DETERMINATION OF SPECIES ABUNDANCE, DIVERSITY AND CARBON STOCKS IN KAKAMEGA FOREST ECOSYSTEM

BY

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DECLARATION

Declaration by the Candidate

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DEDICATION

I dedicate this thesis to my late grandmother Mary Kaveza Visaho who supported and inspired me and to my children Jaelle Kaveza Agevi and Darrel Visaho Agevi as an inspiration to motivate you to work smart in life.

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ABSTRACT

Agroforestry is an important land use strategy for carbon sequestration. Trees in these landscapes mitigate climate change by storing carbon in tree biomass and by raising soil organic carbon levels. While agroforestry stores larger amounts of carbon, this potential is poorly quantified because of the high spatial and temporal heterogeneity of trees on farmlands, and methodological challenges. As a result, the role of agroforestry in carbon sequestration is poorly understood and often underestimated and the sector is often left out in most national carbon accounting systems. This gap has led to dearth of data, variable conclusions and a fragmented understanding of the role of trees in smallholder farms in climate change and development. In addition, the relationship between tree species diversity and carbon stocks in different agroforestry practices is poorly understood. The aim of this study was to i) determine tree species diversity under different agroforestry practices in Kakamega Forest ecosystem; ii) determine tree biomass and soil organic carbon under different agroforestry practices in Kakamega Forest ecosystem and iii) extrapolate biomass and soil carbon stocks in Agroforestry practices in Kakamega Forest ecosystem for the next 50 years. The study was conducted at two sites (Kakamega North and Kakamega South) adjacent to Kakamega Forest. A total of 16 farms were randomly selected, 8 farms from each of the sites. An inventory of all trees in each of the farms was conducted, capturing diameter at breast height (DBH), the species name, and the management of trees within two dominant agroforestry practices-homegardens and hedgerows. Tree circumference at breast height, 1.3 m from the ground was measured by use of tape measure for trees ≥5cm. Measurement of circumference was converted to DBH by dividing pi (π = 3.142) with circumference. Soil samples were taken at 0-10cm and 10-30cm in each of the 10x10m plots in each of the farms. Soil Organic Carbon (SOC) was determined by Walkley and Black method. Biomass and SOC simulations were determined using CO_2FIX model. Aboveground biomass (AGB) of trees was determined by applying allometric equations to DBH measurements. Two models $0.091\times (DBH)^{2.472}$ by Kuyah and $2.134\times (DBH)^{2.53}$ for tropical dry forests by Brown were used for estimation of biomass from tree measurements. Below ground biomass (BGB) was estimated by using a root-to-shoot ratio of 0.26. Homegardens had both a high number of tree species (n=48) and high tree density in the two sites combined, and in each of the sites - 562 trees per hectare in Kakamega North and 408 trees per hectare in Kakamega South. Shannon diversity index revealed a high tree diversity in Kakamega north (H´=1.92±0.13) than Kakamega south (H´=1.71±0.16), and in homegardens (H´=1.98±0.14) than in hedgerows (H´=1.65±0.14). A total of 13.96±0.37 Mgha^{-1}(6.4MgCha/ha) of aboveground biomass was estimated for the study area using the equation by Kuyah. Below ground biomass was estimated to be 3.45±0.09 Mg ha^{-1}(1.6MgC/ha), giving total biomass held in live trees on farms to be 17.22±1.65 Mgha^{-1}(8.0MgC/ha). Equation by Brown consistently gave higher estimates per site and agroforestry practice. Kakamega North had significantly (F=35.03; p=0.01) higher biomass (9.7Mg/ha) compared to Kakamega South (7.51Mg/ha); corresponding to the higher tree density in the north compared to the southern part. Similarly, home gardens had significantly higher (F=45.2; p=0.001) aboveground biomass (9.85Mg/ha) than hedgerows (7.36Mg/ha). SOC determined in the two study sites was 14.91MgC/ha. Kakamega North had 6.9MgC/ha while Kakamega South had 8.01MgC/ha. The two sites showed a decline in SOC with depth. The CO2FIX model simulated the SOC and total carbon stocks in the studied agroforestry practices, but the prediction of the biomass carbon stocks could be improved by acquiring more accurate input parameter values for running the model.

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ABBREVIATIONS AND ACRONYMS

AFS	Agroforestry systems
AGB	Aboveground biomass
ANOVA	Analysis of variance
BGB	Belowground Biomass
C	Carbon
CAI	Current annual increment
CAM	Carbon accounting models
CO_2	Carbon dioxide
$CuSO_4$	Copper Sulphate
DBH	Diameter at breast height
FAO	Food and agriculture organization of the United Nations
Fe_2SO_4	Ferrous sulphate
GHG	Greenhouse gas
GPS	Global positioning system
H_2SO_4	Sulphuric acid
ha	Hectare
IPCC	Intergovernmental Panel on climate change
Kg	Kilogram
KKN	Kakamega north
KKS	Kakamega south
MAI	Mean annual increment
Mg	Mega grams
MRV	Monitoring reporting and verification
NACOSTI	National commission for Science, Technology and Innovation

REDD+	Reducing emissions from deforestation and forest degradation
SD	Standard deviation
SE	Standard error
SLEEK	System for Land based Emission Estimation in Kenya
SLM	Sustainable Land Management
SOC	Soil Organic carbon
SOM	Soil organic Matter
TB	Total biomass
TC	Total carbon
TN	Total nitrogen
ρb	Bulk density

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Agroforestry traditionally includes trees under different systems, including silvopastoral (trees and animals), agrisilvicultural (crops and trees), and agrosilvopastoral systems (crops, trees and animals) (Nair, 1993). The components of these systems include perennials such as trees and shrubs, crops and other herbaceous species, and animals (Nyaga *et al*., 2015). Agroforestry practices include woodlots, home gardens, hedgerow intercropping, boundary planting/live fence, trees on grazing lands, Taungya, improved fallow among others (Mbow *et al*., 2014). Trees in these systems are introduced into farms for particular reason(s), or are selectively retained after land use changes (Agevi *et al*., 2019).

Farmers plant and manage a mix of exotic, indigenous trees and other high value tree crops, like the fruit trees and medicinal trees (Kuyah, 2008). Globally, they account for 45% while in sub- Saharan Africa, they account for 87% adding up to 10% tree cover (Kuyah and Rosenstock, 2014; Zomer *et al*., 2014). The retention of trees delivers multiple ecosystem services on farms (Dawson *et al*., 2013; Mpanda *et al*., 2014; Nyaga *et al*., 2015). There are also some trees species that could be in existence before the establishment of the farms (Montagnini and Nair, 2004).Other natural trees could have established from the natural regeneration after the farms were established (Ordonez *et al*., 2014). This makes agroforestry a land use that can enhance agro-biodiversity and contribute to conservation of landscape biodiversity, while at the same time leaving out huge land for agricultural production (Dawson *et al*., 2013).

In addition to contributing to the diversity of trees in the landscape, integration of agroforestry in agricultural operations can reduce pressure on natural forests and protected conservation areas, create habitat for wild species and mitigate loss of biodiversity on farms (Asaseh and Tetteh, 2016; Ali and Mattson, 2017). This is because they supply timber and fuel wood which would have otherwise been sourced from the forest (Albrecht and Kandji, 2003). The multifunctional roles of trees in farmlands make them important candidates for enhancing the provision of multiple ecosystem services such as soil protection, water regulation, enhancement of local climatic and provision of shade and shelter (Mbow *et al*., 2014; Kuyah *et al*., 2016b; Kuyah *et al*., 2017) and provision of habitat for pollinators and natural enemies (Sileshi *et al*., 2014; Pumariño *et al*., 2015).

