# COMPARISON OF SOIL CARBON STOCKS AND CARBON DIOXIDE EFFLUXES IN DIFFERENT FOREST MANAGEMENT REGIMES IN EASTERN MAU FOREST RESERVE, KENYA

**Tarus George Kipkorir**

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## DECLARATION AND RECOMMENDATION

### Declaration

I hereby declare that this thesis is my original work and has not been presented for the award of degree in this university or any other university and that all the sources used herein have been acknowledged.

Signature ______________________________ ______________________________

**Tarus George Kipkorir** **Date**

**Reg No NM11/3698/13**

### Recommendation

This thesis has been submitted with our approval as university supervisors

Signature______________________________ Date________________________

**Dr. Bernard K. Kirui (PhD)**

Department of Natural Resources

EGERTON UNIVERSITY

Signature______________________________ Date____________________________

**Gilbert O. Obwoyere (Dr.rer.nat)**

Department of Natural Resources

EGERTON UNIVERSITY

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**ABSTRACT**

The attainment of green economy and low carbon climate resilient development in Kenya may be hindered by competing human interest on forests and other natural resources. Eastern Mau forest has experienced anthropogenic disturbance through encroachment and forest fires; that situation prompted the deployment of heterogeneous forest management. This study aimed at comparing the soil carbon stocks and soil $CO_2$ effluxes in different forest management regimes on as well as how soil temperature and soil moisture impacts on carbon stocks and soil $CO_2$ effluxes in the study area. The study was conducted between January and June 2016 in Sururu block of Eastern Mau forest reserve, Kenya. A nested experimental design was used in data collection; where thirty two sample plots were nested into four blocks (disturbed (fire) natural, undisturbed natural, plantation and glades) established on the basis of forest management types. Ina $10m^2$ plot, data was collected on soil carbon stocks, soil $CO_2$ efflux and environmental controls (soil temperature and soil moisture). The results indicated that estimated soil carbon stocks were as follows: undisturbed natural (135.17± 35.99.0 Mg $C^{-ha}$), disturbed natural forest by fire ( 134.52± 38.11 Mg $C^{-ha}$) glades (122.4 ±64.9 Mg $C^{-ha}$), and plantation forest (116.51± 39.77 Mg $C^{-ha}$ ). However, there were no significant differences in the mean carbon stocks between the four forest management regimes ($F_{4, 16}$. =0.61, p=0.613). The mean soil $CO_2$ efflux between the four forest management types was significantly difference ($F_{1\ 32}$. =3.01, p=0.033). The soil $CO_2$ efflux levels recorded were as follows; plantation forest (9.219 ± 3.067 g C M-$^{2}$day-1), undisturbed natural forest (8.665 ± 4.818 g C M-$^{2}$day$^{-1}$), glades (8.592 ± 3.253 g C M-$^{2}$day$^{-1}$) and fire disturbed natural forest (7.198 ± 3.457 g C M-$^{2}$day$^{-1}$). Based on the results; forest disturbance impacts on soil stocks and therefore for Kenya to achieves its Nationally Determined Contribution (NDC) targets of reducing Green House Gases(GHG) emission by 30% relative to business as usual (BAU) emissions of 22 $MtCO_2e$ in 2030, natural forests and glades management regimes presented the best options. Therefore the use of natural forest management regimes in the conservation of soil carbon stocks and in reducing carbon dioxide efflux from the forests is recommended. Additionally a paradigm shift in forest management to include management for non wood forest products and service such as carbon stocks and climate stabilization is needed. Finally REDD+ process in Kenya should consider the carbon stored by forests in its reference level establishment.

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## LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| **CDM** | : Clean Development Mechanism |
| **$CO_2$** | : Carbon dioxide |
| **FRL** | : Forest Reference Level |
| **IPCC** | : Intergovernmental Panel on Climate Change |
| **IRGA** | : Infra-red gas analyzer |
| **ITCZ** | : Intertropical Convergence Zone |
| **KFS** | : Kenya Forest Service |
| **LULUCF** | : Land use, Land use change and Forestry |
| **MASULICOFA** | : Mau Sururu and Likia Community Forest Association |
| **NDC** | : Nationally Determined Contribution |
| **REDD+** | : Reduction of Emission from Deforestation and forest Degradation, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks |
| **SOC** | : Soil Organic Carbon |
| **SOM** | : Soil Organic Matter |
| **UNFCCC** | : United Nations Framework Convention on Climate Change |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background to the study

Forest soils are a major sink of terrestrial carbon containing more than double the amount of carbon found in forest tree biomass (Zheng *et al.*, 2008, Scharlemann *et al.*, 2014) and it plays a very important role in the global carbon cycle. However, large uncertainties in emission estimates exists due to inadequate data on the carbon density of forests such that it's not possible to know whether forest is a net sink or source (Baccini *et al.*, 2017) and consequently there is an urgent need for improved data sets that characterize the role of soils as a source or sink for carbon on a global scale due to its importance in assessing changes in atmospheric carbon dioxide concentrations and promoting conservation and sustainable management of the forest resources (Johnson and Curtis, 2001, Viet *et al.*, 2017 ).

Traditionally forest management studies have focused on increasing the forest productivity and growing stock with little effort on the soil carbon dynamics. However with recent interest in reduction of the green house emission, attention on the role of forest soil in capturing and storing carbon has increased. Carbon dioxide ($CO_2$) efflux from soil is the second largest carbon (C) efflux in most terrestrial ecosystems (Kuzyakov, 2006) and therefore measurements of soil $CO_2$ efflux can be used as an indicator of forest ecosystem processes. These ecosystem processes includes metabolic activity in soil, persistence and decomposition of plant residue in soil and conversion of soil organic carbon to atmospheric $CO_2$ (Ryan and Law, 2005). Frequent measurements of $CO_2$ efflux can help to uncover environmental factors influencing heterotrophic respiration. To a large extent, temporal and spatial variation in soil $CO_2$ and its components is driven by differences in soil temperature and moisture.

While there are many studies on a variety of aspects related to forestry in Africa, few studies have focused on soil carbon stocks (Maher *et al.*, 2010, Pfeifer *et al.*, 2012) and soil $CO_2$ efflux. Soil $CO_2$ efflux is an important parameter in carbon cycle and it is affected by environmental factors such as temperature, moisture and disturbance. Therefore changes in soil temperature or soil moisture could distort the equilibrium of soil carbon pool from being a net store/sink to net source of carbon. A study by Son *et.al* (2003) showed that soil $CO_2$ evolution related with soil temperature. Separately Nouvellon *et al* (2008) in a study of soil respiration in a 3-year-old Eucalyptus plantation in coastal Congo observed that there was a maximum soil respiration at high soil water content. However, temperature has been reported as the single best predictor of soil respiration, but inclusion of moisture in the regression increase the predictive power of the model. Based on the above observation this study opines that a positive exponential relationship between soil $CO_2$ evolution and soil temperature existed

**1.2 Statement of the Problem**

The carbon balance of tropical ecosystems remains uncertain, with top-down atmospheric studies suggesting an overall sink and bottom-up ecological approaches indicating a modest net source. The need to understand precisely what is happening in forest ecosystems is further amplified by the problems associated with increased levels of atmospheric $CO_{2\ and}$ the major role the forests can play as major carbon sink and mitigating against climate change. East Mau forest reserve plays multiple roles for the current and future generation, but it has previously faced wide range of anthropogenic disturbances. In order to reverse on those negative trends a number of policy and restoration interventions were implemented. These intervention included a raft of forest management techniques geared at optimal resource management However, forest management affects carbon cycle within a forest ecosystem and therefore this study sought to understand how those operations impacted on carbon stocks and effluxes within East Mau forest reserve since no previous study have attempted to document and explain the effects of forest management on carbon dynamics.

## 1.3 Objectives of the Study

### 1.3.1. Broad objective

The broad objective of this study was to compare the soil carbon stocks and carbon dioxide effluxes in Eastern Mau Forest reserve subjected to different forest management regimes

### 1.3.2. Specific Objectives

1. To quantify soil carbon stocks under different forest management regimes
2. To quantify the effects of forest management on soil carbon efflux (soil respiration)
3. To assess the relationship between environmental controls (soil moisture and soil temperature) and soil carbon effluxes

## 1.4 Null Hypotheses

$H_1$: Carbon stocks do not vary between undisturbed natural forest, disturbed (fire) natural forest, plantation and glades

$H_2$: Soil carbon effluxes do not vary between undisturbed natural forest, disturbed (fire) natural forest, plantation and glades

$H_3$: There is no significant relationship between environmental controls (soil moisture and soil temperature) and soil carbon effluxes

## 1.5 Justification of the Study

Changes in the forest ecosystems, interferes with vital ecosystem processes and forest productivity including carbon stocks and effluxes, therefore its critical to monitor changes in soil respiration as an indicator for soil carbon sequestration. The level of soil respiration in forest ecosystem is an indicator of ecosystem processes such as decomposition and microbial activities. In particular, decomposition leads to transfers of carbon from one pool to another and sometimes removal though emissions. Interestingly, heterotrophic respiration is influenced by environmental controls such as soil moisture and soil temperature among other factors. Therefore it is important to understand the level of these two factors in the soils at one particular time or season. Measurement of carbon dioxide efflux from the soil helps in assessing the effects of natural or artificial disturbance on the forest ecosystem. It is also important to measure soil temperature and moisture content in order to explain the resultant effluxes.

This study was driven by the need to understand the impacts of the forest management on soil carbon dynamics in the Eastern Mau forest reserve. The forest reserve is subjected to different forest management regimes due to varied past disturbance levels and as well as the existing resource types. These management activities are anticipated will have an effect of carbon dynamics such as carbon emission and sequestration. Better understanding of soil carbon stocks and flows is essential for better carbon management and climate change mitigation options such as REDD+, as well as to help parameterize global circulation models used to guide climate policy (Scharlemann *et al.*, 2014). In Kenya the best available forest inventory data are largely outdated (Stiebert *et al.*, 2012) and when coupled with the requirements of processes such as GHG reporting and accounting, Forest Reference Level (FRL) and REDD+ strategy development and implementation the need for recent data become a priority. Additionally the actualization of management regimes contained in Sururu Participatory Forest Management Plan (PFMP) and Forest Management Agreement signed between Kenya Forest Service and Mau Sururu and Likia Community Forest Association (MASULICOFA) especially on benefit sharing accrued from trading of forest carbon rights is dependent on updated information.

### 1.6 Scope of the Study

The study was conducted in Sururu forest block of Eastern Mau forest reserve located in Njoro division in Nakuru County. The study was undertaken between January and June, 2016, this period covered both the dry and wet season of the forest area. Measurement of soil carbon stocks was undertaken using Loss-on-ignition technique by analyzing soil samples collected between the depths of 0-10 cm while soil carbon dioxide effluxes measurement was done using soda lime method. Thermometer was used to measure soil temperature whereas proxy technique of collecting wet soil sample and oven drying it and the resultant difference in the two weights was used to determine soil moisture content. The above measurements were carried out during the dry and wet seasons of the study area in order to document seasonality.

### 1.7 Limitations and assumptions to the study

The study had a number of limitation that included; the absence of a weighing scale with higher sensitivity upto six decimal place within the University as well as the laboratory regulation on use of equipment and access by other students. Nevertheless the four decimal weighing scale within the Department of Biochemistry still provided accurate results while special arrangement by laboratory staff and other students solved mitigated on the access to the laboratory equipment challenge. This study assumed that no external interference occurred to the experimental chambers in the field.

## 1.8 Definition of terms

**Chambers**: They are a hard plastic buckets that are cut on the base and inserted into the soil to provide for measurement of soil respiration through soda lime method.

**Disturbed natural forest**: This forest consist of a suite of tree species that are naturally occurring with very limited human interventions, the forest experienced an extreme fire event in 2005, 2007 and 2014.

**Environmental controls**: These are environmental factors that regulates the rate of decomposition and root respiration and therefore the rate of $CO_2$ emission from soils and they include; soil moisture and soil temperature.

**Forest management**: Forest management is the process of planning and implementing practices for the stewardship and use of forests and other wooded land to meet specific environmental, economic, social and cultural objectives.

**Glades**: Naturally existing areas within the forest that is predominantly occupied by grasses and has limited possibility of converting naturally into a forest.

