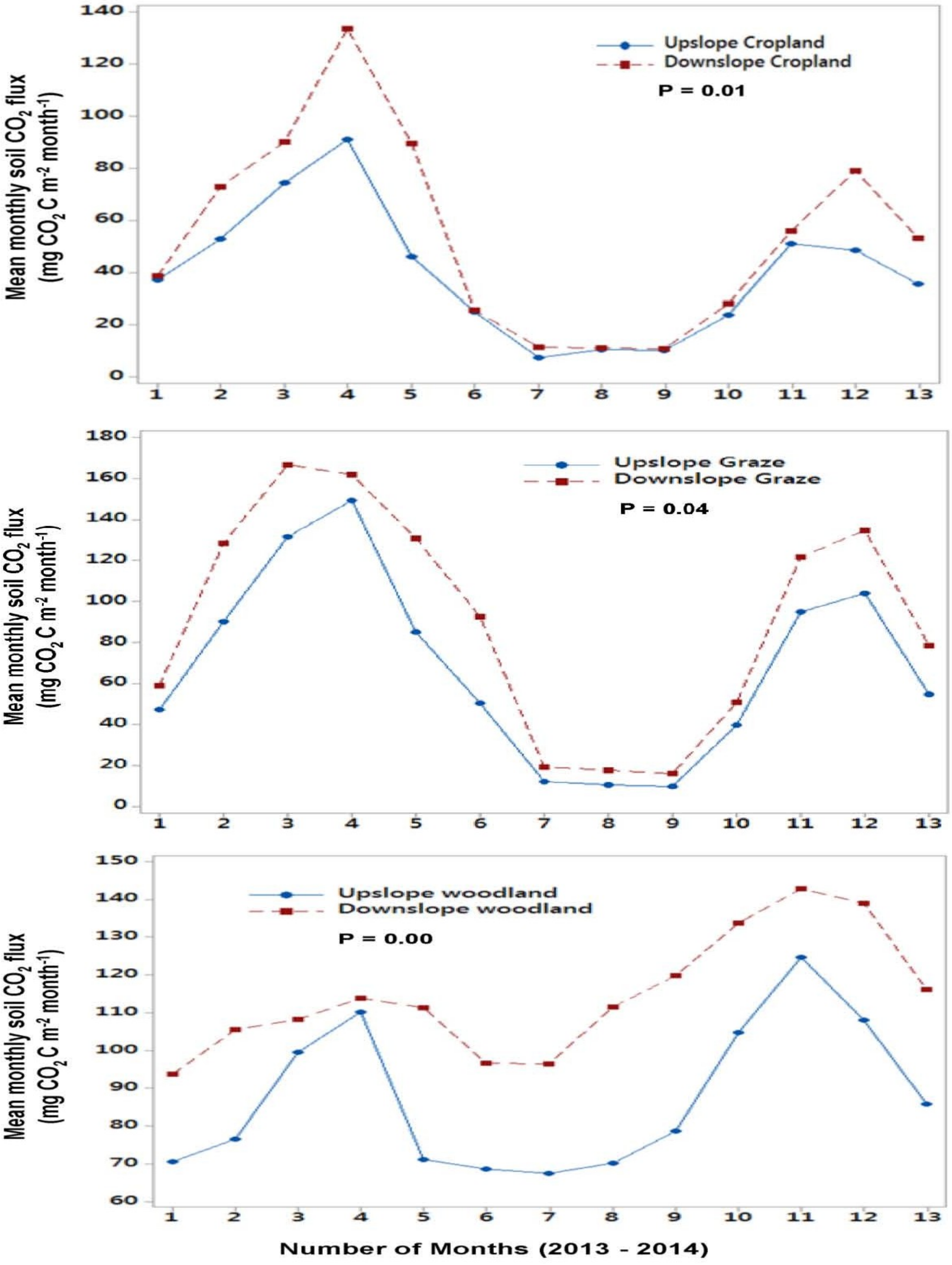


Figure 4.9: Effects of topography on mean monthly soil $CO_2$ flux (g $CO_2$ C $m^{-2}$ $month^{-1}$) under cropland (a), graze-land (b) and woodland (c) in the Vea catchment

Other previous studies have also established that topographic locations can influence soil respiration through the formation of micro-sites with relatively different micro-site factors, such as soil temperature (Kang *et al.,* 2000), soil water content (Western *et al.,* 1998), incident solar radiation (Kang *et al.*, 2002) and evapo-transpiration (Running *et al.,* 1987), These together influence the soil formation processes, soil nutrients and soil moisture dynamics and soil microbial activities, thereby affecting the spatial pattern of soil carbon dioxide efflux at a particular micro-site.

Table 4.7: Paired sample statistics for slope position comparison of predominant land-uses

| Effect of Slope position | | Mean | Std. Deviation | Std. Error | P value |
|---|---|---|---|---|---|
| Pair 1 | Upslope cropland | 39.3454 | 1.15482 | 0.66673 | |
| | Downslope cropland | 53.7235 | 1.76332 | 1.01805 | **0.009<0.05** |
| Pair 2 | Upslope graze-land | 67.7393 | 1.13675 | 0.65630 | |
| | Downslope graze-land | 90.5744 | 7.51073 | 4.33632 | **0.042<0.05** |
| Pair 3 | Upslope woodland | 87.3567 | 11.42118 | 6.59402 | |
| | Downslope woodland | 114.4989 | 11.08689 | 6.40102 | **0.000<0.05** |

(Note: N= 3, DF = 2)

### 4.9 Seasonal and Spatial Variations in Soil Respiration in the Study Field

The variations in soil $CO_2$ emissions are influenced by several soil properties related to $CO_2$ production and its diffusion in the soil. Seasonal and spatial variations in soil $CO_2$ flux information are essential to understanding how environmental and biological factors regulate soil $CO_2$ flux of an ecosystem.