Agroforestry systems have been cited as some of the most promising land use strategies for carbon sequestration (IPCC, 2007). It is therefore critical to quantify the biomass of trees in agricultural lands in order to establish their role in the global carbon budgets (Kuyah *et al*., 2016a).Carbon stocks in these systems is substantial because of the spatial extend of agricultural land with trees, and large unproductive croplands that can be converted to agroforestry (Zomer *et al*., 2014).Scientific evidence shows that agroforestry sequesters larger amounts of carbon than monoculture field crops or pastures (Jose *et al*., 2009; Kuyah *et al*., 2016a; Agevi *et al*., 2017).

In Africa, this land use system is estimated to stock between 3 and 18 $Mgha^{-1}$ of carbon in aboveground biomass, with carbon sequestration potential from 0.4 to 3.5 $Mgha^{-1}$ of carbon per year (Nair and Nair, 2014). The amount of aboveground biomass that has been estimated in trees on agricultural lands is less than that in the forests. However, is significant due to the spatial extend of farmlands with some tree cover (Zomer *et al*., 2009). This potential is context specific and depends on the tree species present on the farm, agroforestry practice, the management of trees, prevailing environmental conditions of the area and the site quality characteristics (Nair *et al*., 2010). In addition, communities in these countries are continuously opening up fragile lands to increase agricultural production, with the potential to release the carbon "securely" held in vegetation and in the soil (Kumar, 2006).

The role played by woody vegetation in the global carbon cycle has led to increased interest in estimation of biomass carbon held in all land uses, including agroforestry (Nair and Nair, 2014). Tree cover has been decreasing within natural forests which have led to release of C into the atmosphere (IPCC, 2003). There has been however initiatives to help increase tree cover on agricultural lands to expand the existing carbon sinks in addition to conserving available carbon pools and new opportunities for carbon credits (Velarde *et al*., 2010; Zomer *et al*., 2014). However, their ability to enhance carbon stock is poorly quantified because of the high spatial and temporal heterogeneity of trees on farmlands (de Foresta *et al*., 2013; Chave *et al*., 2016) and methodological challenges such as invalidated methods for quantifying carbon stocks in such systems (Kuyah *et al*., 2012a). As a result, the role of agroforestry in carbon sequestration is poorly understood and often underestimated. This makes the sector to often be left out in most national carbon accounting systems (Kuyah *et al*., 2012b; Zomer *et al*., 2016). Measurement of biomass in these trees can help establish the role of smallholder systems in climate change mitigation (Kuyah *et al*., 2013).

For efficient accurate determination of carbon stocks in trees in agroforestry systems, combination of field inventory and modelling is encouraged. This is a tier 3 method that ensures correct and accurate validation (IPCC, 2014). Field inventory involve measurements of tree parameters that will be fitted in allometric equations in determining tree biomass and those that will be fitted in the model. Tree diameter at breast height (DBH) is the most widely applied predictor of biomass and is contained in virtually all allometric equations that are not based solely on remotely-sensed crown area (Brown, 2002). Height, crown area, and wood density have been reported to be useful supplements for improving the accuracy of biomass equations based on diameter at breast height (Ketterings *et al*., 2001; Chave *et al*., 2005; Kuyah *et al*., 2012a). However, these additional measurements can be costly and are prone to errors.

Errors arising in the field clearly propagate into misleading biomass estimates for the subject population and subsequent studies that combine the use of existing equations. Diameter is preferred as predictor variable because it can be measured with ease and high accuracy, and explains over 95% of the variability observed in aboveground biomass (Kuyah and Rosenstock, 2014). Modelling of the biomass and soil carbon stocks is essential for future predictions and planning in relation to carbon sequestration potentials. CO_2FIX model (Masera *et al*., 2003; Negash and Kanninen, 2015) is preferred since it is a user-friendly model for dynamically estimating the carbon sequestration potential in agroforestry.

Studies on biomass estimation in agroforestry systems have been done with a view of creating opportunities for smallholder farmers to benefit from emerging green economies (Takimoto, 2007). Majority of these studies identify trees on farms as valuable tools in mitigating climate change. This is because they store carbon as biomass and soils in these farmlands also enhance carbon sequestration potential.

However, little attention has been given to trees on farms neighbouring forest ecosystems such as Kakamega Forest. This gap has led to dearth of data, variable conclusions and a fragmented understanding of the role trees in smallholder farms in climate change and development (Kuyah and Rosenstock, 2014). In addition, the relationship between tree species diversity and carbon stocks in different agroforestry practices is poorly understood. People living closer to forests ecosystems modify natural and semi-natural vegetation for livelihood (e.g. agricultural production); in the process, they establish and maintain agroforestry systems that contribute to biodiversity and carbon sequestration (Kindt *et al*., 2013). This study therefore sought to determine tree species diversity and biomass of carbon stocks and soil carbon in two different sub-groups of agroforestry practices in western Kenya and modelling using CO_2FIX model to predict the future scenarios of this carbon for the next 50 years.

1.2 Statement of the Problem

Most studies on carbon sequestration potential have been done mainly in forest ecosystems and selected pure stand plantations (de Foresta *et al*., 2013). Given the vast scale of available agricultural land, trees on agricultural lands have recently received much attention and have been estimated globally. Their greater role in the global carbon budget in carbon sequestration as an adaptation and mitigation strategy has been recognized recently (IPCC, 2014; Mbow *et al*., 2014). However, knowledge of carbon stocks and stock changes is fairly poor, in part due to their high spatial extent and temporal heterogeneity and methodological difficulties(Kuyah and Rosenstock, 2014; Zomer *et al*., 2016).

The allometric models developed for trees in agricultural lands have not been validated. In addition, most studies have focussed on humid and temperate regions but few in the tropics especially sub-Saharan Africa where the current research was done.This has made it difficult for these trees to be systematically accounted for in either global carbon budgets or national carbon accounting adequately. Studies on soil organic carbon stocks have been done at a global scale (Abegaz *et al*., 2016). There is less localised data on soil organic carbon stocks for western Kenya and especially around Kakamega Forest ecosystem. In addition, the few studies done have not adequately given combination of studies on tree biomass carbon stocks, soil carbon stocks and simulating the future scenario of the same when trees that are retained in these land-use systems.

1.3 Justification

Focus and greater attention has recently been drawn to assessment of carbon stocks and sequestration on farms through agroforestry for carbon monitoring. This is because of their ability to store carbon in aboveground biomass and in soil (Nair *et al*., 2014). This has been occasioned by the decreasing forest cover which primarily has been seen as a carbon sink. It is important to increase the carbon sinks by looking at other land-use systems including trees on farms. Studies need to look at the carbon dynamics within such systems to increase the available information. Data that will be obtained in this research will help rapidly increase the volume and quality of data for trees on farms including agroforestry as carbon storage. Sequestering carbon through agroforestry is now considered as an attractive economic opportunity for mitigating global climate change (Goswami, Verma and Kaushal, 2013). Despite the importance of agroforestry in sequestration carbon, there is little information on the importance of different agroforestry systems in terms of their potential in carbon sequestration. This research will therefore provide the necessary information on how agroforestry practices sequesters carbon. The data will also help to mitigate and adapt against effects of climate change through increased awareness and motivation for more on farm tree farming. The findings will be vital for individuals, projects, and communities that may benefit from emerging climate change mitigation opportunities.

1.4 Objectives

1.4.1 General objective

The general objective of this study was to determine tree abundance, diversity, carbon stocks and stock changes in agroforestry practises and extrapolates biomass and soil carbon using the CO_2FIX model for the next 50 years in Kakamega Forest Ecosystem.