**Heterogeneous forest management:** This is the deployment of a number of silvicultural treatments, intervention or diverse forest management activities within a forest area. This management approach is aimed of achieving a suite of ecosystem goods and services

**Plantation forest**: This forest management type involved schedule human activities that range from land preparation, seedling planting, deliberate seeding or coppicing, where the coppicing is of previously planted trees, thinning, and pruning among other silvicultural operations.

**Soil carbon stock**: Soils contain carbon in organic and inorganic forms. The majority of carbon in most soils is stored as soil organic carbon in the form of soil organic matter, composed of decaying plant, animal, fungal, bacterial matter and live fine roots of less than (suggested) 2mm diameter within the soil.

**Soil $CO_2$ efflux**: Is the carbon dioxide released to the atmosphere as an output from the process of respiration by roots and soil micro-organisms

**Undisturbed natural forest**: Forest which has spontaneously generated itself on the location and which consists of naturally immigrant tree species and strains with less or clearly no visible indications of human activity and ecological processes are not significantly disturbed

# CHAPTER TWO
# LITERATURE REVIEW

## 2.1 Forest management in Eastern Mau reserve

The Mau Forests Complex forms the largest closed-canopy forest ecosystem in Kenya covering over 400,000 hectares. This forest ecosystem has various forest blocks that include Eastern Mau forest reserve. This forest provide critical ecological services to the country, in terms of water storage; river flow regulation; flood mitigation; recharge of groundwater; reduced soil erosion and siltation; water purification; conservation of biodiversity; and, micro-climate regulation (Olang and Kundu, 2011, KFS, 2011,Langat *et al*.2016). Despite its critical importance for sustaining current and future economic development, the Mau Forest Complex has been impacted by extensive irregular and ill-planned settlements, as well as illegal forest resources extraction that have reduced cover by more than 7 % in the past 21 years (Boitt, 2016).To address this negative trends the government enhanced forest management through deployment of various intervention that included policy and restoration measures.

## 2.2 Forest management in Sururu Forest Reserve

Sururu forest reserve forms part of Eastern Mau reserve and measures approximately 13364.4 hectares and is composed of varied plant formations and fauna. The forest can be distinctively classified into three strata based on plant type or formation; natural forest, plantation and glades. Each of the stratums requires a set of operations based on management regime to be achieved. The natural forest in this study has been classified into two classes because the strategies being employed in the burnt area are not the same with the undisturbed natural forest. Studies (Jandl *et al.*, 2007, Vesterdal and Leifeld, 2007, Scharlemann *et al.*, 2014) have documented the influence forest management has on soil carbon stocks and its flows. Therefore Sururu forest is implementing four management regimes in order to achieve forest productivity, provision of ecosystem goods and services, conservation of genetic diversity, climate change mitigation among other goals. Below are explanations of each forest management regime.

### 2.2.1 Plantation Forest Management Regime

The plantation management involves establishing trees in even age or uneven age monoculture or mixed species depending on management regimes. The selected study site (Figure 4) is a cypress (*Cupressus lusitanica*) plantation established in 1994 to meet sawn wood management regime. The plantation covers an area of 12 ha and has been subjected to silvicultural operations though not in strict conformity to the technical order prescribed schedule. The goal of this management regime is to increase stock growth and quality wood product for the sawmilling industry in Kenya.

Plate 1: Section of Cypress plantation under plantation forest management regime

### 2.2.2 Undisturbed Natural Forest Management Regime

This form of management involves limited human interferences in the forest growth dynamics, such that the forest establishes itself naturally through ecological and succession till it reaches its climax state. Here there are limited human interferences in the form of; protection for natural regeneration, enrichment planting when necessary and fire management. Natural forest management regimes are geared at continuous production of ecosystem good and services, conservation of biological diversity and climate system services. The study site is part of over 12114.5 ha of natural forest in Sururu forest reserve. The site is characterized by high canopy forest with climbers as well as diverse tree species

Plate 2: A section of Intact Natural forest under natural forest management regime

### 2.2.3 Disturbed (fire) Natural Forest Management Regime

This forest consist of a suite of tree species that are naturally occurring with very limited human interventions, the portion of the forest experienced an extreme fire event in 2005,2007 and 2014. Currently the goal its management is full recovery from the disturbance, through aided regeneration, closer for natural regeneration and minimal limited human interference except events of fire suppression.

Plate 3: Burnt Natural Forest under fire disturbed natural forest management regime

### 2.2.4 Glades Management Regime

These sections of the forest are open spaces that are naturally occurring within the forest and have ecological conditions that support naturally predominantly grass species only. The glades within Sururu forest are fragmented and covers in total approximately 1200ha. Glades provides a suite of ecological goods and services that includes ;grazing for the local forest adjacent community and important habitats for moles, hare and birds .Theses sections faces periodic fires incidences as a result of deliberate burning to encourage fresh pastures once in a while though the records in this specific study site are low. There are limited forest management activities in this section of the forest.

Plate 4: Forest glades under glades management regime

Forest management implies purposeful manipulation of stand and site, which can result in a changed ecosystem. The more natural conditions are controlled and modified through operational processes, the more intensive a management approach might be considered (Allard *et al.*, 2006). Various factors, such as controllability, the amount of usage (i.e. extracted volume of biomass), and the degree of modification of natural conditions required to achieve management regimes can point out at the level of carbon stock interference.

**2.3 Factors affecting forest carbon**

Forests and forest soils are the primary terrestrial sinks for atmospheric carbon and more than half of ecosystem carbon commonly occurs in the upper horizons of mineral soil. Because forests store vast amounts of atmospheric carbon, forest management has been questioned based on perceptions on impacts it has on carbon budget including losses of carbon from mineral soil (Bradley and Scott, 2011). Even though the effects of forest management on soil carbon stocks are generally not well known (Vesterdal and Leifeld, 2007) forest management affects carbon gains and losses by changing the level of inputs to the soil carbon pool, rates of microbial decomposition, changing environmental conditions such as temperature and moisture, and changing the quality of litter (Vesterdal and Leifeld, 2007, Scharlemann *et al.*, 2014).

The type of forest management can be classified along the economic axis which focuses on the productive function, or along the ecological axis which tends to focus on the protective functions. These decisions on the kind of forest management are usually driven by policy. For example the European the forest management is characterized by introduced species (Karjalainen *et al.*, 2002) a situation that can be document in Kenya especially with regard to plantation forests. The current scarcity of natural resources has placed lot of challenge on land, forest and water managers to maximize the wide range of forest benefits without interfering with water resources and ecosystem functions, particularly in the context of adaptation to climate change.

**2.4 Sustainable forest management for optimal carbon sequestration**

The forest managers must develop optimal management actions to meet new objectives (Jones and O'hara, 2012), which increasingly reinforces the importance of sustainable forest management. Sustainable forest management (SFM) is a key concept that underpins modern forestry practice by recognizing the need to balance the social, ecological, and economic outputs from forests (Duncker *et al.*, 2012). Since the United Nations Conference on Environment and Development (UNCED) in 1992, the issue of sustainable forest management has been at the centre of the international policy debate relating to forests, and underpinned in many national policy initiatives (Allard *et al.*, 2006). The applicability of this concept in forestry is dependent on a number of factors including impact of forest management on carbon emissions.

Thurig (2005) observed that even-aged and multi-aged forest management actions may have different impacts on carbon sequestration at the individual and stand level. This is caused by the differences in harvest intensity and frequency. Even-aged management will result in greater swings in carbon storage when the stands are cleared. Most even aged forest crops are clear felled unlike multi-aged forests where selective harvesting is done. Clear felling involves high harvesting intensity which directly affects the above ground carbon pools with some leakage from the pool into the atmosphere. A situation which is less prevalent where selective harvesting is done, mostly under mixed aged management actions.

Since little has been done to directly compare carbon emissions associated with these forest management systems, it is impossible to state which silvicultural options sequester the greatest amount of carbon per unit area over the long term. The implementation of a silvicultural system involves a number of decisions on the type of operations to employ at the various phases of the development of a stand or group of trees. These operations can affect one or more key stand variables, such as tree species composition, stand density and age structure or site conditions. And the resultant condition may have an influence on the provision of a range of ecosystem services (Allard *et al.*, 2006).

### 2.5 Impacts of land use on soil carbon stocks

Land use and management affects soil organic carbon (SOC) and the nutrients existing in that particular soils (Girmay and Singh, 2012). The total soil C pool is determined by the balance between soil respiration, where C is released from the soil, and the incoming C from litter fall and rhizodeposition. Both of these factors can be influenced by forest management practices such as thinning, harvesting, soil preparation and fertilization. Therefore forest management practices can have an effect on soil carbon sequestration (Jandl *et al.*, 2007).

The utilization of land and the intensity of usage will determine the fertility and health of soils. Since land use change is a dynamic process that plays a crucial role in relation to global carbon (C) dynamics (Bhattarai, 2015). It is expected to cumulatively influence the levels of the various carbon forms in the carbon cycle. However, changes in land use significantly influence the soil quality and both above and belowground carbon stocks.

A study in Ethiopia (Girmay and Singh, 2012) showed that soil organic carbon and nutrients varies as a results of complex processes such as land management, biological cycling, leaching, illuviation, soil erosion, weathering of minerals and atmospheric deposition. Deforestation and inappropriate land use practice have resulted in several environmental problems including declining SOC through decreased carbon sequestration and increased carbon dioxide emission to the atmosphere (Shrestha *et al.*, 2008) which contributes to global warming. Plants have continued to convert atmospheric $CO_2$ into immeasurable inorganic and organic compounds; however anthropogenic activities altering the land have led to imbalance in carbon cycle. The use of non-clean energy for example has led to conversion of fossilized carbon into the atmosphere. This has led to greenhouse effect increasing the global temperature and thus the experienced global warming (Hairiah *et al.*, 2011).

Conversion of land use from one use to another upsets both the terrestrial and aquatic carbon balance and the resultant emission may not be sequestered fully. It is vital to understand the net C uptake of 0.7 Gt C $yr^{-1}$ by terrestrial system is small relative to the efflux (Hairiah *et al.*, 2011). United Nations Framework Convention on Climate Change (UNFCCC) fully understanding the potential effect of land use sanctioned checking of dangerous anthropogenic activities. These activities might interfere with the climatic pattern and as a safeguard guideline on Land use; Land use change and Forestry (LULUCF) were developed by Intergovernmental Parties on Climate Change (IPCC). The full potential have not been realized, but nevertheless carbon accounting mechanism is slowly being adopted, while it is becoming increasingly essential to understand the carbon foot print of every activity. Carbon accounting has reached the vanguard of national resource management prompting development of varying systems based on the local conditions and users' needs. For standard procedure in carbon accounting method IPCC provided guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use (Hairiah *et al.*, 2011).

### 2.6 Partioning of below ground carbon effluxes in terrestrial ecosystem

Soil is the biggest carbon pool of the continental biosphere and requires a particular attention (Nouvellon *et al.*, 2008). The majority of soils in the world are covered with vegetation, and the vegetation may contribute strongly to the total $CO_2$ efflux by root and rhizomicrobial respiration. However, this contribution of vegetation to total soil $CO_2$ efflux has no effect on long-term C balance in soils (Kuzyakov, 2006). A review by Kuzyakov (2006) classified sources of $CO_2$ efflux from soil into; microbial decomposition of soil organic matter in root free soil without undecomposed plant remains, or basal respiration, microbial decomposition of SOM in root affected or plant residue affected soil, microbial decomposition of dead plant remains, microbial decomposition of rhizodeposits from living roots or, 'rhizomicrobial respiration', and root respiration. Separately Davidson and Janssens (2006) observed that the production of $CO_2$ in soils is almost entirely from root respiration and microbial decomposition of organic matter. The study further notes that like all chemical and biochemical reactions, production of $CO_2$ in soils are temperature-dependent and limited by water.