### 4.9.1 Seasonal variations in soil respiration in the study field

Figure 4.10 shows the seasonal pattern of soil $CO_2$ fluxes (mg $CO_2$ C $m^{-2}$ $h^{-1}$) in croplands, graze-lands and woodlands in the experimental period. Plots *a, b, c* and *d* denote soil respiration measurements in the wet period (June - September), wet - dry transition period (October - November), dry period (December - March) and transition between dry and wet (April - May) respectively with their corresponding Julian days (JD). Soil respiration varied markedly during the experimental year with relatively high soil $CO_2$ flux (200 - 250 mg $CO_2$ C $m^{-2}$ $h^{-1}$) in the wet periods compared to the dry periods (< 100 mg $CO_2$ C $m^{-2}$ $h^{-1}$) for all the land-uses except woodland. Coincidentally, average soil temperatures were relatively low (about 30°C) in the wet and high (about 39°C) in dry periods respectively. Similarly, a relatively high soil $CO_2$ fluxes (100 - 260 mg $CO_2$ C $m^{-2}$ $h^{-1}$) were observed during the period immediately preceding the dry spells commonly called the dry-wet transition period. However, the pattern of soil respiration during this transition period appears to follow directly the rainfall distribution with wet days recording high rates and dry days recording relatively low rates of respiration (Figure 4.10d).

The generally high soil $CO_2$ fluxes in the wet period (Figure 4.10a) was due to the influence of soil moisture on the plants physiological activities including increase in leaf area index (LAI) and photosynthetic supply to the roots as well as increase in decomposition in the soil which lead to the production of $CO_2$. For woodland, differences in soil $CO_2$ fluxes between wet and dry periods were quite small. This may be due to the influence of the litter layer above the soil and therefore woodland soils could retain moisture for relatively longer periods compared to cropland and graze-land. During the dry period (Figure 4.10c), the soils under crops and graze fields are subject to a combination of high temperature and water stress, which tend to control the soil $CO_2$ effluxes. Thus for graze-land and cropland the factor limiting soil respiration was mainly soil moisture but the effect is accentuated by the high soil temperature during these periods. Therefore, the occurrence of small rain event increases the soil moisture content and the soil $CO_2$ fluxes. This explains the fluctuating pattern of soil $CO_2$ fluxes during the transition periods as the soil temperatures are moderated by the rain events.

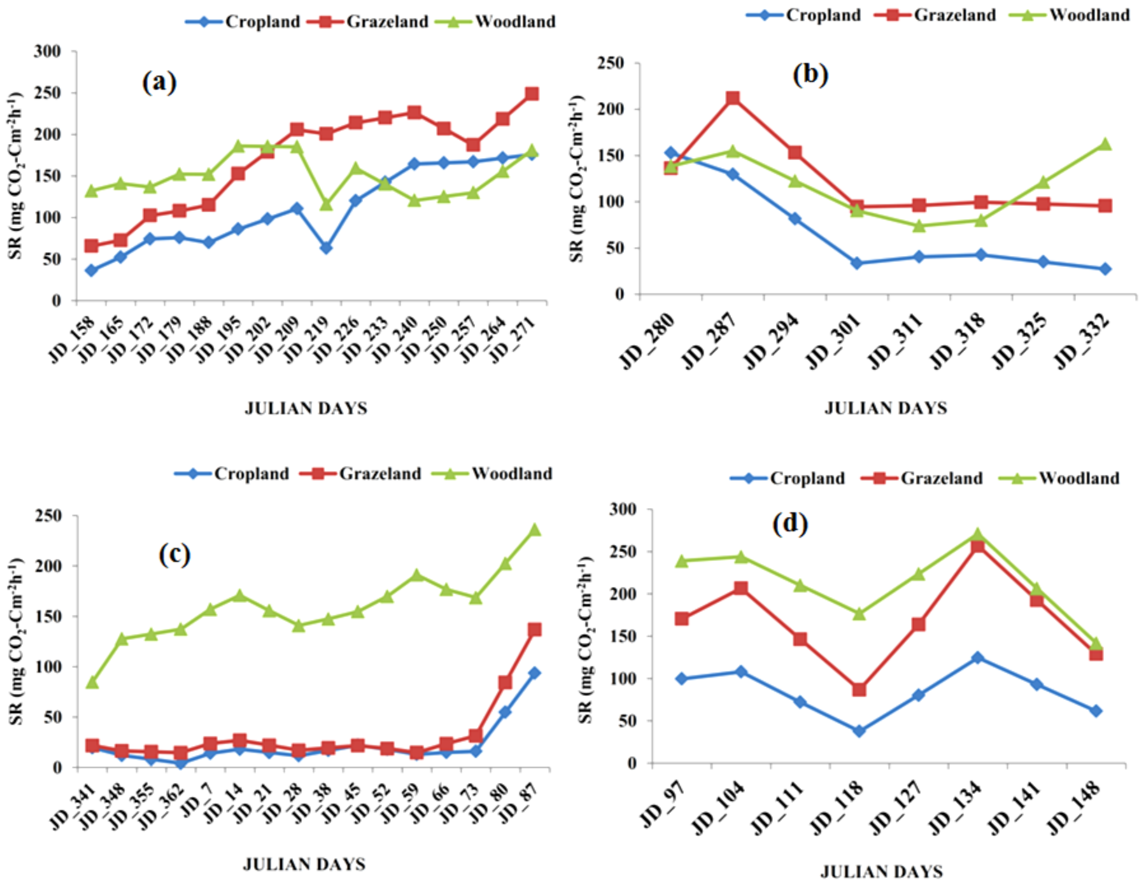


Figure 4.10: Seasonal pattern of soil respiration (SR, mg $CO_2$ C $m^{-2}$ $h^{-1}$) in croplands, grazelands and woodlands. Plots a, b, c and d denote soil $CO_2$ fluxes in the wet, wet – dry transition, dry and dry – wet transition periods respectively.

The statistical evaluation of the seasonal pattern of soil $CO_2$ fluxes (Figure 4.11) shows the mean soil $CO_2$ flux across the different land-uses with respect to seasons; wet, dry, transition 1 (wet - dry) and transition 2 (dry - wet).