1.4.2 Specific objectives

The specific objectives of this study were to:

1. Determine tree species abundance and diversity under different agroforestry practices in Kakamega Forest ecosystem;
2. Estimate tree biomass and soil carbon stocks under different agroforestry practices in Kakamega Forest ecosystem;
3. Extrapolate biomass and soil carbon stocks in agroforestry practices using CO_2FIX model in the next 50 years Kakamega Forest ecosystem;

1.5 Research Questions

1. How does diversity of tree species under different agroforestry practises differ within Kakamega Forest ecosystem?
2. What is the carbon storage potential for trees and soils under the different agroforestry practices in Kakamega Forest ecosystem?
3. How are the levels of carbon stocks under different agroforestry practices expected to change in the 50 years time in Kakamega Forest Ecosystem?

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter describes the literature related to this research. It describes research review on topics herein: tree abundance and diversity in agroforestry practices; estimation of tree biomass in agroforestry; significance of estimating tree biomass; soil organic carbon; carbon sequestration in agroforestry systems; factors affecting carbon sequestration in agroforestry systems; Modeling carbon stocks in agroforestry systems, CO_2FIX model; input variables for CO_2FIX model; basic data required for the model; why CO_2FIX model is required and limitations of carbon accounting models and modelling SOC change. It then highlights the research gap that the anticipated research intends to fill.

2.2 Tree Species Abundance and Diversity in Agroforestry Practices

Agricultural lands and especially within the tropics have diverse of woody trees (Guyassa and Raj, 2013). The trees on these lands can result from three processes: retention of trees that were present before farms were established, tolerance (and protection) of natural tree regeneration after farms were established, or active planting by farmers of selected trees in preferred locations through a number of agroforestry practices (Kindt *et al*., 2013). Tree diversity and density on these farms can be increased using anthropogenic sources of indigenous or exotic planting material (planted or grafted), which are usually produced on-farm or off-farm tree nurseries (Oloo *et al*., 2013). Tree species diversity tends to decrease with altitude. In addition, the farm characteristics such as the farm size, shape, species adaptability to the environment, nature of cropping pattern, management practices by the farmer, local socio-economic and physical conditions also affect the structure and composition of trees in agroforestry practices (Kumar, 2004).

The distance of a farm to major roads influences tree species diversity and density. Farms close to main roads always have fewer tree species, lower tree density and less homogeneous population of trees. This is because the roads have increased market access to the farmers who sell different wood products on the roadside that are then, transported to traders and consumers in big towns. Proximity to roads has therefore given a better market access to wood products than the physical proximity to local markets (Abebe *et al*., 2013).

Tree species in a number of studies for example Guyassa and Raj, (2013) and Abebe *et al*., (2013), among others have found that tree diversity is always high in homegardens compared to hedgerows. Tree evenness however is usually low in some agroforestry practices due to dominance of some tree species on the farms (Henry *et al*., 2011). This is especially in hedgerows and woodlots consisting of majorly the *Eucalyptus* spp. Their densely stocked trees within woodlots have contributed to the high density of trees (Bardhan *et al*., 2012). Density of trees is thus heavily associated with the size of woodlots while dominance is attributed to the use to which the tree is put into and to those that are early maturing trees (Mbow *et al*., 2014). Diversity of trees and shrubs in agricultural systems contributes to provision of wood and non-wood products, and protects the environment, thereby, enhancing socioeconomic and ecological sustainability of the systems (Abebe *et al*., 2013).

2.3 Tree Biomass Estimation in Agroforestry Systems

The use of allometric equations is the most appropriate technique in the estimation of tree biomass since it is non-destructive. Tree variables such as DBH, height, crown area, are measured and fitted in as allometric equations (Chave *et al*., 2005). These measurements are used to improve the accuracy of biomass equations based on DBH. In studies done in western Kenya by Kuyah and Rosenstock (2014), it was found out that inclusion of height, wood density or crown area as tree variables in the biomass equation changed biomass estimates by a trivial amount, less than 1.2 Mg or 1.3% of total biomass, from those obtained by using the DBH alone in the equation. According to Kuyah *et al* (2012a), tree diameter at breast is the most widely preferred predictor variable because it can be measured with ease and high accuracy, and explains over 95% of the variability observed in aboveground biomass.

A study by Sileshi (2014) and Kuyah *et al*., (2016a) in Miombo woodlands in Malawi found out that diameter at breast height was significantly correlated with the aboveground biomass of trees, accounted for over 95% of the variation in aboveground biomass. It was therefore concluded that DBH alone is a robust proxy for trees on farms, particularly because DBH only equations are simpler, less costly and provide more accurate predictions in estimating biomass in agricultural lands. However, Kuyah *et al*., (2016a) noted that published models overestimate biomass, a demonstration of the need to consider the DBH range in applying biomass models. The application of models outside their DBH range will result in bigger errors, especially for the larger trees. Information on error breakdown is important since uncertainty in the resultant biomass depends on the size of the tree, and the individual trees of a particular size (Kuyah and Rosenstock, 2014).

The quality of the allometric equation depends on the empirical data used. A major limitation to in the use of allometric equations in estimation of biomass for agricultural landscapes is the non-representativeness of the data from which the equations are constructed (Brown, 1997). When allometric equations are constructed from a small sample, they are unlikely to be truly representative of the landscape population in terms of size and species distribution (Kuyah, 2012). In most cases, larger diameter trees are often underrepresented and only few species of interest are captured (Eamus *et al*., 2000). The choice of the equation therefore has to factor criteria that were used in their development to enable accurate biomass estimation in these landscapes.

2.4 Significance of Estimating Tree Biomass

Quantification of biomass in trees in agricultural landscapes is receiving greater attention (Kuyah and Rosenstock, 2014). There is a growing interest in the assessments of carbon stocks for carbon monitoring, reporting and verification (MRV) needs (Kuyah *et al*., 2012b). Accurate and reliable estimation of biomass in agricultural landscapes is desired to meet Monitoring Reporting and Verification requirements for carbon accounting for any broader based approaches including, anthropogenically modified landscapes (Kuyah *et al*., 2013). Estimation of tree biomass in agricultural ecosystems is essential for the sustainable management of woody vegetation as well as an important component of monitoring carbon sequestration (Mattson *et al*., 2015). Periodic measurement of biomass accumulation can be used to establish the value of a given agroforestry practice. This can as well help determine the production potential or suitability of a certain species for a particular purpose, e.g. charcoal production (Okello *et al*., 2001; Kuyah, 2012; Sileshi *et al*., 2014).

Measurement approaches can also be designed to predict yield, thus helping to assess biomass loss or accumulation over time. Through the establishment of the rate of biomass production, one can determine carbon sequestration potential of particular species (Eamus *et al*., 2000). This allows the potential of trees in agricultural landscapes to offset anthropogenic carbon emissions to be established (Kuyah, 2012). Therefore, development of high quality and representative allometric equations cannot be overstated.

2.5 Soil Organic Carbon

Soil is the largest pool of terrestrial organic carbon in the biosphere, storing more carbon than is contained in plants and the atmosphere combined and a relatively stable pool of various organic and inorganic fractions of carbon(Post and Kwon, 2000).It plays a key role in the global carbon budget and greenhouse effect by acting as major carbon sinks. Soil contain 3.5% of the earth's carbon reserves, compared with 1.7% in the atmosphere, 8.9% in fossil fuels, 1.0% in biota and 84.9% in the oceans (Lal, 2004a). Surface soils (0–30 cm depth) store almost half of soil organic carbon and upto three times of the above-ground carbon stored in vegetation. The total quantity of organic carbon in soils is approximately 1500 Pg (Lal, 2004 a), which is approximately two times the carbon content present in the atmosphere (Lal, 2007). Changes in soil organic carbon will produce obvious undesirable consequences on the current patterns of climate change. Thus, the soil carbon pools may act as a source of atmospheric carbon (Davidson and Janssen, 2006). The adoption of sustainable land management (SLM) practices, has enhanced the potential of agricultural ecosystems to be a potential sink of atmospheric carbon and reduce greenhouse gas emissions (Lal, 2004a; Davidson and Janssen, 2006; Song *et al*., 2013).