Soils are complex and dynamic ecosystems that play hosts to communities of organisms (Simmons, 2009) apart from carrying out other essential ecosystem services like water storage, filtration and decomposition. One of the main pathways of effluxes in the global carbon cycles is soil respiration (Mehmet *et al.*, 2010) this is indicative of soil biological activities from plant roots/necromass. Spatial heterogeneity of soil respiration has been related to root biomass, microbial biomass, litter amount, soil organic carbon, soil nitrogen, cation exchange capacity, soil bulk density, soil porosity, soil PH, or site topography. The study further noted for better understanding of biospheric effluxes and stocks in relation to increasing atmospheric $CO_2$ and effects of climate change. It is vital to understand soil respiration which is one form of ecosystem respiration. A view strongly backed by studies done by (Ryan *et al.*, 2010, Olatunde *et al.*, 2013, Bhattarai, 2015) who noted a better understanding of soil respiration is necessary in designing effective climate change mitigation strategies.

Soil respiration is a sensitive indicator of several essential ecosystem processes, including metabolic activity, persistence and decomposition of plant residue and conversion of soil organic carbon to atmospheric $CO_2$. Decomposition in soils is a key ecosystem function that in part determines the productivity and health of plants growing anywhere. It further forms an important part of global carbon cycle. The carbon cycle is a cyclic movement of carbon atoms from atmosphere to the biosphere/lithosphere and back to atmosphere (Simmons, 2009).When the magnitude of $CO_2$ in the atmosphere rises beyond certain levels, because of conversion of organic carbon stored in plants to gaseous form a green gas effect is created leading to global warming.

**2.7 Soil carbon dioxide efflux assessment in forest ecosystems**

The global carbon budgets must be better understood if we are to address potential climatic changes resulting from anthropogenic activity. Important gaps in our understanding of the global carbon budgets include uncertainties about ecosystem carbon cycling within forest ecosystems of which soil $CO_2$ is an important component (Davidson and Janssens, 2006). Carbon dioxide release from soil is an indicator of microbial and root activity and as such is an essential component of terrestrial carbon budgets and models of ecosystem carbon cycling (Grogan, 1998). Soil $CO_2$ efflux is the result of two main processes: the production of $CO_2$ in the soil and its transport from the soil to the atmosphere (Davidson and Janssens, 2006). Soil respiratory activities releases large amount of $CO_2$ into the soil pore space and this may lead to higher concentration in the soil air sometimes and even exceeding atmospheric $CO_2$ storage in forests. Therefore terrestrial ecosystems are characterized by their exchange of carbon with the atmosphere (Norman *et al.*, 1997). The effluxes into and out of these ecosystems can have a significant impact on atmospheric carbon dioxide concentration. Thus giving a major feedback between the biosphere and atmosphere that must be understood before the consequence of climate change can be evaluated.

Deforestation have led to significant loss of both organic and inorganic carbon (Girmay and Singh, 2012). These forms of carbon are stored at atmospheric, terrestrial and aquatic systems. The methods used for assessment of these forms of carbon effluxes and systems are varied but can be broadly classified into above and below ground assessment methods (Guner *et al.*, 2010, Ryan *et al.*, 2010, Bradley and Scott, 2011, Bhattarai, 2015). Above ground carbon stocks consists of all carbon pools above the ground which include tree/plant biomass, undergrowth, litter fall and deadwood. Belowground carbon includes all living biomass of live roots. Fine roots of less than (suggested) 2mm diameter are often excluded, or measured as part of the soil carbon pool, because it is impractical to try to remove very fine roots and root hairs from the soil.

The mode of undertaking the assessment will vary depending on the carbon form being measured; however they can be broadly grouped in to destructive and non-destructive mode/method. In situ measurements of the $CO_2$ efflux from SOC decomposition are difficult since the $CO_2$ produced by that process is usually mixed with effluxes from other pathways, particularly litter decomposition and autotrophic respiration by roots and symbiosis (Chen *et al.*, 2015).

**2.7.1 Assessment of soil carbon dioxide using soda lime technique**

There are many methods of measuring soil $CO_2$ efflux including; InfraRed Gas Analyser (IRGA), Rayment system, Crill system and Savage systems, Baldocchi Eddy correlation system ,Static chamber technique, Soda lime and Striegl system , however there are large differences in accuracy, spatial and temporal resolutions and applicability (Davidson and Janssens, 2006).Therefore the choice of method is often a trade-off between requirement (accuracy and resolution) and feasibility (applicability and cost).Furthermore there is no standard or reference to test accuracy since considerable uncertainty characterizes all types of $CO_2$ measurement (Pumpanen *et al.*, 2004).

The soda lime technique has been used extensively for more than 30 years to measure $CO_2$ effluxes from soil under field conditions (Grogan, 1998). This is mainly because of advantages for making field estimates of $CO_2$ effluxes and they include; (1) it can readily provide single integrated measures over a daily time scale and thus incorporate the effects of diurnal fluctuations in a biotic variables that control $CO_2$ release; (2) it is robust and economical, making it more appropriate for large number of replicate field measurement necessary to account for enormous spatial heterogeneity associated with soil surface $CO_2$ effluxes (Grogan, 1998). However, it has limitation of underestimation of $CO_2$ effluxes due to incomplete oxidation and production of toxic dichromate. But because of the feasibility, cost and resolution consideration the soda lime technique is likely to continue to have applications for in situ field measurement of soil respiration (Grogan, 1998) and therefore it was adopted in this study.

The soda lime methods uses chamber with soda lime to absorb of evolved $CO_2$ as detailed by (Kelting *et al.*, 1998). Soda lime granules consist of NaOH and $Ca(OH)_2$ and absorbed water of about 20%. Water plays an important role in chemical absorption of $CO_2$ to form $Na_2CO_3$ and $CaCO_3$. Carbonate formation is reflected in weight gain of granules. Weight gain of soda lime must be measured on oven dried granules so that difference in water content of the initial batch of soda lime, and water absorption during the exposure do not interfere with measured weight gain of $CO_2$. Inaccuracies with the method arise because the $CO_2$ adsorption rate of soda lime is rarely in equilibrium with the efflux rate being measured.

**2.8 Effects of environmental controls on soil carbon dioxide efflux**

Efflux of $CO_2$ from the process of soil respiration is a major contributor to net carbon exchange in terrestrial ecosystems, second only in magnitude to photosynthesis by plants. Soil $CO_2$ efflux is therefore an important parameter in carbon cycle, however it's affected by environmental factors such as temperature, moisture and disturbance (Wong, 2006). Soil moisture has an influences on nutrient availability which direct or indirectly determines the kind of plants that can grow within a given ecosystem and controls gas diffusivity (Bréchet *et al.*, 2011). However the soil moisture is strongly impacted by the local topography through influencing soil water content and physical soil properties.

Soil temperature on the other hand affects the physical, chemical and biological process in the soil and the plants growing in it (Beldini *et al.*, 2010). Thus seasonality in soil respiration has often been associated with either changes in soil temperature or changes in both soil temperature and water content ( Nouvellon *et al.*, 2008). According to (Nsabimana, 2009) seasonal variations of soil $CO_2$ efflux followed the pattern of precipitation and were highest in rainy seasons and lowest in dry seasons. The study findings showed that soil $CO_2$ efflux increased with increasing soil water content but appeared to saturate or decrease above a soil water content of 0.25 $m^3$.

The global carbon cycles are influenced by soil respiration; therefore any factor that influences the soil respiration is contributing to the global carbon cycle balance or imbalance. Conversion of native forests to other use has been shown to alter the soil and air temperature which in turn affects the carbon cycling and SOM dynamics. Higher soil temperature could lead to increased soil decomposition of soil organic matter and thus reducing the carbon storage in the soil resulting in increase in the atmospheric concentration. Mineralization is accelerated and rapid release of nutrients in warmer soils has been noted. This rapid increase will lead to a cascade of environmental impacts such as global warming, sea level rises, alteration of precipitation patterns and increased storm severity (IPCC, 2007). These effects are being experienced in many parts of the world; however UNFCCC provided guideline on combating the effects of climate change which includes $REDD^+$ and Clean Development Mechanism (CDM).

### 2.9 Research gaps on carbon stocks and fluxes

Most information on the role of forests in the carbon stock and efflux processes between plants, soil and atmosphere generally comes from boreal and temperate regions, and tropical America, but less attention has been given to Africa (Nsabimana, 2009). However the need for better understanding of soil carbon sequestration as a strategy to mitigate climate change has seen some research activities. The research on the role of forests in the carbon cycle is emerging in the African continent. For example, a study in Congo focused on investigating both temporal and spatial variations of this major component of ecosystem respiration and documented that spatial heterogeneity of soil respiration was clearly affected by management practices. In another study (Nsabimana, 2009) collected quantitative data on climate, carbon stocks, annual carbon increment, litter production and soil $CO_2$ effluxes in Nyungwe forest and Ruhande Arboretum in Rwanda.

Similarly other studies for example (Girmay and Singh, 2012, Olatunde *et al.*, 2013, Were, 2015) have looked at various aspects of land use changes and its effects on carbon stocks in different study sites. While (Mills and Cowling, 2010, Ryan *et al.*, 2010) studied both aboveground and below ground carbon stocks within their respective study sites. Despite numerous research on climate change (Nsabimana, 2009) observes that soil respiration still requires additional research work mainly because previous soil respiration studies had limited spatial coverage and variability such that most African forest systems are under studied.

#### 2.9.1 Conceptual framework of the study

Forest management or events associated with a management type impacts on soil carbon stocks and soil $CO_2$ effluxes (Mbaabu, 2014, Simona, 2015). The soil $CO_2$ effluxes are affected by soil temperature and soil moisture. The forest management regimes are treated as independent variables while environmental controls are the intervening variables in this study. This relationship will impact on level of soil carbon stocks and soil carbon dioxide efflux, which are dependent variable (Figure 1)

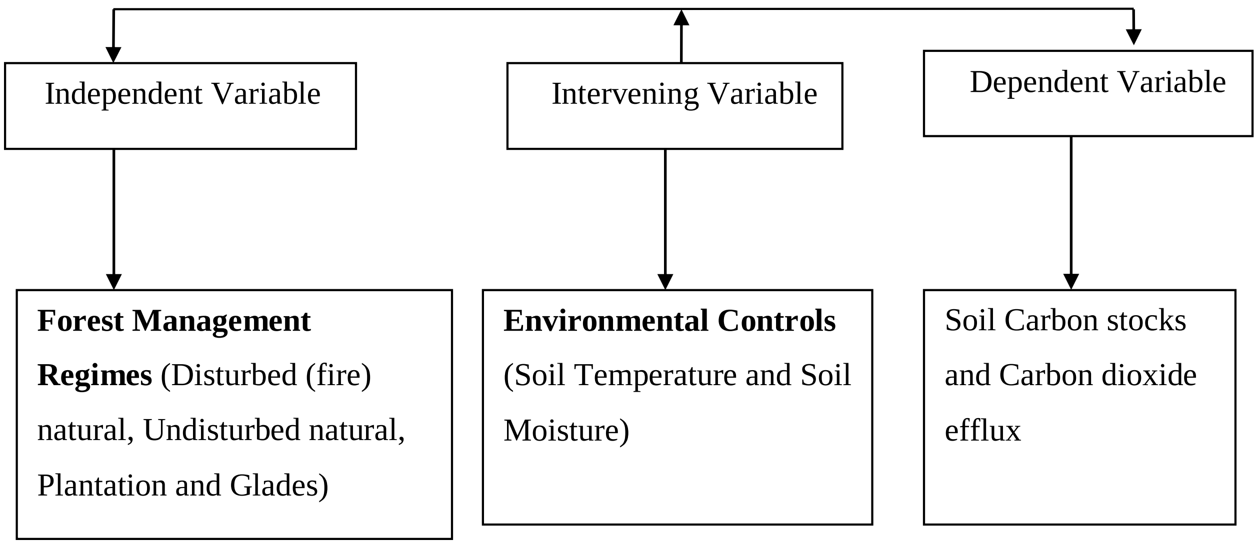


Figure 1: Conceptual framework for the study in Sururu forest reserve

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Description of the study area

### 3.1.1 Geographical Location

The study was conducted in Sururu forest which is part of extensive East Mau Forest reserve. It has an area of approximately 13364.4 ha. It is geographically located within the following UTM coordinate bounds: (161237, 9937639); (161237, 9924748); (1773018, 9937639) and (1773018, 9924748) (KFS, 2011). The forest lies within 1,200–2,600m above sea level.