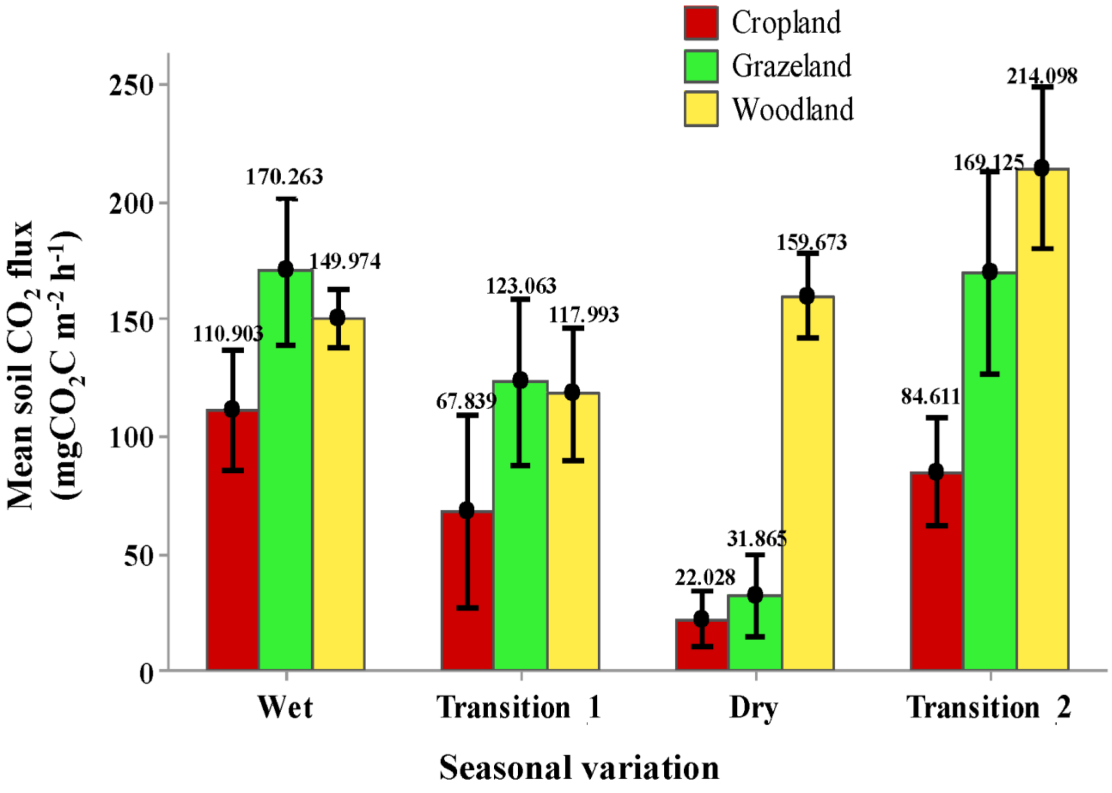


Figure 4.11: Mean soil $CO_2$ flux (mg $CO_2$ C $m^{-2}$ $h^{-1}$) for Wet or Growing seasons (June-September), Transition 1- wet to dry (October-November), Dry (December-March) and Transition 2 – dry to wet (April - May) in the three major land-uses

In the dry period (December – March), the highest mean $CO_2$ flux obtained for woodland (159.67 mg $CO_2$ C $m^{-2}$ $h^{-1}$) was significantly different ($p<0.05$) from graze-land (31.87 mg $CO_2$ C$m^{-2}$ $h^{-1}$) and cropland (22.03 mg$CO_2$ C $m^{-2}$ $h^{-1}$). The proportion of the soil $CO_2$ fluxes within the dry period was 7:1:1 for woodland, graze-land and cropland respectively. Thus about 78% of the total mean soil $CO_2$ flux recorded for the period was in the woodland. However, during the wet period, graze-land obtained relatively high mean flux of 170.26 mg $CO_2$ C $m^{-2}$ $h^{-1}$ compared to cropland (110.90 mg$CO_2$ C $m^{-2}$ $h^{-1}$) and woodland (149.97 mg $CO_2$ C $m^{-2}$ $h^{-1}$), although there were no significant differences ($p > 0.05$) between soil $CO_2$ fluxes from graze land and woodland. Flux measurements in Transition 1 (wet-to-dry) showed no significant differences between soil $CO_2$ fluxes under the various land-use systems but during Transition 2, (dry-wet), that is April – May the mean soil $CO_2$ flux recorded in all the land-use systems were significantly different ($p<0.05$). The mean soil $CO_2$ fluxes were in the order woodland (214.10 mg $CO_2$ $Cm^{-2}$ $h^{-1}$) followed by graze-land (169.13 mg $CO_2$ C $m^{-2}$ $h^{-1}$) with crop field obtaining the least (84.61 mg $CO_2$ C $m^{-2}$ $h^{-1}$). In general, an increasing trend in the measured soil $CO_2$ fluxes was observed for all crop and graze fields across the respective seasons, dry, transition 1, transition 2 and wet. The highest mean soil $CO_2$ flux for cropland (110.90 mg $CO_2$ C $m^{-2}$ $h^{-1}$) and graze-land (170.26 mg $CO_2$ C $m^{-2}$ $h^{-1}$) occurred in the wet season whilst the lowest for cropland (22.03 mg $CO_2$ C $m^{-2}$ $h^{-1}$) and graze-land (31.87 mg $CO_2$ C $m^{-2}$ $h^{-1}$) occurred on the dry season (Figure 4.11). However, soil $CO_2$ fluxes under woodland showed an irregular pattern with seasons.

Seasonal variability of soil respiration is influenced by climatic conditions which influence soil moisture and soil temperature, and other climatic factors such as minimum and maximum temperature, wind effects and relative humidity. In savannah ecosystems, there are marked seasonal variations in soil respiration due to the influence of soil moisture dynamics and fire regimes. According to Longdoz *et al.* (2000) seasonal variations of soil respiration have often been associated with either changes in soil temperature or changes in both soil temperature and soil water content (Davidson *et al.,* 1998; Xu and Qi, 2001). Temperature plays a significant role in the wet season whilst soil moisture is important during the dry and warm season in regulating soil respiration (McCulley *et al.,* 2004). Thus, soil respiration responds most to the factor (either temperature or moisture) that is more limiting in the soil environment. Again, the magnitude of seasonal changes in soil respiration correlates positively with the seasonal changes leaf area index and increases in root production and biomass (Thomas *et al.,* 2000).

Merbold *et al.* (2011) observed that almost 75% of the various carbon fluxes (e.g. above-ground, below-ground and total ecosystem) in savannah ecosystems occur during the wet or rainy season but soon after the rainy season this changes to the opposite. Thus, savannas become a weak source of carbon due to carbon mineralisation during rainy season just before starting the dry season (Chen *et al.*, 2003).