The amount of soil organic carbon represents the net balance between carbon inputs in the form of leaf, stem, and root litter and carbon outputs including the decomposition of carbon by soil microbes as well as carbon loss to downwind or downstream systems (Regnier *et al*., 2013). Changes in soil carbon result from an imbalance between the carbon fluxes into and out of the soil (Lal, 2007). When more carbon is brought to the soil than is released, carbon accumulates in the soil, and vice versa. Increments in plant productivity and input of plant residues to soil thus have an increasing effect on soil carbon stock. Land-use and land cover change may induce quite rapid changes in soil carbon as a result of altered carbon input to the soil or decomposition conditions or both (Zingore *et al*., 2005).

2.5.1 Agroforestry and Soil Organic Carbon

Agroforestry systems can either be sinks or sources of carbon and other green-house gases (Mattsson *et al*., 2015). Some agroforestry systems, especially those that include trees and crops (agrisilviculture) can be carbon sinks and temporarily store carbon, while others (e.g. ruminant-based agrosilvopastoral systems) are probably sources of carbon and other greenhouse gases (Gupta *et al*., 2017). In tropical regions, agroforestry systems can be significant sources of greenhouse gases where practices such as tillage, burning, manuring, chemical fertilization, and frequent disturbance can lead to emissions of CO_2, CH_4 and N_2O from soils and vegetation to the atmosphere. Silvopastoral systems, when practiced in an unsustainable manner, can result in soil compaction and erosion with losses of carbon and nitrogen from soils. Whether agroforestry systems can be a sink or a source of carbon depends on the land-use systems that they replace: if they replace natural primary or secondary forests, they will accumulate comparatively lower biomass and carbon, but if they are established on degraded or otherwise tree-less lands, their carbon sequestration value is considerably increased (Montagnini and Nair, 2004).

The impact of any agroforestry system on soil carbon sequestration largely depends on the amount and quality of input provided by tree and non-tree components of the system and on properties of the soils themselves; such assoil structure and their aggregations (Jackson *et al*., 2000). For example, in the establishment of silvopastoral systems, when trees are allowed to grow in grass dominated landscapes such as an open pasture, some functional consequences are inevitable, most notably alterations in above and belowground total productivity, modifications to rooting depth and distribution, and changes in the quantity and quality of litter inputs (Jobbagy and Jackson, 2000). These changes in vegetation component, litter, and soil characteristics modify the carbon dynamics and storage in the ecosystem; which in turn may lead to alterations of local and regional climate systems. Humification (conversion of biomass into humus), aggregation (formation of organic mineral complexes as secondary particles), trans-location of biomass into subsoil by deep roots, and leaching of soil inorganic carbon into groundwater as bicarbonates are processes that lead to SOC sequestration (Lal, 2001). All these processes are operational in tree-based land-use systems.

2.5.2 Factors affecting Soil Organic Carbon (SOC)

Soil Organic Carbon varies considerably both with land-use types and soil depths (Lal, 2007; Gupta *et al*., 2017). The quantity and quality of SOC stocks are influenced by the complex interactions of climatic factors (e.g. temperature and moisture regime), edaphic factors (e.g. parent materials, soil drainage, texture etc.), and management practices carried out on the soils and tree species that is growing in that particular site (Lal, 2005). A growing body of evidence has demonstrated that tree species can differ in their influence on soil properties. In particular, differences between N_2-fixing and non-N_2-fixing species, between gymnosperms and angiosperms, and between native and exotic species are often highlighted (Kassa *et al*., 2017; Agevi *et al*., 2019).

Land use and management affects the SOC and nutrient in the soil. Restoration and management of degraded lands with various conservation measures or disturbing virgin lands may significantly contribute to enhance or degrade soil quality (Lal, 2007). Changes in soil management may affect numerous factors that are directly or indirectly related to temperature and moisture, modifying the dynamics of soil CO_2Carbon emission (Oelbermann and Voroney, 2007). These trends lead to changes on moisture, temperature, nutrient and carbon cycling, directly affecting C emissions. Analyzing the changes on moisture and soil temperature and carbon storing will provide insights that are necessary for making justifiable recommendations about the implementation of these systems and to assess soil quality in tropical zones. The increase of soil organic carbon pools are key to mitigation and adaptation strategies related to climatic changes (Jobbagy and Jackson, 2000). Two aspects are imperative in identifying effective strategies for land-based climate change mitigation under possible future climate change scenarios: first is how different agricultural management practices or changes in land use create soil organic carbon sinks (accumulating additional carbon); secondly, how they act as carbon sources (emitting carbon) or maintain stocks at current levels (Kassa *et al*., 2017).

2.6 Carbon Dynamics Modelling Tools used in Accounting

One way to improve the precision and accuracy of estimating carbon stocks and fluxes in the forest sector and in agricultural lands in relation to their response to management, disturbances or climate is through the development, calibration and validation of carbon dynamics modelling tools for terrestrial ecosystems (Kurz *et al*., 2009; Huntzinger *et al*., 2012). Models are powerful tools that enable the quantification of forest carbon dynamics through the synthesis and integration of data derived across different spatial and temporal scales (Lemay, 2008; Kurz *et al*., 2009).

They help us understand the mechanisms controlling carbon exchanges between the land and atmosphere, identify gaps in information, and guide future research to fill in these gaps in a cost-effective manner (Huntzinger *et al*., 2012; IPCC, 2010).

Models are also the best tools available to create and compare scenarios that examine the effects of different activities on forest systems (e.g., management, land-use change and natural disturbances) that have not yet been observed (Kurz *et al*., 2009; IPCC, 2010). They use detailed ecophysiological relationships between plants, soil and the atmosphere (process models), and those that use information contained in forest inventories (empirical models). The first group of models requires information normally available at intensive monitoring sites such as leaf area index, inter annual climatic variability and soil conditions, among other variables, to simulate carbon dynamics driven by photosynthetic processes (e.g., CENTURY, 3-PG, Biome- BGC) (Masera *et al*., 2003). The second group of models use information derived from forest inventories and management plans such as wood volume yield data (e.g., CBM-CFS3, CO_2FIX) (Masera *et al*., 2003; Kurz *et al*., 2009).

Empirical models are well suited to represent carbon stock changes of the different carbon pools due to impacts from management activities, fires, pests and land-use change; to quantify the uncertainty of directly measured carbon pools and to validate the independent estimates from process models (Kurz *et al*., 2009; Stinson *et al*., 2011). Use of modelling tools is valuable for improving monitoring and reporting of GHG dynamics in countries that are signatories to the Kyoto Protocol and does the monitoring and reporting activities annually (Masera *et al*, 2003). When based on the best available scientific and technical information, models can help understand past GHG emissions and removals, identify key contributors to the GHG net balance(human or natural) and estimate the impact of specific policy-mitigation activities (e.g., REDD+) on future GHG emissions and removals dynamics (Kurz, 2013). Despite there being many models suited for specific data and land uses, most emphasis is placed on CO_2FIX model as it is applicable in agroforestry systems (Kaonga and Bayliss-Smith, 2012).