### 3.1.2 Forest Vegetation and Importance

The forest regulates the local hydrological flows, thus helping to control flooding and maintain a water catchment area that drains into Lake Nakuru, Lake Elementaita and Lake Victoria. The vegetation patterns are complex, but there is a broad altitudinal zonation into lower montane forest that falls below 2,300 m giving way to thickets of bamboo (*Arundinaria alpine)* mixed with forest and grassland and finally to montane *Sclerophyllou*s forest near the escarpment crest. The lower montane forest is in best condition within the forest, with characteristic trees that includes; *Aningeria adolfi-friedericii* and *Strombosia scheffleri*

### 3.1.3 Soils and topography

The local topography is dominated by hills and valleys comprised of quaternary and volcanic deposits. These deposits have influenced the soil type for example the mollic andosols soil type found in the study area was developed from pyroclastic rocks and volcanic ashes. The soils are well drained, deep, dark brown to grey brown, friable and smeary clay loam with thick humic topsoil. These soil types supports the intensive agricultural activities in around the forest and as result the region has high human population densities (Olang and Kundu, 2011).

### 3.1.4 Climate

The weather of Mau complex is largely influenced by the North-South movement of Inter-tropical Convergence Zone (ITCZ) modified by local orographic effects. The climate is characterized by a trimodal precipitation pattern with the long and intense rains from April to June; short rains in August; and shorter, less intense rains from November to December with mean monthly rainfall between 30mm and 120mm and total annual precipitation of 1200mm (Langat *et al*.2016). The study site has dry spell between January and March, September and October. The mean annual temperature ranges between 17-23$^{o}$C. The climatic conditions of Sururu are influenced by altitude and aspect (Kundu *et al.*, 2003).

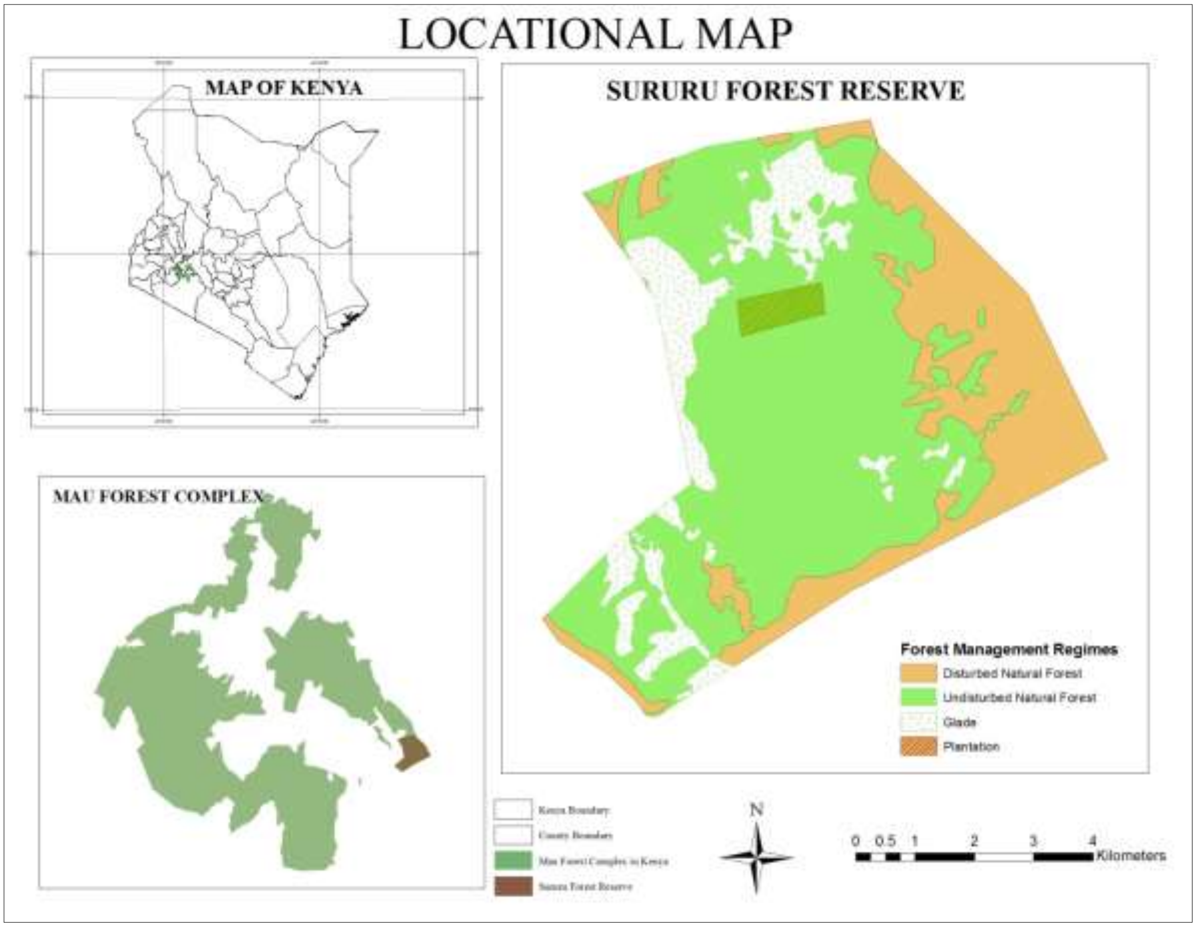


Figure 2: Location of the study site within Kenya

### 3.1.4 Forest adjacent communities

Sururu forest is surrounded by human settlement actively engaged in agricultural activities. These agricultural activities are crop production that comprises mainly of potatoes, peas, carrots, wheat, maize and vegetable and livestock production mainly from cattle, sheep, poultry and donkey.

### 3.2 Research and Sampling Design

Nested Experimental research design was used in determining the amount of soil carbon stocks and carbon dioxide effluxes in relation to forest management types and environmental controls, as well as comparing their levels in different seasons. Within each of the four forest management types (Plantation, Undisturbed natural forest, Disturbed (fire) natural forest and Glades), two systematic blocks measuring 50mby 50m were established. In each block four random plots measuring 10m by 10m were nested and in each plot one $CO_2$ chamber was established randomly. On every occasion when soil $CO_2$ efflux measurement was taken, soil samples were randomly collected for onward analysis of carbon stock.

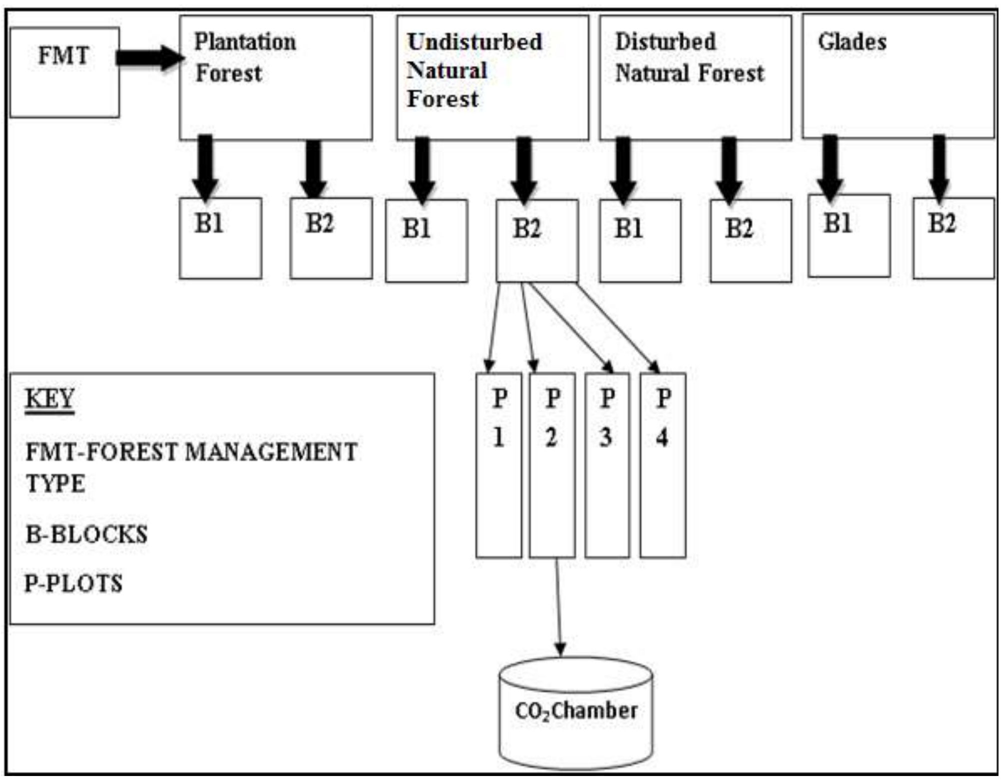


Figure 3: Research design of soil carbon and effluxes measurement in Sururu forest reserve

### 3.3 Data Collection

#### 3.3.1 Measurement of soil carbon stocks

Soil organic carbon analysis was done to determine the carbon stocks in soil organic matter (SOM) using Loss-on-ignition (LOI). The soil sample was collected at five random points within the plot at 0-10 cm, then composited to make one sample per plot see (Appendix 1). The samples were oven dried and crushed using mortar and mixed to homogenize it. It was then sieved using a 2mm sieve to remove debris. Two 5 grams of the sample was sub-sampled and put in pre-weighed crucible and then combusted at $450^0$C for 8 hours and then cooled and weight is recorded see ( Appendix 2)

The differences in mass of weights of soil before and after heating represent soil organic carbon (SOC) (Schulte and Hopkins, 1996)

$$\textit{SOC content} = \frac{\textit{Initial weight (g)} - \textit{Final weight (g)}}{\textit{Initial weight (g)}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\textit{Equation 1}$$

Soil organic carbon (SOC) was determined per plot and extrapolated to per hectare in order to estimate total organic carbon (TOC) for the study area based on (Wright, 2008).

$$\textit{TOC } (MgCha^{-1}) = \textit{Bulk Density} * \textit{Soil Depth interval (cm)} * \%C \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\textit{Equation 2}$$

#### 3.3.2 Measurement of Soil carbon effluxes

Soil $CO_2$ efflux rates were measured every fortnight for a period of one month in each of the rainy and dry months respectively using the soda lime method (Edwards, 1982, Raich *et al.*, 1990). The clustering of measurement into rainy and dry months was intended to capture the seasonality of environmental controls. Though the method may underestimate actual soil respiration at higher efflux rates, it was sensitive when doing comparison between sites. A White plastic bucket (8.6 cm high and 30 cm in diameter) was inserted 2 cm into the ground floor within the plots (Plate 5). These buckets were left inverted for 24 hours after all the vegetation within were cleared. Glass jars containing approximately 50 g of soda-lime (pre-dried 48 hours at 105°C) were placed at the centre of each of the buckets for a period of 24 hours before its lids being tightly reinforced to guard external $CO_2$ entry and interference (Plate 6). After this, the jars were sealed and taken to the laboratory (at Egerton University) and oven-dried for 48 hours at 105°C and their dry weights (Plate 7) and recorded see (Appendix 3). Blanks were used to account for $CO_2$ absorption during drying and handling. Soda lime weight gains were multiplied by 1.69 to account for water loss. The difference in dry weight before and after the sampling represents the carbon dioxide absorbed.

Plate 5: Plastic chamber inserted into the forest floor

Plate 6: Soil $CO_2$ efflux measurement in the field


Plate 7: Laboratory measurement of soda lime

### 3.3.3 Assessment of Soil Moisture and Soil Temperature

Gravimetric soil moisture content was measured by taking soil sample at a depth of 0-5cm at five points within the plot. The small containers were weighed before adding the soil sample. The sample were weighed before oven drying it for 24 hours at 105°C and reweighing done after cooling and results recorded see ( Appendix 4). The moisture content was determined as described by (Trautmann and Richards, 1996) and using a formula below:

$M_{n(\%)} = [(W_w – W_s/W_w)] \times 100$…………………………………………………………….*Equation 3*

Where: $M_n$=moisture content (%) in the soil

$W_w$=wet weight of the soil sample  $W_s$=weight of the sample after drying.