### 4.9.2 Spatial variations in soil respiration in the study field

Figure 4.12 presents the results based on the Geostatistical analysis which was used to determine the spatial variation in soil $CO_2$ flux across the study field by interpolating the point measurements of soil $CO_2$ fluxes from the predominant land-uses. Across the field, the highest mean soil $CO_2$ flux obtained was 189.69 whilst the lowest was 48.58 mg $CO_2$ C $m^{-2}$ $h^{-1}$. Similarly, the mean volumetric moisture content (VMC) at 5cm depth ranged between 5.15% and 12.90 % whilst soil temperature at 5cm was between 31.6 °C and 36.87 °C across the land-uses on the landscape. Clearly, locations with relatively lower VMC and higher soil temperature (North eastern corner) corresponded with lower soil $CO_2$ efflux whilst a relatively higher soil respiration occurred at the opposite location (North western corner) with high soil moisture and optimum soil temperature. This observation is in line with that of Kang *et al.* (2003), who reported that soil temperature and soil water content, or their interaction account for variability of soil respiration of a landscape.

In general, soil respiration is highly variable across a field due to soils' high spatial heterogeneity which has been related to differences in root biomass, microbial biomass, litter amount, soil organic carbon and other soil chemical attributes, soil bulk density, soil porosity, soil pH or site topography (Xu and Qi, 2001; Soe and Buchmann, 2005; Knohl *et al.,* 2008). These factors which influence the heterogeneity of soil properties are dependent on the type of land-use or land management prevalent at a landscape. Thus, the spatial pattern in soil $CO_2$ efflux observed in the current study might be due to several other controlling factors apart from soil moisture and soil temperature variability. The reason is that the average soil temperature is high (about 34°C) and therefore, soil moisture alone or combination of soil temperature and soil moisture may not be the only controlling factors of variability of soil $CO_2$ flux.

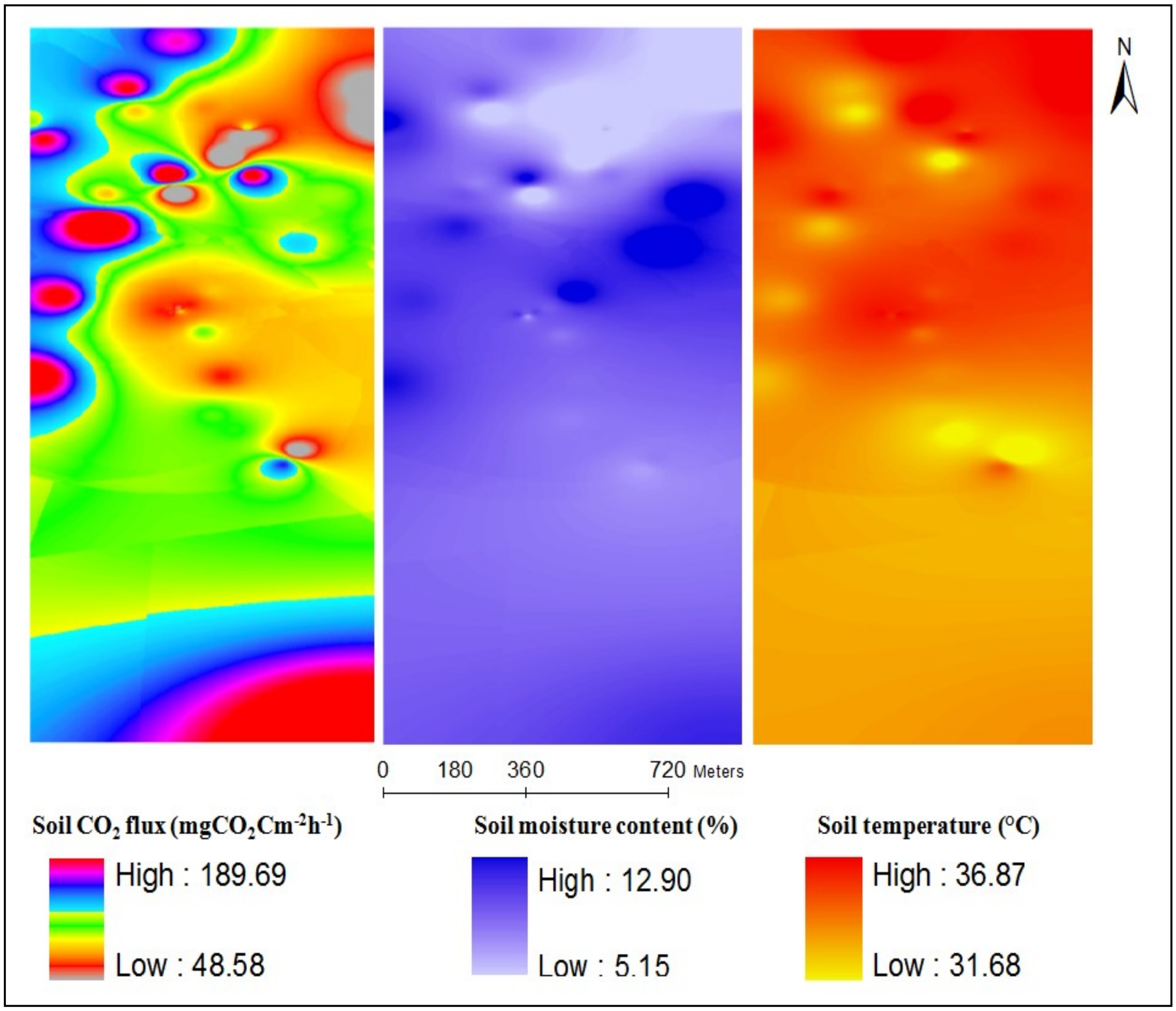


Figure 4.12: Interpolated map of soil $CO_2$ flux ($mgCO_2Cm^{-2}h^{-1}$) volumetric moisture content (VMC, %) at 5cm and soil temperature (° C) at 5cm across the field

Land-use appeared to be the dominant controlling factor as areas dominated by woodland had the highest soil $CO_2$ flux (189.69 mg $CO_2$ C $m^{-2}$ $h^{-1}$) whilst the lowest soil $CO_2$ flux (48.58 mg $CO_2$ C $m^{-2}$ $h^{-1}$) was measured at cropland areas (Figure 4.13). Land-uses have considerable effects on soil temperature and soil water content (Davidson *et al.*, 1998), soil microbial population (Klopatek, 2002), soil carbon substrates availability (Campbell *et al.,* 2004), plant root activity levels (Bowden *et al.*, 1993), plant growth and physiological activity (Rochette *et al.*, 1999) and vegetation type (Raich and Schlesinger , 1992).