2.7 CO_2FIX Model

The CO_2FIX model is a model that quantifies the carbon stocks and fluxes in the forest, in plantations and in multistrata agroforestry (Masera *et al*., 2003; Schelhaas *et al*., 2004; Negash and Kanninen, 2015). It was developed as aninter-institutional collaborative project involving ALTERRA, Netherland; The Instiluto de Ecology of University of Mexico, Mexico; The Centro Agronomics Tropical de Investigaciony Ensenanza (CATIE) Costa Rica and European Forest Institute, Finland. The model is a multi-cohort carbon simulation model with the ability to produce carbon yields from known merchantable volume yields based on incremental (m^3 ha^{-1} yr^{-1}) growth of cohorts (Masera *et al*., 2003).

The CO_2FIX model calculates changes in carbon pools with time-steps of one year in the biomass, soil (litter and humus) and the wood products chain using carbon accounting approach which converts accumulated biomass into carbon sequestration and storage (Schelhaas *et al*., 2004).The model has biomass, soil, products, financial, bio energy, and carbon accounting modules. The CO_2FIX model generates numbers for net photosynthate production, and allocates this production to foliage, branches, stems, roots and litter. The model requires stem volume growth and associated partitioning of biomass compartments (foliage, branches, and roots), and long term climatic data such as mean monthly temperature and precipitation. The model provides two alternative ways to define stem growth of each cohort: (a) as a function of tree or stand age, and (b) as a function of the cohort total and maximum aboveground biomass. The latter input option has been added because in tropical forests often diameter dependent growth of trees rather than age dependent growth is normal.

The CO_2FIX model estimates SOC stocks and flows through the YASSO model as a function of litter input (Liski *et al*., 2003) on a hectare scale using time steps of one year. The YASSO model consists of a non-woody litter component (leaf), two woody compartments (fine wood litter and coarse woody litter), and five decomposition compartments (extractives, holocellulose, lignin-like compounds, fast decomposing humus, and slow decomposing humus. The CO_2FIX model thus holds great promise for improving impact assessments of ecosystem based mitigation and adaptation to climate change through agroforestry practices (Kaonga and Bayliss-Smith, 2012).

The CO_2FIXmodel can thus help in improving assessments of ecosystem-based climate change mitigation efforts through agroforestry. This model has been used for carbon accounting in plantations and agroforestry in Africa (Lemma *et al*., 2007; Kaonga and Bayliss-Smith, 2012) and even for multistrata agroforestry systems in Latin America (Masera *et al*., 2003).In addition, several studies have been conducted with temperate and tropical plantations (Schelhaas *et al*., 2004; Nabuurs and Schelhaas, 2002; de Jong *et al*., 2007; Nabuurs *et al*., 2008; Stolpe *et al*., 2010; Kaul *et al*., 2010). However, the model has been applied less for a variety of agroforestry systems in sub-Saharan Africa. This therefore needs to be considered as a factor in future researches.

2.7.1 Input parameters for the CO_2FIX model

The main input parameters relevant to CO_2FIX model are the cohort wise values for the stem-CAI (current annual increment in m^3 ha^{-1} yr^{-1}) over years; relative growth of the foliage, branches, leaf and root with respect to the stem growth over years; turn overrates for foliage, branches and roots; and climate data of the site (annual precipitation in mm and monthly values of minimum and maximum temperatures in ^oC) (Kaonga, 2005). Other inputs to the model include initial surface soil organic carbon (Mg C ha^{-1}), rotation length for the tree species, per cent carbon content in different tree parts, wood density and initial values of baseline carbon (Mg C ha^{-1}) in different tree parts, when the simulation are being carried out for the existing tree plantations as in the present case (Masera *et al*., 2003).

2.7.2 Basic Data Required for the CO_2FIX Model

For the purpose of simulating carbon stocks under agroforestry practises, the modules taken into considerations are biomass, soil and carbon accounting modules (Kaonga and Bayliss-Smith, 2012). CO_2FIX model requires primary as well as secondary data on tree and crop components (‘cohorts’) in CO_2FIX terminology for preparing the account of carbon sequestered under agroforestry systems on per hectare basis (Jose and Bardhan, 2012; Negash and Starr, 2015). The primary data includes name of the existing tree species on farmlands along with their number, diameter at breast height (DBH), crops grown on farmlands along with their productivity, area coverage etc. (Nabuurs and Schelhaas, 2002).

2.7.3 Why CO_2FIX is preferred (Gaps)

CO_2FIXis preferred over others for instance PROCOMAP, CENTURY and ROTH C since only CO_2FIX can simulate the carbon dynamics of single /multiple species simultaneously, and can handle trees with varied ages and agroforestry systems (AFS)

(Kaonga and Bliss 2012). Moreover, CO_2FIXoutputs the biomass and carbon separately in above and below ground tree components cohort wise (i.e. species wise) in addition to soil carbon dynamics. According to Nair *et al*. (2010), CO_2FIX is a user-friendly model for dynamically estimating the carbon sequestration potential of forest management and afforestation project and is readily adaptable for agroforestry. However, this model has not been tested using empirical data from agroforestry systems in Kenya (Jose and Bardhan, 2012; Negash and Kanninen, 2015).

2.8 Limitations of Carbon Accounting Models (CAM)

Carbon Accounting Models (CAMs) account for the flux in various carbon pools due to forestry activities in a location, but do not attempt to model the processes that cause this accumulation. Instead fluxes of carbon through various pools are estimated using production or yield data from the harvesting of the trees, biomass coefficients and assumptions concerning the turnover and decomposition of biomass in various pools (litter, soil, products etc) (Negash and Starr, 2015). Most models (CO2FIX inclusive,) require information on growth characteristics of trees. For some commercial species, established yield tables for the different tree species provide robust and well documented data from which estimates of total stand biomass can be obtained and fluxes over time represented (Kaonga, 2005). This information is lacking for many species, particularly for agroforestry projects that aim to use local tree species.

When the yield tables for the trees are absent, it may be necessary to estimate tree growth characteristics from measurements of tree in the local area (Masera *et al*., 2003).This gives accurate information which will help model carbon stocks localised for the specific area under study. The carbon sequestration potential of activities that aim to create a semi-natural habitat though mixed species plantings, agroforestry, and non-standard thinning regimes is not well documented and more so within agroforestry practices in East Africa region. Assumptions are therefore made based on the best existing information. Carbon storage in forest products will be, in most cases, a small component of the overall carbon sequestration potential. CO_2FIX includes a module for simulation of the fate of forest products. However, tracking the fate of forest products can be problematic and the assumptions behind these simulations are likely to be generalised.

2.9 Modelling Soil Organic Carbon Change

Implementing carbon sequestration in biomass and soil as a CO_2mitigation option requires the reliable quantification of carbon held in soil organic matter (SOM) at field or watershed level (Lal, 2005). However, changes in soil carbon stocks are slow under field conditions, taking several years to assess. Furthermore, long-term field experiments including soil carbon measurements are scant in the developing world. This leaves modelling as the best practical means of making projections for most developing countries (Kaonga, 2005; Lal, 2007).

The soil carbon models used in model-based soil carbon monitoring systems are generally dynamic or static models. The essential difference between these model types is that the dynamic models account for the element of time, unlike the static models. The dynamic models are considered to be more suitable for simulating carbon cycling in soil, because the carbon pool of soil consists of different age classes and these classes may respond to changes in conditions indifferent ways. Consequently, changes in the carbon pool of soil do not depend only on conditions at a particular moment but also on conditions in the past. It is worth pointing out that the simplest IPCC Tier 1 and 2 methods, commonly applied when there is only limited information, are based on static models (emissions factors or soil carbon contents by land-use category, etc.),whereas an application of a dynamic model belongs to a more advanced Tier 3methodology in the current IPCC classification (IPCC, 2007).