Soil temperature was measured at a 5cm soil depth adjacent to each bucket in the midday. The measurement was done every fortnight on the same day as efflux determination was done. To estimate soil bulk density, the oven dried soil used for soil moisture determination was utilized (Kauffman and Donato 2012).

$$\text{Bulk density } (gcm^{-3}) = \frac{\text{Mass of oven dried sample (g)}}{\text{Volume of the sample } (cm^3)}$$ ……………………………………*Equation 4*

### 3.4 Data Analysis

Collected data was summarized and subjected to tests of normality and homogeneity of variance before being transformed where necessary. Variations in soil carbon stocks and $CO_2$ effluxes, between the different forest management types were assessed using Analysis of variance (ANOVA). Sampling frequencies of soil $CO_2$ was categorized into wet and dry seasons and 2 sample t- tests was used to assess the effects of season. Table 1 below summarizes the data analysis.

**Table 1: Summary of data analysis**

| Null Hypothesis | Variables | Data analysis |
|---|---|---|
| Carbon stocks do not vary between intact natural forest, disturbed(fire) natural forest, plantation and glades and seasons | Carbon stock, and forest management types | ANOVA |
| Soil carbon efflux do not vary between undisturbed, disturbed, plantation and glades and seasons | Soil carbon efflux and forest management types | ANOVA |
| There is no relationship between environmental controls (soil moisture and soil temperature) and soil carbon effluxes | Soil temperature, soil moisture content and forest management types | Simple Linear Regression |

# CHAPTER FOUR

## 4.0 RESULTS

### 4.1 Soil carbon stocks under different forest management regimes and seasons

Bulk density is an important parameter in determining the total carbon stocks in soils. The study results show that there is no significant difference in bulk density between forest management regimes ($F_3$. =0.17, p >0.05).The mean bulk density for dry and wet season were 0.63g/cm$^3$ and 0.62g/cm$^3$. Forest management regimes recorded slight variation in bulk density between the two seasons under study. However less variation in bulk density during the dry season was recorded (Figure 4). Undisturbed natural forest management had the highest mean bulk density of 0.66g/cm$^3$ while disturbed (fire) natural forest had the lowest mean of 0.59 g/cm$^3$. *The error bar on the graphs below indicates the standard error*

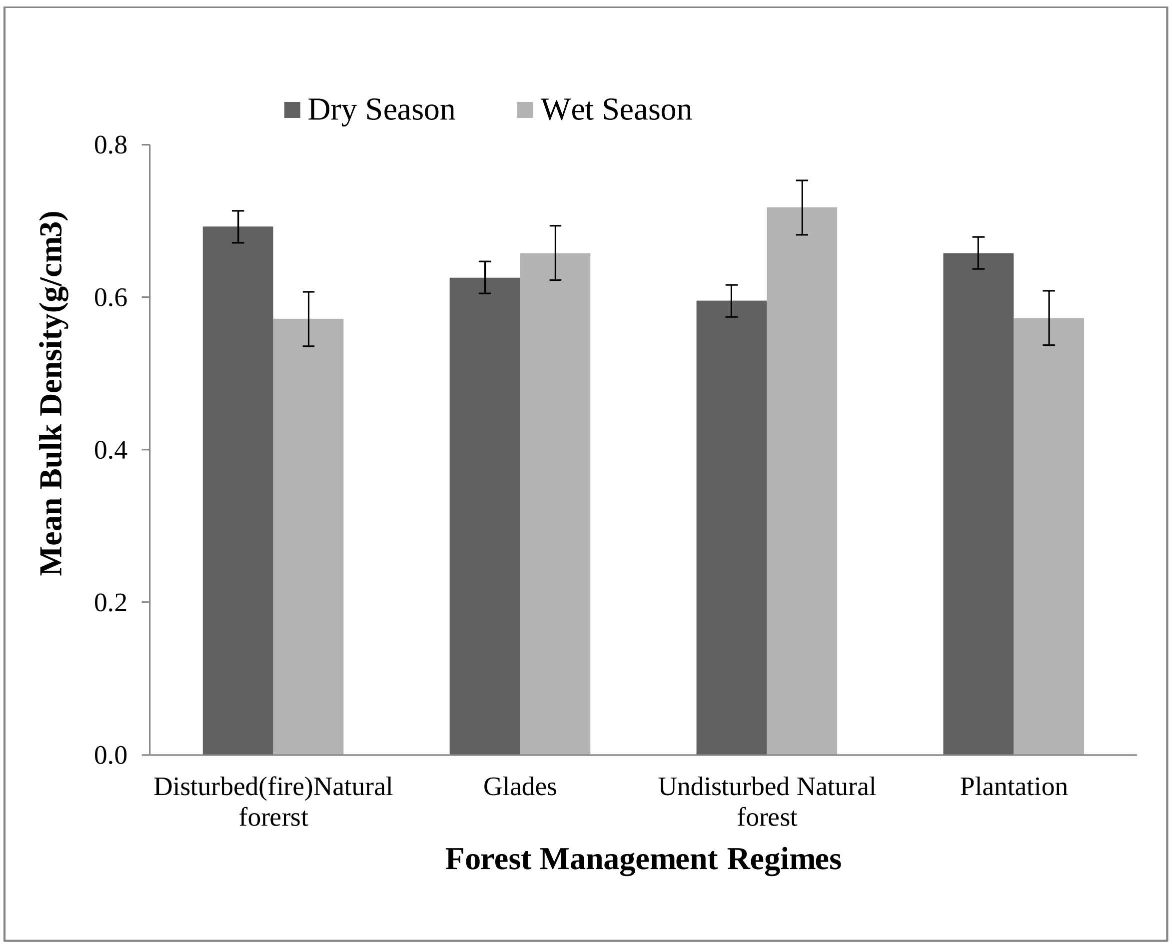


Figure 4: Mean Soil bulk density in different seasons in Sururu Forest reserve

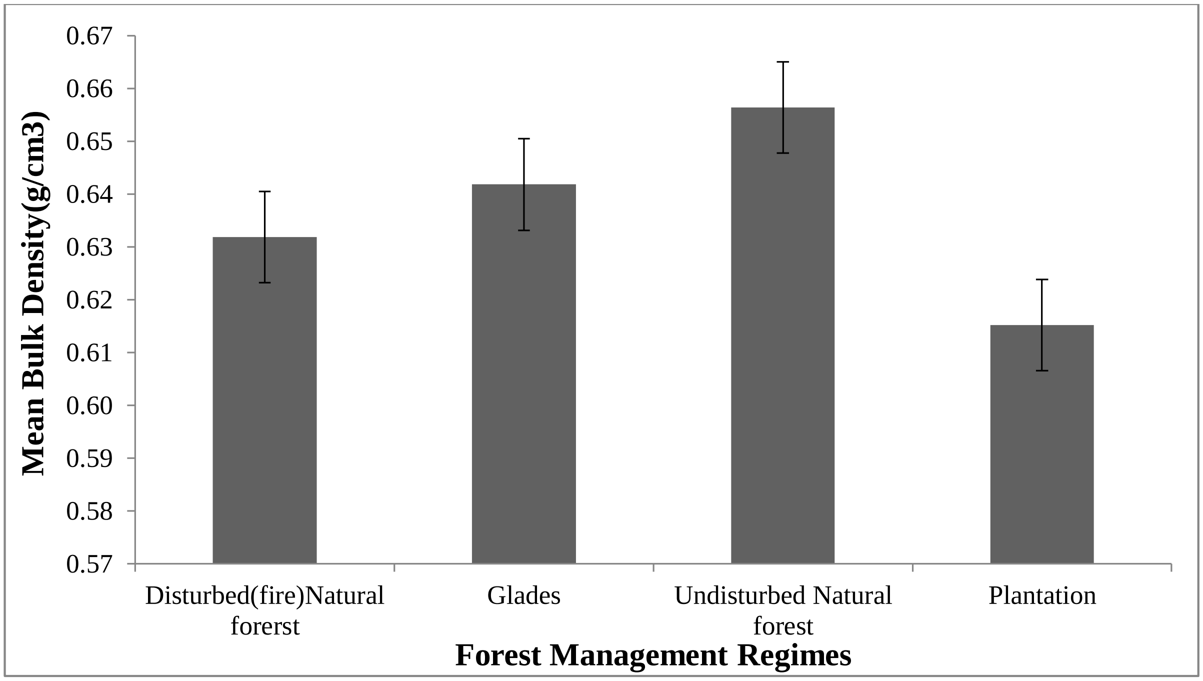


Figure 5: Mean Soil bulk density in Sururu Forest reserve

Sururu forest reserve has stable total soil carbon stocks as shown by the study (Figure 5). The glades (112.1 Mg C/ha) and plantation (115.6 Mg C/ha) recorded lower stocks during the dry season (Figure 6). The study indicates that the dry season (124.34Mg C/ha) had lower mean soil carbon stocks than during the wet season (130. Mg C/ha).

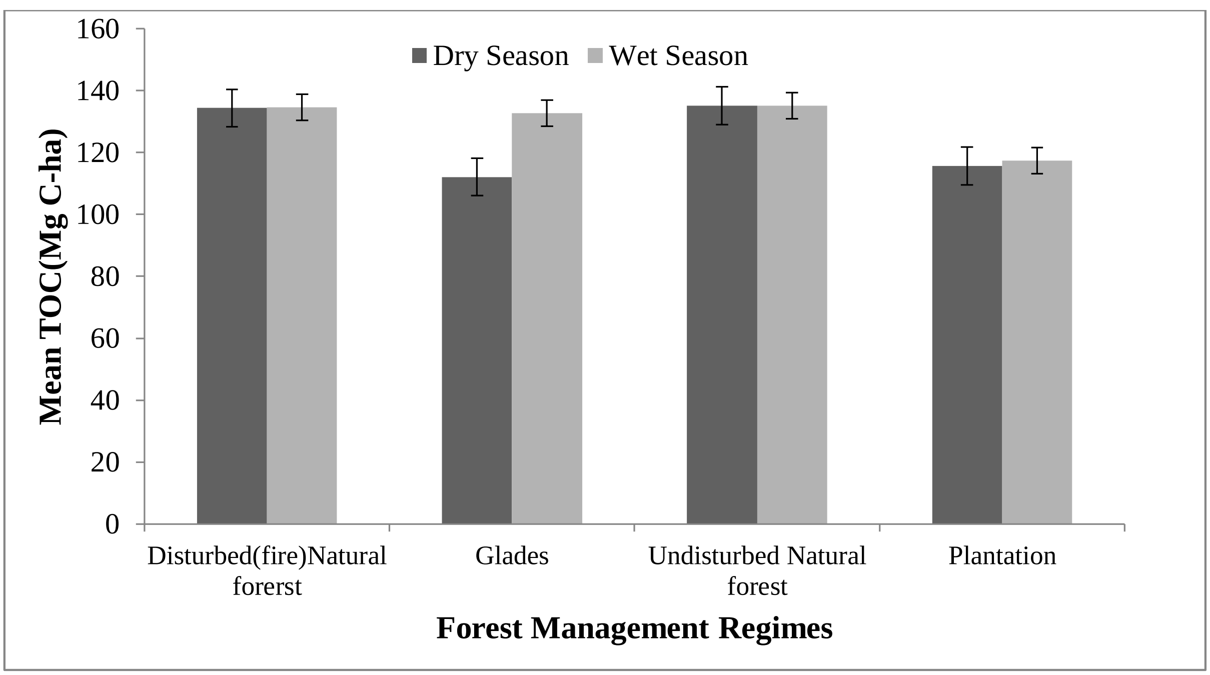


Figure 6: Mean carbon stocks in different forest management regimes and seasons

There was no significant difference in the mean carbon stocks among the four different forest management regime ($F_{4, 16}$. =0.61, p >0.05). However, the individual mean levels were varied. The undisturbed natural forest had the highest mean soil carbon stocks (135.2± 360 Mg C/ha) followed by disturbed natural forest ( 134.5± 38.1 Mg C/ha) , glades (122.4 ±64.9 Mg C/ha), and plantation forest(116.5± 40.Mg C/ha) (Figure 7)..