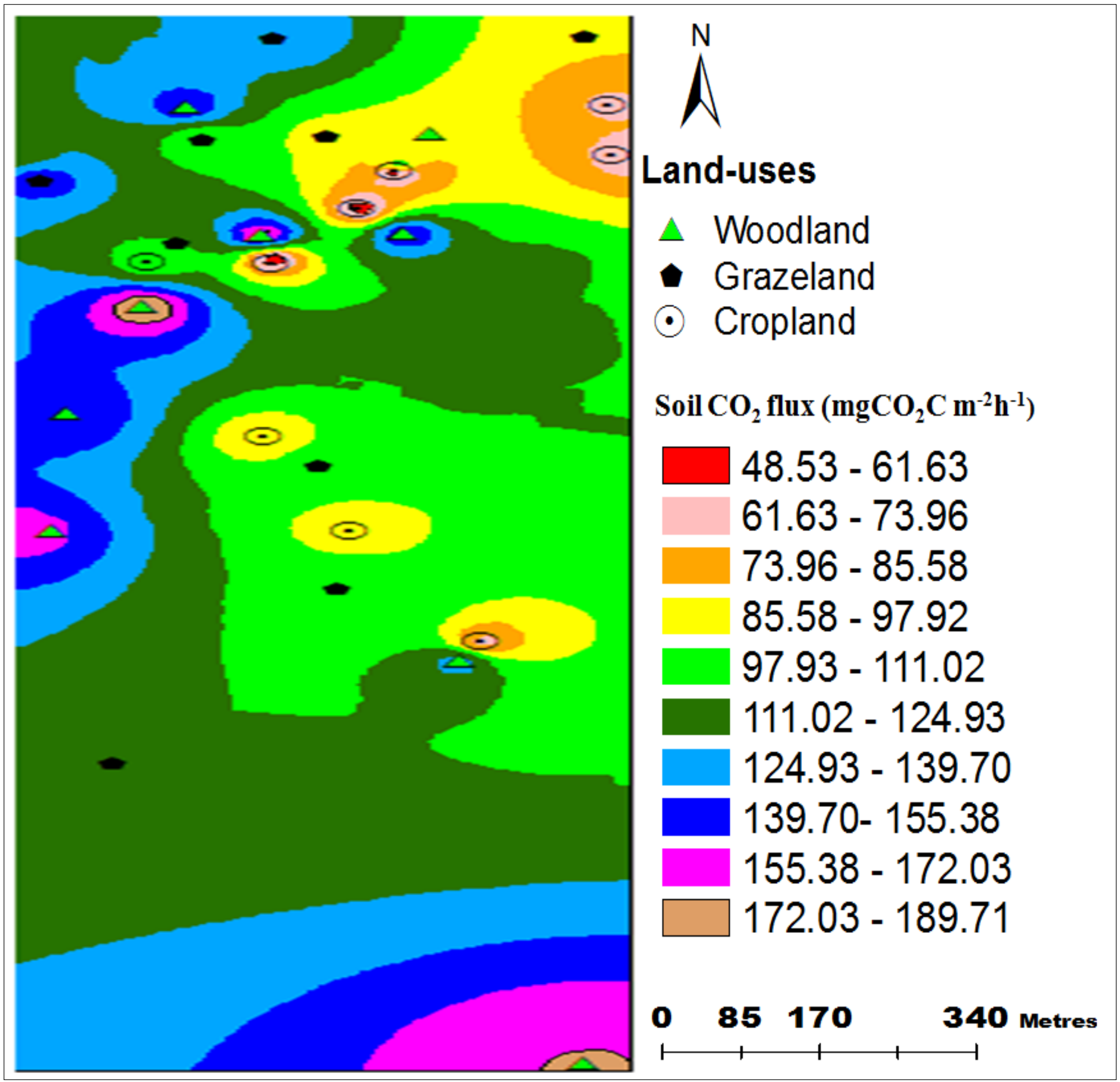


Figure 4.13: Interpolated map of soil $CO_2$ flux (mg$CO_2$ C $m^{-2}$ $h^{-1}$) across the land-uses on the study field

These factors affect not only the soil heterogeneity but also the biological activities in the soil which in turn influence the spatial variability of soil CO2 fluxes. Thus as noted by Buchmann (2000), the sources of spatial heterogeneity in soils are variable although they are essential to estimate soil $CO_2$ flux accurately in order to evaluate the carbon budget of an ecosystem and for scaling soil respiration from small scale to large scale level (Tang and Baldocchi, 2005).

### 4.9.3 Underlying factors explaining the spatial variations in soil respiration

Underlying the land-uses were several other independent explanatory variables including soil moisture, soil temperature, air temperature, pH, porosity and bulk density which influence the spatial variability of soil $CO_2$ fluxes across the study field. The PCA run initially extracted two (2) principal components (PC) with total Eigen values greater than 1.0, that accounted for 80.6 % of the total variance of the original independent variables (Table 4.8). Accordingly, PC1 and PC2 were able to explain 61.3 % and 19.3 % of the total information whilst the rotated component matrix helped to determine what the components represent (Table 4.9).

In Table 4.9, the principal component 1 (PC1) is strongly related to soil moisture content (loading $b$ = 0.79), porosity ($b$ = 0.92), soil $CO_2$ flux ($b$ = 0.80) but negatively related to bulk density ($b$ = 0.92) whilst principal component 2 (PC2) is strongly correlated with soil temperature ($b$ = 0.98). Pair correlations among porosity and bulk density indicate that the variables are highly multi-collinear and since porosity has a relatively high loading, it was the best representative for the pair of variables.