There are already established dynamic soil carbon models that can be used and have been used as part of model-based soil carbon monitoring systems, such as CENTURY-developed by Natural Resource Ecology Laboratory, Colorado State University (Parton *et al.*, 1987); Roth C (Coleman and Jenkinson, 1996); SOILN (Eckersten and Beier, 1998); ROMUL (Chertov *et al*., 2001); Yasso or Yasso 07 (Liski *et al*., 2005; Tuomi *et al*., 2009; 2011). From the point of view of a user, these models differ from each other in complexity and requirements of input information (Peltoniemi *et al*., 2007). The complex models need more complicated and more detailed input information than the simple models. Yasso 07 and ROTH-developed by Rothmsted Agriculture Research Station, UK (Coleman and Jenkinson, 1996) are examples of simple soil carbon models requiring only basic input data, whereas CENTURY and ROMUL represent more complicated soil carbon models with more demanding input data requirements. Estimating current SOC stocks provides information on the immediate resource base.

However, in order to make appropriate management decisions we need to be able to predict how SOC stocks will change as a function of changes in land use and climate. Soil carbon modelling is often used as an alternative or a complement to repeated soil carbon inventories to estimate and report the changes in soil carbon stock (Peltoniemi *et al*., 2007).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter describes in detail the study area, research design, methods of data collection and data analysis.

3.2 Study Area

The study was conducted on smallholder farms in Kakamega County, western Kenya at two sites adjacent to Kakamega Forest (Figure 3.1). Kakamega north (KKN) site is located on northern side of the Kakamega forest (0036.046´N, 034º 88.419´E) while Kakamega South (KKS) site is located on the southern part from the forest (0023.002´N, 034º 82.428´E).Kakamega Forest is situated 5km from Kakamega town and about 50 km from Lake Victoria (Tsingalia, 2009; BIOTA, 2010). The forest ecosystem is made up of forest fragments of different size, structure and distances to each other which have arose due to the high population of the forest adjacent communities (FAC) (Tsingalia, 2009; Agevi *et al*., 2014).

Agriculture is the main economic activity in the area; land-use systems vary from subsistence agriculture (maize, beans, and banana and sweet potatoes) to a few cash crop-oriented farms (tea and sugarcane) (Henri *et al*., 2011). Farms to the South and West of the forest are bound by a maize-growing belt and sugarcane growing belt to the North (Tsingalia and Kassilly, 2009). Woody vegetation forms part of the complex agricultural mosaic on smallholder farms, varying from individual free-standing trees to pockets of stands that consist of indigenous and exotic forms managed in different ways (Henri *et al*., 2011). Trees are grown around homesteads, in cropland and along farm boundaries, while woodlots occur mainly as small, mono-specific clusters of exotic trees, usually eucalyptus (Kuyah *et al*., 2013).

Rainfall in the area is bimodal, with distinct peaks in March through to May (long rains), and August to October (short rains). The dry season runs from December to February. Kakamega Forest and environs receives an average of 2100 mm per year, with an average temperature of 10.6°C (rainy season) and 27.7°C (dry season) (Mukhongo *et al*., 2011). The area is characterized by the Nyanzian and Kavirondian rock formations; the underlying rocks consist of undifferentiated /mudstone and ancient gneisses (Ojany and Ogendo, 1987). Soils are classified as acric ferralsols (FAO, 1990) or as very fine kaolinitic, isohyperthermic kandiudalfic eutrodox (Oxisols) in USDA soil taxonomy; they are acidic and nutrient poor (Musila, 2007).

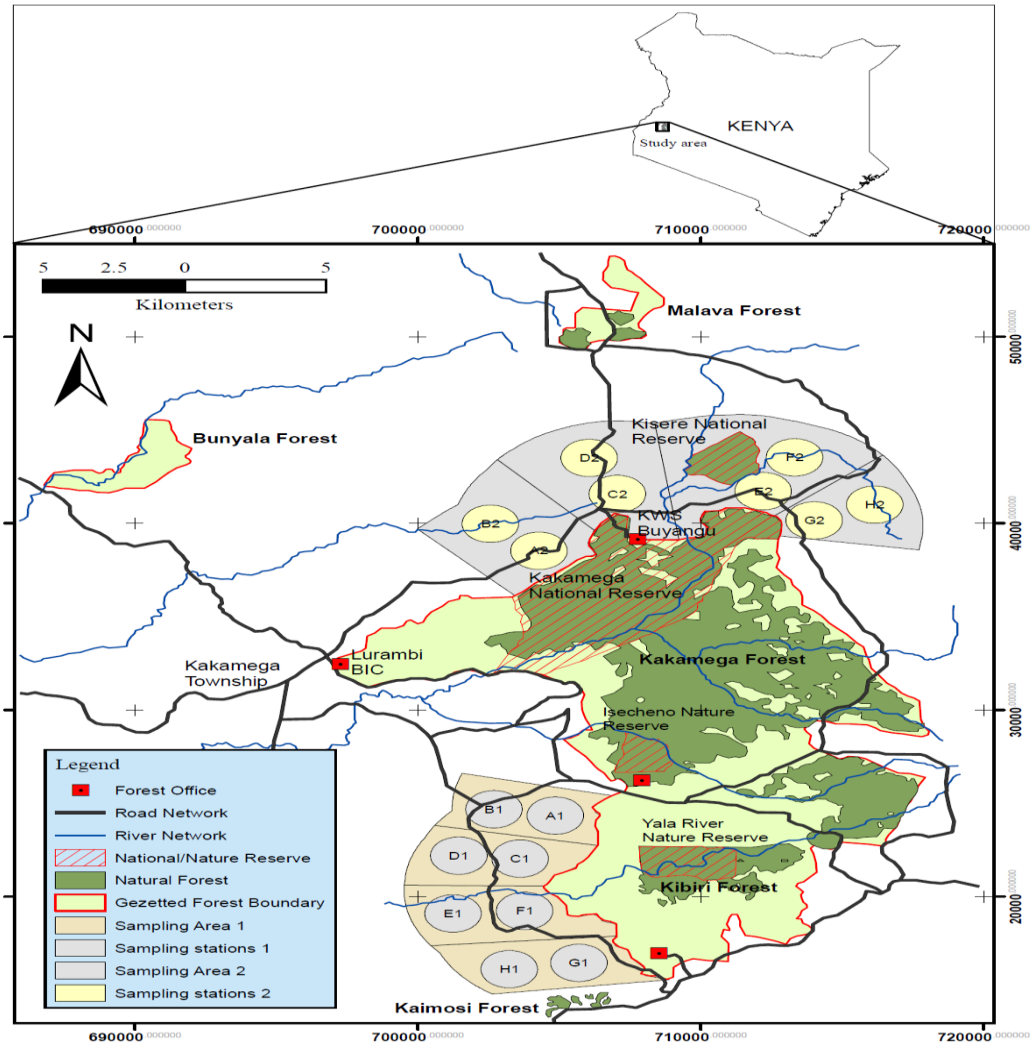

Figure 3.1: Map of Kakamega forest ecosystem with the study areas (Kakamega North and Kakamega South) adjacent to the forest: Modified from BIOTA 2011.