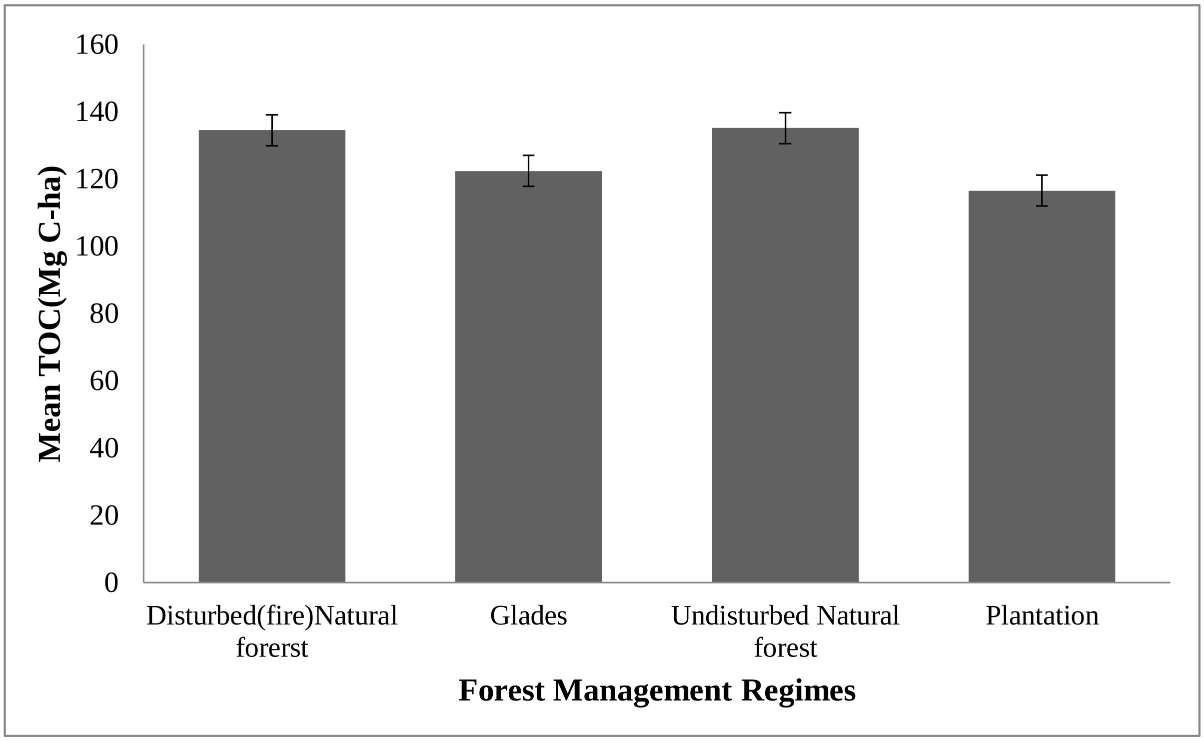


Figure 7: Mean soil carbon stocks in different forest management regimes

**4.2 Soil carbon dioxide efflux under different forest management regime and seasons**

The study findings shows that disturbed natural forest had lower mean soil efflux levels (5.4 g C $M^{-2}day^{-1}$), glades had (7 g C $M^{-2}day^{-1}$), undisturbed natural forest recorded (8.60 g C $M^{-2}day^{-1}$) and plantation had (8.94 g C $M^{-2}day^{-1}$) during the dry season. During the wet season the mean efflux levels recorded were; glades (10.19 g C $M^{-2}day^{-1}$), undisturbed natural forest (8.73 g C $M^{-2}day^{-1}$), plantation (9.50 g C $M^{-2}day^{-1}$) and disturbed natural forest (9.0 g C $M^{-2}day^{-1}$). There were higher mean efflux levels during the wet season (9.35 g C $M^{-2}day^{-1}$) than during the dry season (7.48 g C $M^{-2}day^{-1}$) (Figure 8)

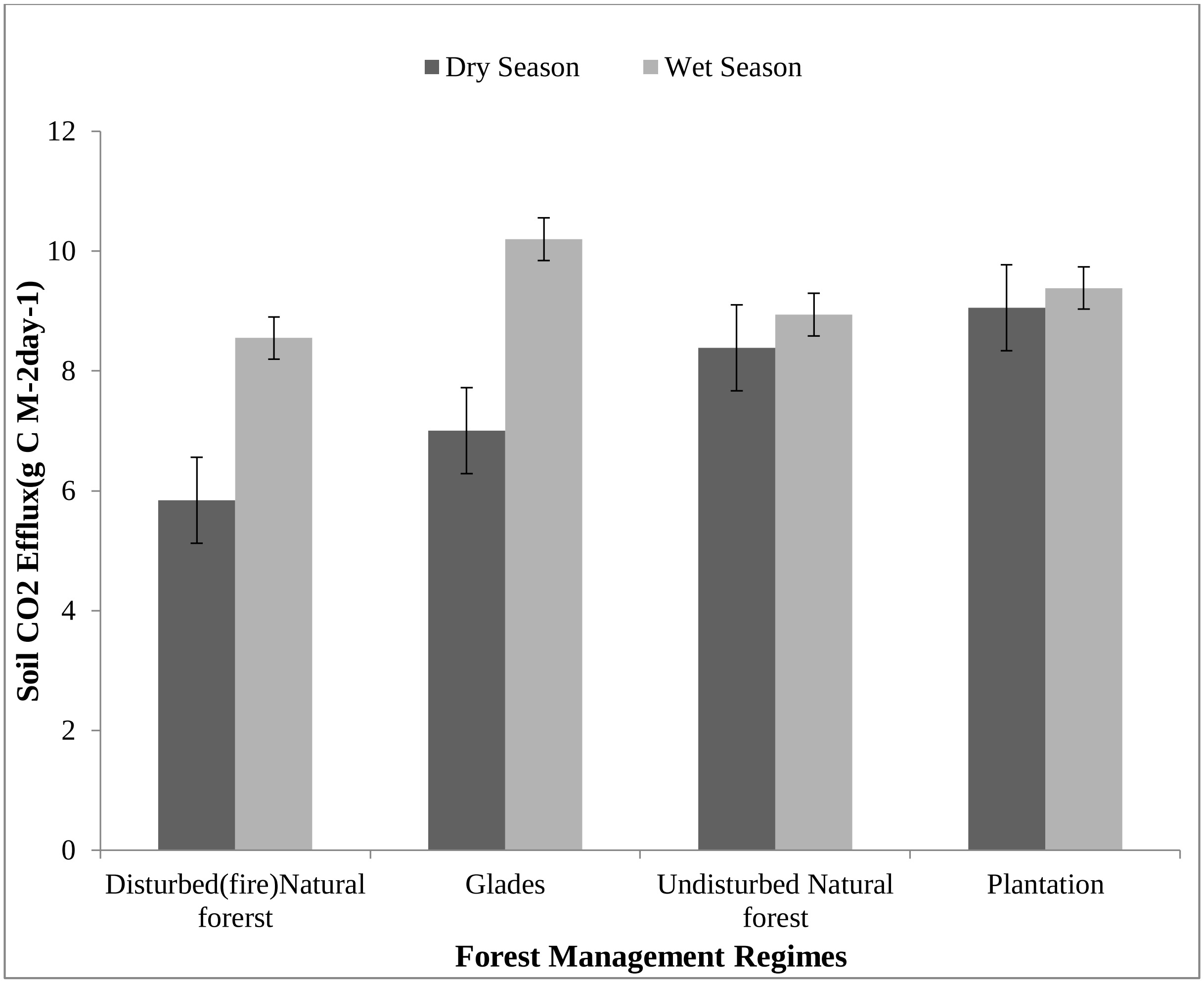


Figure 8: Mean soil $CO_2$ efflux under different forest management regimes and seasons

There was significant mean difference ($F_{1\ 32}$. =3.01, $p < 0.05$) in mean soil $CO_2$ efflux between the four forest management regimes  The results indicates varying levels of soil $CO_2$ efflux, the plantation forest had the highest mean soil $CO_2$ efflux (9.219 ± 3.067 g C $M^{-2}day^{-1}$) followed by undisturbed natural forest (8.665 ± 4.818 g C $M^{-2}day^{-1}$) , glades (8.592 ± 3.253 g C $M^{-2}day^{-1}$) and fire disturbed natural forest had the lowest mean soil $CO_2$ efflux ( 7.198 ± 3.457 g C $M^{-2}day^{-1}$) respectively (Figure 9).

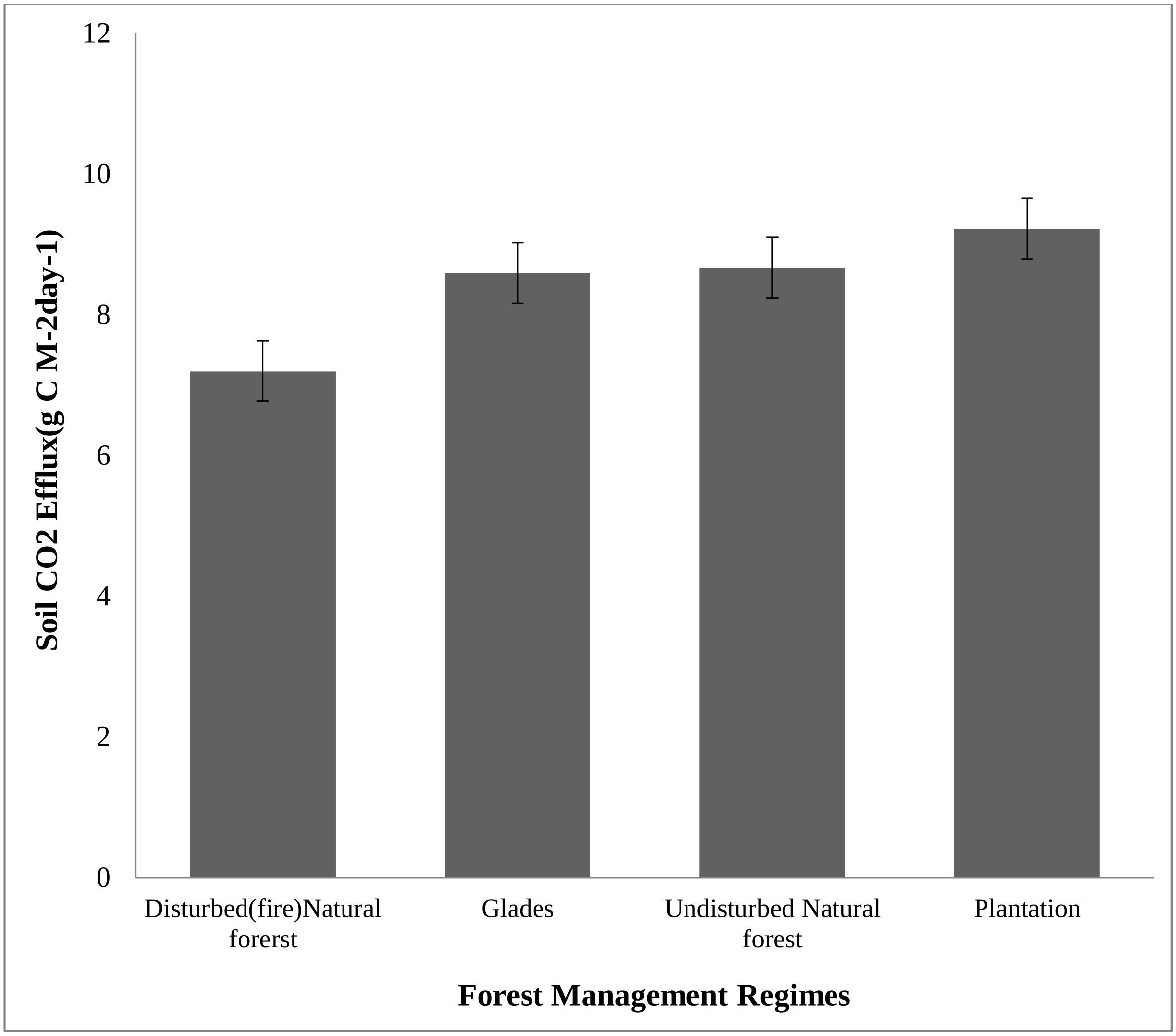


Figure 9: Mean soil carbon dioxide efflux under different forest management regimes

The posthoc test analysis was done to understand which mean was significantly different from the other. The findings indicated that the mean for disturbed natural forest is significantly different from mean of undisturbed natural forests, but were not significantly different from means of glades and plantation. The study further showed no significant difference existed between means of glades versus undisturbed natural forest and plantation. Similarly no significant difference was found between the means of undisturbed natural forests and plantation (Table 2)

Table 2: Tukey test: All Pairwise comparisons of efflux levels

| Forest management regime = Disturbed(fire)Natural forest subtracted from: | | | |
|---|---|---|---|
| Forest management Regime | Lower | Center | Upper |
| Glades | -0.717 | 1.394 | 3.504 |
| Undisturbed natural forest | 0.262 | 2.408 | 4.553 |
| Plantation | -0.09 | 2.021 | 4.132 |
| | | | |
| Forest management regime = Glades subtracted from: | | | |
| Forest management Regime | Lower | Center | Upper |
| Undisturbed natural forest | -1.132 | 1.014 | 3.16 |
| Plantation | -1.483 | 0.628 | 2.738 |
| | | | |
| Forest management regime = Undisturbed natural forest: | | | |
| Forest management Regime | Lower | Center | Upper |
| Plantation | -2.532 | -0.386 | 1.759 |

**4.3 Relationship between environmental controls (soil temperature and soil moisture) and soil carbon dioxide efflux**

There was a significant and strong relationship between soil carbon dioxide efflux and seasons ($p<0.05$, $R^2 = 0.9149$).The mean efflux were higher during wet season ( 9.360 g C M-$^{2}$day$^{-1-1}$) than dry season (7.477 g C M-$^{2}$day$^{-1}$).