Table 4.8: Explanation of total variance by extracted components using Principal Component Analysis (PCA)

| | Initial eigen values | | | Extraction sums of squared loadings | | | Rotation sums of squared loadings | | |
|---|---|---|---|---|---|---|---|---|---|
| Component | Total | % of Variance | Cumulative % | Total | % of Variance | Cumulative % | Total | % of Variance | Cumulative % |
| 1 | 3.065 | 61.304 | 61.304 | 3.065 | 61.304 | 61.304 | 2.972 | 59.441 | 59.441 |
| 2 | 0.965 | 19.293 | 80.597 | 0.965 | 19.293 | 80.597 | 1.058 | 21.156 | 80.597 |
| 3 | 0.564 | 11.285 | 91.882 | | | | | | |
| 4 | 0.402 | 8.048 | 99.930 | | | | | | |
| 5 | 0.003 | 0.070 | 100.000 | | | | | | |

Table 4.9: Rotated component matrix using Varimax rotation with Kaiser normalization of first two principal components

| Variable | Principal Component | |
|---|---|---|
| | *1* | *2* |
| Soil moisture | 0.789 | 0.114 |
| Soil temperature | -0.092 | 0.982 |
| Bulk density | -0.920 | 0.193 |
| Porosity | 0.921 | -0.168 |
| Soil $CO_2$ flux | 0.804 | -0.125 |

The K-CA run - using the standardised scores of the two principal components with several iterations (*k* = 3) resulted in four land-use groups / categories I, II, III and IV with group sizes 5, 12, 13 and 6, respectively.

Land-use category I comprises about 60% graze-lands and 40% croplands. The radar diagram shows that soils under this group emit relatively high $CO_2$ flux at high moisture content, optimum soil temperature and medium porosity (Figure 4.14a). The standardised scores of the major underlying variables clearly indicate that when the soil $CO_2$ flux was 0.6, the soil moisture content was also 0.6, whilst soil temperature and porosity were about 0.48 and 0.5 respectively. This indicates that in this land-use group, soil temperature and porosity are regulated by soil moisture content, such that the occurrence of high soil moisture moderates soil temperature and regulates porosity, resulting in relatively high soil $CO_2$ fluxes.

Land-use category II comprises about 60% of croplands, 30% of graze-land, and 10 % woodland. Compared to land-use group I, the soils under this land-use group had relatively low soil $CO_2$ flux (score of about 0.54) at medium moisture content (score of 0.5), high soil temperature (score 0.54) and high porosity (0.6) (Figure 4.14b). Since this group is dominated by cropland and graze-land which are poorly managed, they tend to sequester relatively low carbon in the soil resulting in low soil $CO_2$ flux. Moreover, the poor organic matter content of their soils makes soils porous with low moisture retention capacity

This group (land-use category III) is made up of about 60% wetland, 25% woodland and 15% graze-land. As this group is dominated by wetland, the soils have quite low porosity (0.32), whilst soil temperature and soil moisture tend to be relatively high with respective standardised scores of about 0.51 and 0.53 (Figure 4.14c). As a result, soil $CO_2$ fluxes under this group were relatively low with a standardised score of about 0.46.

The land-uses of this group (land-use category IV) comprise about 90 % woodland and 10 % graze-land. The radar diagram (Figure 4.14d) of standardised scores of basic soil attributes indicates that at relatively high moisture content (score of 0.56), low soil temperature (score of 0.36) and medium porosity (score of 0.45), the soil $CO_2$ fluxes tend to be relatively low (score of 0.45), since soil temperature is more important for biological activities of soils under woodland which are usually cool due to high amount of litter cover.

Generally, the radar diagram (Figure 4.14) clearly indicate that the factors soil moisture content, porosity (PC1) and soil temperature (PC2), are the major driving factors of spatial variability of soil $CO_2$ flux for all the land-use categories identified at the catchment.