3.3 Study Design

The study was first introduced to the area chief and village elders through an introductory letter from the National Council of Science and Technology (NACOSTI) to seek permission from local authorities or land owners and to explain the purpose of the survey to local communities. The study adopted the Land surveillance Degradation Framework (SLDF) research design for biomass estimation. Each site was stratified into eight clusters measuring 1 km x 1 km. The centre point of each cluster was placed and sampling points randomized around each centre cluster-point, resulting in a spatially stratified, randomized sampling design. Randomization was done in a common spreadsheet program and later downloaded to a Global Positioning System (GPS) devise to enable quick navigation to the sampling points during the inventory surveys. Way points were uploaded in a GPS that helped to locate the blocks and farms on the ground. In each of the sentinel cluster, one point was randomly chosen that became the farm in which sampling was done. A total of 16 farms were selected, 1 farm from each of the cluster, 8 farms from each of the sites. Area of the farms was determined by dividing the farm into rectangles and determining their measurements by using a tape measure. Total area of all the rectangles per farm was the area of each farm in m^2.

3.4 Field Measurements

3.4.1 Tree species diversity

An inventory of all trees within each of the farms was conducted, capturing diameter at breast height (DBH), the species name, and the management of trees within two dominant agroforestry practices: (1) Home gardens, defined as multi-storey combination of several multipurpose trees and crops in homesteads. According to Nair *et al*., (2010), the gardens are small in size and managed intensively by family labour. (2) Hedgerows, defined as woody species grown in crop fields as hedges, along boundaries or contours (Nair *et al*., 2010). When scientific names of the trees could not be established in the field, the local name was provided by para-taxonimists who participated in the data collection, and the species name later identified with the help of a taxonomist or a manual of woody tree species within and around Kakamega Forest. Tree circumference at breast height, 1.3 m from the ground was measured by use of tape measure for trees ≥5cm. Conventional methods of measuring DBH were used on fluted trees, trees with multiple stems and leaning trees etc. Measurement of circumference was converted to DBH by dividing circumference with pi ($\pi = 3.142$).

3.4.2 Wood Density

Wood densities for tree species were obtained from the global database http://db.worldagroforestry.org/wd. For those tree species whose value was not found within the global database, then the density was determined. This was determined by coring about 50% deep into the stem at 1.3 m using a carpenter's awl and 2.5 cm bit. The cored material was collected from the hole with a spatula then its weight determined in the field. Width and depth of the core were determined as variables for determining the volume. Cored samples were then oven dried at 105^{o}C for 24 hours (Kuyah and Rosenstock, 2014). For some species wood density was obtained from previous studies in the same area and also other areas with similar climatic conditions like the study area and with similar tree species type.

3.4.3 Composite Soil Sampling

In each of the farm in the study area, a 10 x 10m plot was established. Within each of the plots, 4 samples of soils were obtained from four sampling points. One at the centre point and 3 others laid at a pattern of three axis separated by 120^{o} with respect to initial axis (Figure 3.2). The locations were georeferenced using GPS sampling location. Top and subsoil samples were obtained with a soil auger from the centre of the plot at 0-10 cm and 10-30 cm depth increments, respectively. Topsoil samples for each of the sampling point in a plot were pooled (composited) into one sample in bucket labelled (top soil: 0-10cm) mixed thoroughly and cleaned of litter and small plants; the same was done with subsoil samples for each of the sampling points within a plot and put in a basket labelled (sub-soil: 10-30cm). From each bucket, 0.5 kg of soil was then transferred to a plastic bag and transported to the Kabete campus laboratory for chemical analysis of SOC, soil texture, porosity, total nitrogen (TN) and electrical conductivity. Another 0.5 kg was placed into a separate plastic bag for archiving. The plastic bag was labelled with Site name, date of sampling, depth and plot/farm identity.

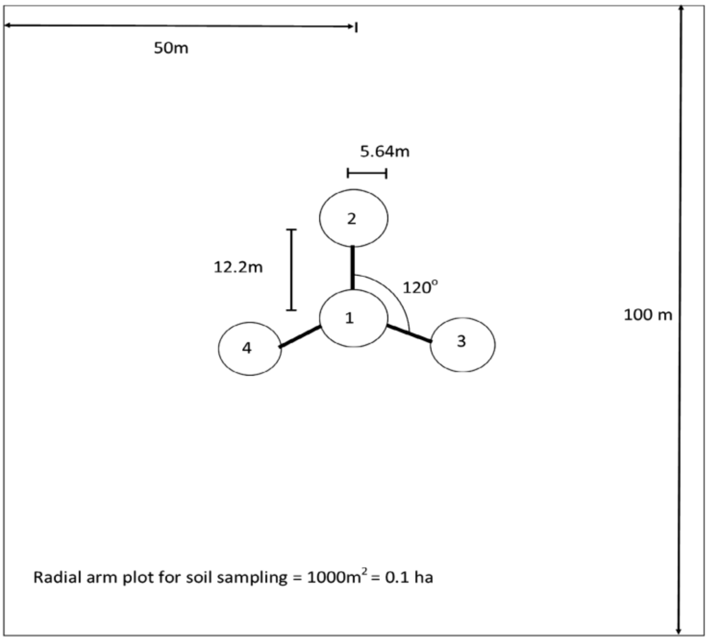

Figure 3.2: Soil sampling design within each of the quadrat

3.4.4 Cumulative Mass Sampling

This was essential for Bulk density (ρb) measurement for each depth and plot. Using a machete, an undisturbed flat horizontal surface in the soil was prepared at the depth of 0-10cm and 10-30 cm. Labelled steel ring was gently hammered into the soil using a wooden block to protect the ring. Care was taken to avoid pushing the ring in too far thereby preventing the soil compaction. Excavation around the ring without disturbing or loosening the soil it contains was done to carefully remove it with the soil intact. Any excess soil from the outside the ring was removed. The soil was poured into the labelled plastic bag and sealed.

3.5 Data Analysis

3.5.1 Tree biomass

Aboveground biomass (AGB) of trees was determined by applying allometric equations to DBH measurements. The study used power function with DBH alone as the predictor variable represented as $Y = aX^b$ where Y is the aboveground biomass, a and b constants and X as the DBH. Such an equation with diameter at breast height (DBH) as a variable was chosen as Diameter at breast height (DBH) has been shown to be an adequate predictor of AGB in agricultural landscapes (Kuyah *et al*., 2012) because it can be measured with ease and high accuracy, and explains over 95% of the variability observed in AGB (Brown, 1997). The study adopted two allometric equations, the Kuyah equation, $0.091 \times (DBH)^{2.472}$ (Kuyah *et al*., 2012) and Brown equation $2.134 \times (DBH)^{2.53}$ for tropical dry forests (Brown 1997) in estimation of biomass from tree measurements.

The equation by Kuyah was selected because it is developed for trees on farms and more so in agroforestry systems in western Kenya which has similar environmental conditions and is within the same climatic condition as the present study. In addition, the equation has low mean relative error making it most accurate as compared to other equations for estimation of biomass in agricultural landscapes based on the validation that were done on the equation (Kuyah *et al*., 2012). The equation by Brown, (1997) for dry tropical forests (1500–4000 mm) was selected because it is a generalised equation commonly used in areas where equations are not available, and was found to give conservative estimates of biomass for trees in the region. Intuitively, the moist tropical equation would have been selected based on rainfall in the study area. This later equation was chosen to help provide plausible ranges within which biomass in the area can be estimated.