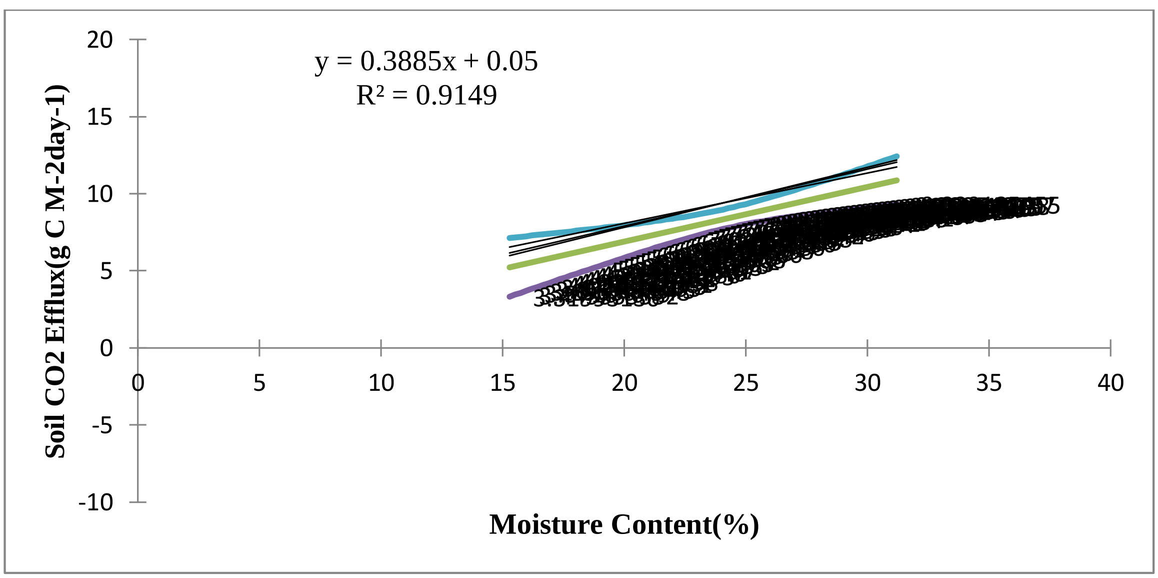


Figure 10: Soil carbon dioxide efflux under varying soil moisture content

The fluxes had a strong significant mean difference with moisture ($p<0.05$) (Figure 10), soil temperature ($p<0.05$) respectively (Figure 11). There was 91.5 % explanation of soil carbon dioxide efflux by the soil moisture data in the study (Figure 10), while a very poor fit of model ($R^2=0.079$) was recorded between soil temperature and soil carbon dioxide efflux (Figure11).

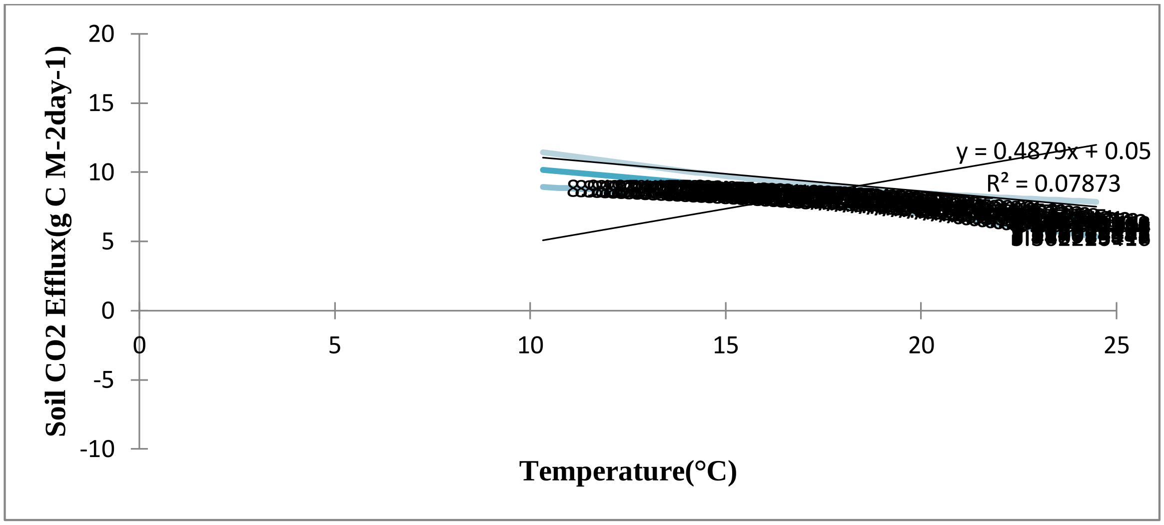


Figure 11: Soil carbon dioxide efflux under varying soil temperature

The environmental controls (soil moisture and soil temperature) and mean soil $CO_2$ had a weak relationship with a poor model fit ($R^2=0.092$)

# CHAPTER FIVE

# 5.0 DISCUSSION

## 5.1 Soil carbon stocks in different forest management regimes

The total soil carbon pool within a forest ecosystem is composed of soil organic carbon and inorganic carbon and is determined by the balance between soil respiration, where carbon is released from the soil, and the incoming carbon from litter fall and rhizode position (Lal, 2005, Jandl *et al.*, 2007, Gershenson and Barsimantov, 2010). Both of these factors can be influenced by favorable abiotic conditions and forest management practices and disturbances.

Soils in our study recorded low bulk density as reported in other studies (Kinyanjui, 2009, Were, 2015 Hafkenscheid, 2000, Jeyanny *et al.*, 2014). The results show that forest management regime has no significant impacts on the soil carbon stock levels ($F_{4,\ 16.}$ =0.61, p >0.05). The undisturbed natural forest had higher carbon stocks levels per hectare followed natural forest disturbed by fire, then glades, and plantation.

The higher carbon stocks within natural forest could be explained by possible biotic factors such as the presences of a closed canopy cover within the stratum which provides favorable condition for carbon preservation through limiting decomposition of non-labile carbon and even where gaps exists in the canopy, the litter turnover compensate for losses (Jandl *et al.*, 2007, Peng *et al.*, 2008, Campbell *et al.*, 2009, Duncker *et al.*, 2012). Also the presence of decomposable organic matter from branches and litter fall increases the amount of soil carbon. The processes could vary for fire disturbed natural forest, depending on the intensity and frequency of forest fire. Higher intensity fire subjected to branches and forest floor litter will lead to instant oxidation where carbon stored in them moves to gaseous state. Similarly low intensity fire may not interfere with soil carbon stock significantly and that explains why the despite the study site having experienced periodic fires in 2005, 2007 and 2014 (KFS,2011) the soil carbon stocks are still higher than in glades and plantation.

Forest fires in most cases instantly consume above ground biomass and forest floor carbon and depending on the fire intensity the belowground systems such as roots and soil carbon may be affected. Where incomplete combustion occurs the woody biomass is converted to biochar or charcoal. Charcoal is resistant to microbial decomposition within the soils, and therefore it can serve as an important long-term soil carbon pool, as well as increase overall soil quality (Gershenson and Barsimantov, 2010). The burnt study sites showed formation of charcoal from previous forest fires and that could explain the high levels of soil carbon within the stratum. Fire does not necessarily lead to a loss of soil C or N and but instead it may cause increases in soil C and N by incorporation of charcoal and hydro-phobic organic matter. However that conclusion cannot be supported strongly by this study due to short period taken in the assessment as well the scope of the study.

Glades are predominantly occupied by grass species, that provides food to grazers and therefore its carbon stock levels will mostly likely be influenced by grazing. Grazing modifies soil organic carbon stocks through inflicting changes in plant productivity, root allocation of plant carbon, changes in species composition and changes in physical soil properties (Vesterdal and Leifeld, 2007). However, due to management of forest grazing to within the carrying capacity by Kenya Forest Service, the study area may not have experienced extreme grazing pressure and that explains the comparatively higher level of stocks recorded.

Plantation forest management mostly focuses on enhanced forest productivity and growing forest stocked by subjecting trees to a number of silvicultural operations that ranges from land preparation, pruning, thinning and clear cut depending on the management regime. The amount of soil carbon gained during stand establishment and development depends, in large part, on the management of the stand between planting and harvest, as well as on climatic variables and species composition (Gershenson and Barsimantov, 2010). For example a study on thinning in a Ponderosa pine stand found that, although soil respiration did not significantly change 3 and 16 years after thinning treatments, overall fine root biomass was lower even after 16 years, and overall soil carbon went from being a slight sink of carbon to being a significant source (200 g C/m2/y) with thinning (Campbell *et al.*, 2009).

The cypress plantation in the study area had the lowest level of carbon levels due to inadequate levels of organic matter decomposition. The plantation in our study area has not been thinned or pruned due to restriction imposed on plantation forests in Kenya that lasted 13 years (KFS,2011). That restriction interfered with silvicutural operations that could have added organic matter into the soil. Also cypress has needle shaped litter that is more resistant to decomposition. Similar observation was noted by (Zheng *et al.*, 2008) in a study in China where broadleaved species decomposed faster than needle litter species.

From the study findings it is evident that soil organic carbon is a factor of organic matter decomposition and accumulation, this observation was reported a previous study (Mwikamba, 2015). The decomposition of organic matter is influenced by presences of microbes as well as favorable a biotic environment. The rate and duration of organic matter accumulation is determined by forest management. The findings on carbon stock support the observation that forest management activities have an effect on soil carbon sequestrations and emission (Jandl *et al.*, 2007)

Our results of soils organic carbon levels (135.17± 35.99.0 Mg $C^{-ha}$- 116.51± 39.77 Mg $C^{-ha}$) compares well with Lüa *et al.*, (2010) and Lal,( 2005) studies which recorded stocks ranges of 87 -102 Mg C $ha^{-1}$ in China and 123 Mg C $ha^{-1}$ for a tropical biome respectively. Previous studies (Kinyanjui, 2009, Were, 2015) within Mau forest reported stock levels of 42.0 to 193.4 Mg C $ha^{-1\ 1}$. In another study in Oregon USA (Law *et al.*, 2004) the stock levels of 111.9 Mg C $ha^{-1}$ -142.4 Mg C $ha^{-1}$ were recorded.