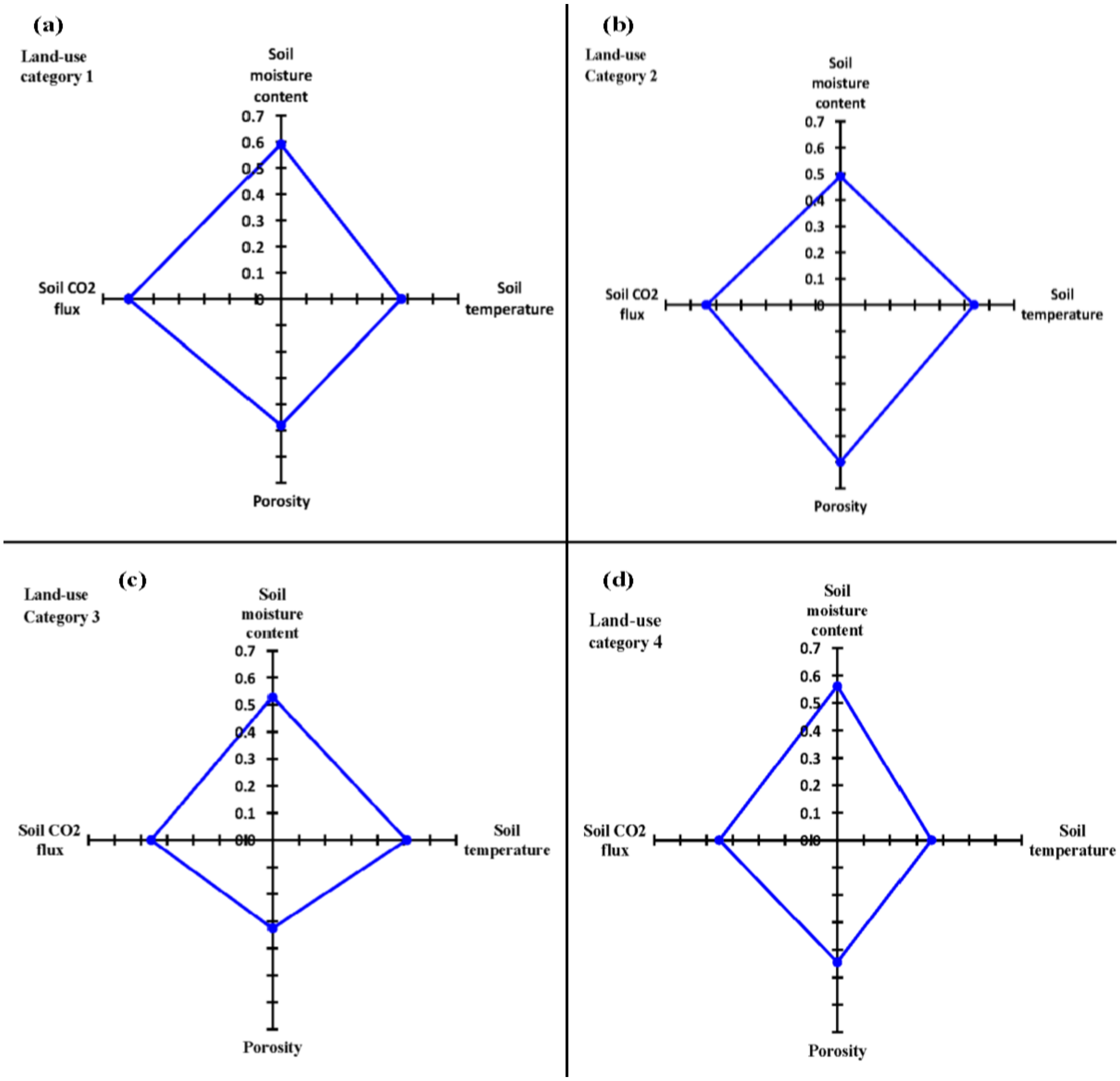


Figure 4.14: Factors influencing the spatial pattern of soil $CO_2$ flux in the study field

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Introduction

This chapter summarises the major findings of the study and the conclusions made based on the set objectives. Recommendations are also made for improved data gathering, knowledge acquisition, policy direction and sustainable management of the semi-arid savannah ecosystem.

## 5.2 Conclusions

Soil respiration measurements at the Vea catchment, a semi-arid savannah ecosystem, provided the opportunity to determine the amount of soil $CO_2$ fluxes exchange between the catchment and the atmosphere. The calibration results demonstrated the feasibility of rapidly undertaken soil $CO_2$ flux measurements in the field with static chambers and the GMD20 transmitter using simple digital voltmeter instead of a relatively sophisticated and costly dataloggers and palmtop computers. This is particularly relevant in chamber- sensor technique soil $CO_2$ flux measurements from a wide range of locations especially in rural communities in West Africa where electricity power supply is unreliable.

The field measurements had been successful in highlighting the hotspots $CO_2$ fluxes and the major drivers of variability in soil $CO_2$ fluxes within the catchment. The study found that the mean total annual soil $CO_2$ flux from the major land-uses at the Vea catchment was 9.23 ± 0.53 (Mean ± SE) t $CO_2$ C $ha^{-1}$ $y^{-1}$. With respect to the individual land-uses, the average annual estimates of soil $CO_2$ flux were significantly different ($p = 0.00$). Soils under woodland had the highest soil $CO_2$ flux with an average annual flux of 12.97 ± 0.89 t $CO_2$ C $ha^{-1}$ $y^{-1}$ followed by graze-land (9.10 ± 0.42 [t $CO_2$ C $ha^{-1}y^{-1}$]) whilst cropland had the least (5.61 ± 0.29 [t $CO_2$ C $ha^{-1}y^{-1}$]). The results implied that soil carbon emission is influenced by land-use in the study area and may be directly related to standing biomass. Fisher's multiple tests at 95 percent ($\alpha=5\%$) showed significant differences ($p<0.05$) in soil $CO_2$ flux estimates between the woodland, graze-land and cropland. Similarly, soil carbon stock density under the major land-uses were statistically different ($p<0.05$) and the mean estimates were in the order of 37.91 ± 1.29 (Mean ± SE) Mg C $ha^{-1}$ for woodland followed by graze-land 29.31 ± 1.74 Mg C $ha^{-1}$ and lastly cropland 27.36 ± 1.70 Mg C $ha^{-1}$. As soil $CO_2$ flux measurements is good indicator of soil quality and soil carbon turnover, croplands with poor SOC density had least $CO_2$ flux whilst woodland with highest SOC density had the highest soil $CO_2$ flux. Graze-land was midway because as native vegetation, potentially, their soil carbon turnover should have been relatively high but they are poorly managed due to intense pressure from over-grazing, trampling and fires. Cropping systems at the catchment is highly exhaustive with very minimal returns to the soil in terms of crop residues. The SOC density predictions (17.52 ± 1.70 Mg C $ha^{-1}$) revealed that the soils will be highly degraded in the next three decades if good management practices are not adopted by farmers. The predicted SOC value was extremely low compared to the IPCC estimate (28.8 Mg C $ha^{-1}$) for the region.

For different cropping systems, soil respiration under mixed cropping system was highest with mean soil $CO_2$ flux of 114.67 ± 3.51 followed by rice monoculture 108.08 ± 2.82 with groundnut monoculture having the least, 83.17 ± 2.85 mg $CO_2$ C $m^{-2}$ $h^{-1}$. Statistically, the soil $CO_2$ efflux estimates were significantly different from each other, based on Fisher's multiple tests at 95 percent ($p < 0.05$). A comparison of current field management practices with recommended ones such as fertilisation and mulching revealed that mean soil $CO_2$ flux (mg $CO_2$ C $m^{-2}$ $h^{-1}$) from mulched soils was highest (127.03 ± 7.61) followed by fertiliser application (114.05 ± 8.68), with the control obtaining slightly higher soil $CO_2$

flux (107.40 ± 4.60) than efflux from soils applied with organic manure (93.36±5.82). Carbon dioxide efflux estimates from mulched soils were significantly different ($p < 0.05$) from all the other practices; there were also significant difference ($P < 0.05$) between $CO_2$ efflux from organic manure and those from fertiliser application and the control experiment. However, between fertiliser application and control field, fluxes were not significantly different ($p > 0.05$). The effect of land preparation activities (manual hoeing, bullock ploughing, and conventional tillage) however, were not significantly different ($p > 0.05$). Conventional tillage practice, however, coupled with poor residue management may accelerate soil erosion making the soil less productive and eventually lead to soil degradation. The findings affirmed the need to adopt proper land management practices such as on-farm tree planting for carbon sequestration.