In contrary a number of similar studies reported lower carbon stocks levels for example ( Jandl *et al.*, 2007) in Europe reported 62-102t C $ha^{-1}$ for plantation forest and (Lee, 2009) in a Korean forest reported 46.8-75.9 Mg $ha^{-1}$.The climatic and species disparity between these studies might be the reason for the distinct variance in the stock levels. In Kenya Glenday, (2006) and Mwikamba, (2015) reported soil carbon stock levels of 14-30 Mg C $ha^{-1}$ respectively for Arabuko Sokoke forest and3.51- 59.71 Mg C $ha^{-1\ 1}$ for rehabilitated sites in Bamburi. These marked difference in the stocks is attributed to possible methodological and ecological, edaphic, climatic and anthropogenic variance between the current study and the other studies

## 5.2 Effects of forest management on soil carbon dioxide efflux

Terrestrial ecosystems are characterised by the ability to facilitate exchange of carbon dioxide with the atmosphere. Carbon dioxide release from the soil is an indicator of microbial and root activity (Grogan, 1998). Efflux of $CO_2$ from the forest soil is a combination of the activity of autotrophic roots and associated rhizosphere organisms, heterotrophic bacteria and fungi active in the organic and mineral soil horizons, and soil faunal activity (Davidson *et al.*, 2002).

The soil $CO_2$ efflux levels shows that plantation forest had higher efflux ($9.219 \pm 3.067$ g C M-$^{2}$day$^{-1}$), followed by undisturbed natural forest ($8.665 \pm 4.818$ g C M-$^{2}$day$^{-1}$) , glades ($8.592 \pm 3.253$ g C M-2day$^{-1}$) and fire disturbed natural forest ( $7.198 \pm 3.457$ g C M-$^{2}$day$^{-1}$) respectively.These findings were significantly different ($F_{1\ 32}$. =3.01, $p < 0.05$) from one another and the posthoc analysis showed that mean efflux levels from fire disturbed natural forest was significantly lower than undisturbed natural forests.

The plantation forest is characterised by species that has fast growth rate than the natural forest.Plant growth involves photosynthetic and respiration processes,the higher levels of efflux in plantation study site could partly be contributed by root respiration associated with faster growth. While lower effluxes in the disturbed natural forest could be attributed to the associated effects of fire on the forest. Zhou *et al.*, 2013 study showed that disturbance caused by burning affected soil $CO_2$ effluxes by depleting the decomposable matter. Burning that results into wood carbonization affects the soil through to the extreme heat generated during the carbonization process and therefore impairing the natural biological processes in the soil.

This suggestion is supported by Hanson *et al.* (2000) observation that the primary source of $CO_2$ efflux from soils had been attributed to decomposition by bacteria. However more analyses suggested that root respiration in soils of forests may commonly exceed the value for decomposition. Secondly silvicultural operation associated with plantation forest management improves the microclimate, increasing light penetration and, therefore, temperature which stimulates microbial activity (Gershenson and Barsimantov, 2010). The lowest level of efflux reported in natural forest burnt can be attributed to low microbial activities due to low organic matter presences in the soil, secondly fire could have destroyed the root network and thus minimal root respiration exists and lastly presence of charcoal within the natural forest disturbed by fire limits decomposition processes leading to lower soil respiration levels

The findings of the study compares favorably to similar studies for example (Wong, 2006) reported a mean efflux range of 1.49 -9.32 C $M^{-2}$ $day^{-1}$ in semi-arid meadow steppe in Northeast China, while (Hashimoto *et al.*, 2004) in Thailand recorded an efflux of 7.01 C $M^{-2}$ $day^{-1.}$ Another study undertaken by (Gavrichkova *et al*,2008) in a transitional forest in Brazil showed a maximum efflux level of 11.1 ± 0.70 C $M^{-2}$ $day^{-1}$ and a minimum of 4.3±0.4 C $M^{-2}$ $day^{-1}$ whereas in a subtropical study (Navarroa, 2013) a lower efflux levels of 3.38-6.08 C $M^{-2}$ $day^{-1}$ in China were observed. For detailed understanding of how forest management activities influences the soil decomposition process as well as the resultant respiration studies have stratified of forest ecosystems based on forest management activities and the results indicates a strong correlation between forest activities and the efflux levels. For example, Adachi *et al.,* (2006) classified the forest into primary forest, secondary forest and plantations and efflux levels of 19.94 ±11.52 C $M^{-2}$ $day^{-1}$,20.22± 3.43 C $M^{-2}$ $day^{-1}$ and 23.18± 14.35C $M^{-2}$ $day^{-1}$ respectively.. Simona,(2015) observed that in tropical montane forests primary forest type emits 16.04± 3.42C $M^{-2}$ $day^{-1}$ while a in a secondary forest type emits 19.77± 3.27 C $M^{-2}$ $day^{-1}$. Similarly Adachi *et al.* (2006) and, Simona (2015) shows that where forest management activities or disturbances are higher the level of efflux are higher and this could be attributed to increased levels of decomposition as result of more organic matter to decompose.

In contrast the current study findings show the undisturbed natural forest has higher mean efflux than other categories like plantation and glades which have higher associated activities. The variance in the findings could be attributed to climatic, ecological and disturbance types between the study sites. However the current study indicates a strong significant difference in the efflux levels in forest management types.

### 5.3 The relationship between environmental controls and soil effluxes

Our study shows a strong relationship between forest management and soil temperature... The high temperature levels in glades are related to the openness of the forest and therefore higher sun energy is being received by the soils. The levels of sun radiations reduce as the canopy of the forest is reduced leading to lower soil temperature in undisturbed natural forest. The solar radiation is absorbed and reflected by leaves and branches in the upper canopy leading to limited rays reaching the forest floor and therefore lower soil temperature. Similar relationships have been documented by studies (Jandl *et al.*, 2007, Nouvellon *et al.*, 2008, Mathiba, 2014) where open forest landscapes records higher soil temperatures.

The inverse correlation between soil temperature and soil moisture is widely documented (Fang and Moncrieff, 2001, Flanagan and Johnson, 2005, Almagro *et al.*, 2009), where higher soil temperature indicates lower moisture content. However that relationship is absent in our study where higher soil temperature in glades resulted on average to higher moisture content while lower temperatures in undisturbed natural forest did not translate to higher moisture content. Figure 11 indicates an inverse relationship between temperature and efflux pointing to the greater influence soil moisture has on efflux levels as previously documented (Flanagan and Johnson, 2005).

Soil moisture also played a major role in the soil $CO_2$ effluxes, which is consistent with other studies where, at constant temperature, wetter soils emitted more $CO_2$ due to better conditions for microbial respiration (Zhou *et al.*, 2013). The study indicates soil moisture levels depends on soil temperature, soil type and forest management. The strong relationship established by the study shows that season which is a proxy for level of temperature and rainfall. Forest management affects the level of moisture available in the soil at a particular moment. This study did not explore all the parameters that impacts on the level of moisture content of soils.

Higher soil moisture results in higher levels of microbial activity, which in turn results in higher carbon losses from soils (Gershenson and Barsimantov, 2010). The amount of active soils is highly seasonal depending on seasonal temperature, soil moisture and available organic matter (Flanagan and Johnson, 2005). Therefore the dry season in the study site may not be having the prerequisite conditions for higher efflux. All of the components of soil $CO_2$ efflux are sensitive to changes in environmental variables such as soil temperature and moisture (Buchmann, 2000). The strong significant differences in the level of soil efflux indicate the said sensitivity. Figure 10 indicates higher effluxes during the wet season despite expected lower kinetic energy necessary for microbial activities. These findings conform to others studies (Jia *et al.*, 2006, Nouvellon *et al.*, 2008) suggesting other factors beyond the general soil temperature, for example soil temperature heterogeneity and fluctuation over different periods from hourly to diurnal, seasonal, and annual.

According to (Zhou *et al.*, 2015) the influence of soil respiration rate at 10 °C ($R_{10}$) and temperature sensitivity ($Q_{10}$, soil respiration change with a proportional change of 10 °C in soil temperature) could be the reason behind higher effluxes during wet season when temperatures are lower. In the current study the lowest temperature was 14.3°C is higher than $Q_{10.}$when coupled with higher decomposition rates during the wet season higher efflux rate will be recorded. Similarly wet season are characterized by rainfall and water infiltration into soil create a wetting front from the surface filling up the pore spaces and displacing soil gases in the process. The displaced gases therefore make the increased efflux during the wet season and this explains the higher rates recorded in the glades. Additionally glades in the study are predominately grass and the landscape has gentle gradient which traps and hold the rain water for percolation into the soil. However, percolation through the soil is usually not uniform horizontally resulting in variability as documented in the efflux level of similar forest management types

The level of soil respiration in forest ecosystem is an indicator of ecosystem processes such as decomposition and microbial activities. In particular, decomposition leads to transfers of carbon from one pool to another and sometimes removal though emissions. Interestingly heterotrophic respiration is influenced by environmental controls such as soil moisture and soil temperature among other factors. Therefore it is important to understand the level of these two factors in the soils at one particular time or season. According to (Nsabimana, 2009) seasonal variations of soil $CO_2$ efflux followed the pattern of precipitation and were highest in rainy seasons and lowest in dry seasons. The study findings showed that soil $CO_2$ efflux increased with increasing soil water content but appeared to saturate or decrease above a soil water content of 0.25 $m^3$.

# CHAPTER SIX

# 6.0 CONCLUSION AND RECOMMENDATIONS

## 6.1 Findings of the study

The findings of this study indicate that forest management regime had no impacts on the soil carbon stock levels. However a trend showing higher carbon stocks in undisturbed natural forest followed by natural forest disturbed by fire, then glades, and plantation respectively was established. Therefore there is evidence to suggest that forest disturbances have an impact on carbon stocks and therefore for effective management of forest towards climate stabilization then disturbance should be avoided.

The significance variation in the levels of soil $CO_2$ efflux suggests an important role played by forest management. The finding shows that plantation forest had the higher mean soil $CO_2$ efflux followed by undisturbed natural forest, glades and fire disturbed natural forest in that order. Therefore while silvicultural operations are key in good plantation forest management,the negative effects due to increased levels of $CO_2$ emission associated with them should be consindered in the computation of forest carbon budgets

The study results shows that level of soil carbon dioxide efflux has a relationship with environmental conditions of the forest. The results indicates that soil moisture content and soil temperature influenced the level of the efflux,however the strength of the relationship varied with soil moisture having strong relationship while soil temperature had a weak relationship.Therefore variability in climatic conditions will strongly influence the level of efflux within forest ecosystems and thus key in addresssing climate change.

## 6.2 Conclusions of the study

The role of forest in the mitigation and adapting to the changing climate has received a lot of focus both locally and internationally. The role of Eastern Mau in Kenya's aspiration to mitigate on climate change as well helping local communities adapt is critical. Therefore the study recommends that

1. Forest managers should minimize forest disturbance in order to store more carbons in soils and similarly carbon stocks under the various forest management types can be utilized in the construction of forest reference level for the REDD+
2. For effective management of carbon dioxide emission from the forests, natural forest management presents the best option and therefore its role in climate change mitigation is vital.
3. Climatic variability potents higher emissions levels from the forest and therefore measures should be enhanced towards addressing climate change
4. For effective maangement of climate change a paradigm shift in forest objectives from intensive forest associated with plantation and disturbances to preservative forest associated with pristine forest or undisturbed

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# APPENDICES

Appendix 1: Field Soil Samples Data Sheet

Recorder…………………………………………………………….

Date………………………………………

Forest type……………………………….Block …………………………… Plot No……

GPS coordinates of Subplot centre…......................................................................................

| Plot no. | Soil Sample No | Remarks |
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Appendix 2: Laboratory Soil Analysis Sheet

Recorder…………………………………………………………….

Date………………………………………

Forest type…………………………………Block.......................Plot No..................

Start time......................................................... End time..............................................

| Soil sample no | Initial soil sample weight ($I_{1}$) | Final soil sample weight ($F_{1}$) | Difference ($F_1$-$I_{1}$) | Remarks |
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Appendix 3: Laboratory Soda lime Sheet

Recorder…………………………………………………………….

Date………………………………………

Forest type…………………………………Block................Plot No..................

Start time...................................................... End time...............................................

| Plot no. | Soda lime initial weight<br>($S_1$) | Soda lime final weight<br>($S_2$) | Difference<br>($S_2$-$S_1$) | Remarks |
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Appendix 4: Laboratory Soil Moisture Analysis Sheet

Recorder…………………………………………………………….

Date………………………………………

Start Time............................................ End time..........................................

| Soil sample no | Initial soil sample weight ($M_1$) | Final soil sample weight ($M_2$) | Difference ($M_1$-$M_2$) | Remarks |
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