Soil $CO_2$ fluxes correlated negatively with soil temperature at high soil temperatures (above 36 °C). The highest mean respiration rates (280 - 300 mg $CO_2$ C $m^{-2}$ $h^{-1}$) were recorded in the wet period when the mean soil temperature was between 30 °C and 33 °C whilst the least respiration rates (3 - 6 mg $CO_2$ C $m^{-2}$ $h^{-1}$) were measured in the dry period when the mean soil temperature was beyond 36°C. However, for all seasons, SR was sensitive to soil moisture although the influence of soil moisture on SR was pronounced in the dry period ($R^2 = 0.40$) than in the wet period ($R^2 = 0.30$). Soils are subject to a combination of high temperatures and water stress during the dry period, which tend to control the soil $CO_2$ fluxes. Thus the occurrence of small rain event increases the soil moisture content and hence the SR rates. Nonetheless, soil moisture content is unevenly distributed across the study field due to land-use influences and the pattern of SR followed the soil moisture distribution. Soils under cropland had the least soil water (5 - 10 %) and least SR rate (50 - 90 mg $CO_2$ C $m^{-2}$ $h^{-1}$) whilst those under woodland with relatively high soil water (12 %)

had the highest SR (190 mg $CO_2$ C $m^{-2}$ $h^{-1}$). The SR rates of waterlogged soils (wetland) were also quite low (80 - 120 mg $CO_2$ C $m^{-2}$ $h^{-1}$) although it had the highest soil water content (13 %) among the land-uses, signifying the suppressing effect of soil water on soil $CO_2$ flux due to limitations on oxygen diffusion and $CO_2$ dissolution within the measurement chamber.

Topography had significant impact on soil $CO_2$ flux. The mean monthly efflux of $CO_2$ at downslope (86.27 ± 9.12 g $CO_2$ C $m^{-2}$ $month^{-1}$) was over 30 percent higher than that from upslope position (64.81 ± 7.23 g $CO_2$ C $m^{-2}$ $month^{-1}$) across the entire study field although the extent is variable among the predominant land-uses. A paired sample statistics revealed that for all the major land-uses, comparisons of soil $CO_2$ flux between upslope and downslope position were significantly different ($p<0.05$). For cropland, the upslope position was 52.57 ± 0.67 whilst the downslope was 72.83 ± 1.02, ($p=0.009$), upslope graze-land was 90.31 ± 0.66 compared to 125.40 ± 4.34 downslope ($p=0.042$). Similarly, for woodland, SR from downslope (118.49 ± 6.40 g $CO_2$ C $m^{-2}$ $month^{-1}$) was significantly different ($p=0.000$) compared with upslope position (117.44 ± 6.59 g $CO_2$ C $m^{-2}$ $month^{-1}$).

Soil $CO_2$ flux varied markedly with seasons and space due to variations in local climate and soil attributes as influenced by the different land-uses. The greater proportion of SR occurred at the wet period compared with the dry period with mean soil $CO_2$ flux ranging between 140-160 and 60-75 $mgCO_2Cm^{-2}h^{-1}$ for wet and dry periods respectively. The seasonal variations were driven mainly by soil moisture and temperature dynamics, implying that savannah ecosystems are hot spots for C emissions during the growing season with consequences on the global C budget. Spatially, the mean SR across the study field ranged between 48.58 and 189.69 $mgCO_2$ C $m^{-2}$ $h^{-1}$ and the observed variations coincided with the spatial distribution of the predominant land-uses. Areas dominated by woodland had the highest SR rates whilst cropland areas had the least. Thus, on weekly basis, land-uses serve as the major driver of SR transferring between 8.16 to 31.87 g of C from respired $CO_2$ per square metre of soil to the surrounding environment including the atmosphere. Similarly, on annual basis, the catchment emits about 9.23 ± 0.53 tons of C from $CO_2$ efflux for every hectare of soil irrespective of land-use. These rates of $CO_2$ emissions are of importance to the global carbon budget considering that $CO_2$ could remain in the atmosphere for up to 200 years. Thus the contribution of not only forests but also savannah ecosystems should be considered in climate change mitigation initiatives.

On the whole, soil respiration at the catchment is driven by environmental conditions such as land-uses, cropping systems and field management practices, topography, porosity and other soil attributes such as soil moisture content and soil temperature which in part depend on local climate. These factors influence the dynamics of soil respiration (temporal and spatial), the SOC density and the exchange of $CO_2$ fluxes between land and the atmosphere. As the savannas represent a huge carbon pool in the terrestrial ecosystem (about 30 percent), it is envisaged that the information generated from the study will provide mechanism for monitoring soil carbon stocks and serve as baseline data for improved land management practices for long-term carbon storage.

## 5.3 Recommendations

The following recommendations are made for improved data gathering, knowledge acquisition, policy and sustainable land management of the semi-arid savannah ecosystem;

i. Further studies should investigate the impact of irrigated systems on soil respiration for comparison with the current data gathered under rainfed agriculture as the influence of soil water content is of crucial importance for the semi-arid ecosystem.
ii. As fires greatly influence the catchment's vegetation dynamics, further studies to assess the impacts of fires on soil $CO_2$ flux and overall effects of tree cover on the ecosystem carbon dynamics should be conducted.
iii. Similarly, as land preparation (tillage practices) significantly affect soil porosity and soil carbon and nutrient turnover, further investigation into their impact on soil $CO_2$ flux should be done to help prescribe appropriate tillage practices for climate smart agriculture.
iv. Future experiments should investigate the impact of soil collar depth on soil respiration as it is hypothesised that with increasing depth of collar in soil some component of respiration (autotrophic) could be eliminated. When proven, the total soil respiration should be partitioned into the autotrophic and heterotrophic components to facilitate the Net Ecosystem Exchange (NEE) estimation.
v. With regards to policy direction, the study could be a useful guide for carbon trading which is a form of payment for carbon sequestration, an ecosystem service, as the magnitude of soil $CO_2$ flux is a sensitive indicator of soil carbon turnover and soil fertility status.
vi. For sustainable land management, on-site planting of trees, particularly native tree species should be undertaken. This will help sequester the tons of carbon emitted annually from the semi-arid savannah ecosystem for climate amelioration, improved soil fertility and food productivity and to curb the ensuing soil degradation due to the unsustainable traditional farming practices at the catchment.

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