Height and crown area were not measured because of the abounding challenges of using these parameters as predictor variables. These included aspects like inability to measure crown area accurately, lack of consistent allometric equations and marginal benefit for including them as additional predictor variables to DBH (Kuyah *et al*., 2013). Diameter measurements were applied to allometric equations to obtain biomass estimates for individual trees in kg per tree. Biomass estimates of trees were summed up to obtain farm/plot level estimates in Megagrams per hectare (Mg ha^{-1}). Below ground biomass (BGB) was estimated using a root-to-shoot ratio of 0.26 (Kuyah *et al*., 2012b). The 0.26 value for trees in agricultural landscapes is similar to that given by Cairns *et al*., (1997) for tropical forests. Total tree biomass was calculated by adding the AGB with the (BGB). Biomass estimates were converted to carbon using the IPCC default value 0.46 of the carbon fraction in wood (IPCC, 2010).

$$AGB = aX^b$$

Where a and b are constants and X the DBH

BGB= AGB* 026

TB= ABG+ BGB

TC =TB*0.46

3.5.2 Soil pH

Soil pH was determined in a 1:1 suspension of soil and water using H1 9017 micro-processor pH meter after calibrating the pH meter with buffer solutions at pH 4.0 and 7.0. The pH was read by immersing the electrode into the upper part of the suspension.

3.5.3 Soil Bulk Density

Soil bulk density was determined using core sampling method (Blake *et al*., 1986).The wet weight of the soil sample was obtained by using a soil core in the field. After that, soil samples were placed in pre- weighted sample bag and labelled based on the farm number and plot ID. The soil samples were placed in the oven at 105^oC for 48 hours. The dried soil was sieved through a 2 mm sieve. Bulk density was then calculated by dividing the mass of dry weight of soil (g) by the soil volume (cm^3). From the bulk density values obtained, porosity, (*f*) was calculated in accordance with the method of Flint and Flint (2002)using the formula:

$$f = 1 - {}^{\rho b}/_{\rho S}$$

where,*f*is porosity, ρb is bulk density and ρsthe particle density taken as 2.65 g cm^{-3}.

3.5.4 Soil Organic Carbon (SOC)

Soil samples (composite and cumulative separately) were air dried at 40°C, then weighed to the nearest 0.1g using a calibrated top-pan balance (KERN EG 220-3NM Balingen). Samples were then sieved using a 2mm mesh size sieve and the coarse fragments (>2 mm) weighed. Composite sub-samples were analysed in the soil laboratory at Kabete campus, University of Nairobi to determine organic carbon stocks by titrating thesamples boiled with H_2SO_4 and Fe_2SO_4 using the Walkley–Black method (Walkley–Black, 1934). After heating, the samples were titrated with ferrous ammonium sulphate against the residual $K_2Cr_2O_7$. From the volume titrated, organic carbon was calculated by procedures described by (Okalebo, Gathua and Woomer, 2002). Soil organic carbon stocks were calculated as:

$$SOC = ({}^{C}/_{100}) X\ \rho \text{ X D X} \left(1 - {}^{\text{frag}}/_{100}\right) \text{X } 100$$

Where SOC = soil organic carbon stock (t Cha^{-1}), C = soil organic carbon concentration determined in the laboratory (g kg^{-1}), ρ = soil bulky density (g cm^{-3}), D = soil depth of sampled soil layer (cm), frag = % volume of coarse fragments/100, 100 = is a conversion factor tot Cha^{-1}.

The SOC stock values for the two layers(0–10 cm and 10–30 cm) were summed to give the SOCstock for the entire 0–30 cm layer.

3.5.5 Soil Organic Matter (SOM)

Soil organic matter estimates were obtained from the measurements of soil organic carbon obtained in the laboratory. A conversion factor of 1.72 was used to convert organic carbon to organic matter. This conversion factor assumed organic matter contains 58 % organic carbon (Edwards *et al*., 1999).

3.5.6 Soil Texture

Soil texture was determined using hydrometer method described by Okalebo *et al*., (2002). Soil samples were dispersed using chemical dispersant (sodium pyrophosphate solution), pouring soil suspensions on to a 0.5-mm fine sieve for separating out sand fraction and washing the clay and silt fractions into sedimentation cylinder. Clay content was subsequently determined from the established USDA soil triangle.

3.5.7 Total Nitrogen (TN)

The nitrogen content was analysed using the micro-Kjeldahl method (AOAC, 1990) by digesting 0.5g of soil in 10ml conc H_2SO_4 using a catalyst mixture of ($CuSO_4$,K_2SO_4) and slenium powder) and distillating with colorimetric determination by spectrophometer. The samples were read on a device that was set at 85ºC (FP 526

LC, LECO). The total nitrogen stock (Kg N m^{-2}) was computed with the method that was used for calculating the SOC stock.

3.5.8 Model Parameterization

CO_2FIX model version 3.2 was parameterized using biomass and soil inputs data in the two types of agroforestry practices identified in the study sites; homegardens and hedgerows. The IPCC tier method 3 was used in simulating carbon storage potential. The model quantifies the carbon stocks and fluxes in the forest, plantation and multistrata agroforestry (Masera *et al*., 2003).It calculates changes in carbon pools with time-steps of one year in the biomass, soil (litter and humus) and the wood products chain using carbon accounting approach in which converting accumulated biomass into carbon sequestration and storage.

The model has widely been used in assessments of ecosystem-based climate change mitigation efforts through agroforestry (Negash, 2015). To run the model, empirical data (tree biomass and soil organic carbon stocks) were collected from the 16 farms (8 farms in each of the sites). Besides, studies previously conducted around the study sites and similar agroforestry systems were employed to supplement the observed data. Simulations were run for a period of 50 years. The model simulated net annual carbon sequestration of the agroforestry trees and soils and for the entire 50-year period. The model gave outputs per hectare.

3.5.8.1 Biomass Carbon Module

Biomass cohort model was used to simulate tree carbon under the two agroforestry practices. Parameters that were required for biomass modelling were: initial biomass in trees, tree growth rates, tree volumes, tree mortality rates, harvesting, and wood density, Current Annual Increments (CAI), Mean Annual Increments (MAI), Biomass content of trees was obtained from the results of the allometric equations which were employed in the study. Wood density values were obtained from the global databases (Zanne *et al*., 2009). Stem growth (CAI) of each cohort was calculated as a function of the cohort's actual biomass over maximum attainable aboveground biomass. From the growth rate of stem volumes, growth rates for foliage, branches and roots were calculated, using time-dependent allocation coefficients.

The model used stem volume growth in $m^3\ ha^{-1}$ per year as the main input. MAI was estimated from the basis of inventory data collected on farms. Supplementary data was obtained from studies previously conducted around the study site and other sites with similar ecological conditions like the study sites with similar agroforestry practices. The carbon stocks in the living biomass were estimated using a cohort module approach. Default values for the turnover coefficients for roots allocation to trees were obtained from Gill and Jackson (2000) while turnover coefficient of branches of tree was approximated from Negash (2015).

3.5.8.2 Soil Carbon Module

To determine the soil carbon stocks, soil carbon module called YASSO (Dynamic Soil Carbon Model) within the CO_2FIX model was employed. The model describes decomposition and dynamics of soil carbon in soils where poor drainage does not slow down decomposition. The model was calibrated to describe the total stock of soil carbon without distinction between soil layers. Parameters required for this module included: quantity of litter fall ($tCha^{-1}$ per year) in the area, climate information (mean annual temperature and precipitation) which were obtained from the meteorological station in Kakamega. Carbon stock and fluxes were then stimulated at hectare scale with steps of one year for a period of 50 years. This period was chosen as it is an appropriate period to observe some change brought about as a result of climate change.

3.6 Statistical Data Analysis

Diversity of trees in each of the agroforestry practice was determined by using Shannon Weiner Index (Shannon and Wiener, 1949; Magurran, 2004). Shannon Index is expressed as:

$$H' = -\sum(pi)xln(pi)$$

Where: $\sum$ is the summation, pi is the proportion of individual species over total number of species, *ln* is the natural log.

The value of the index ranges from 1.5 (low species richness and evenness) to 5.0 (high species evenness and richness). Kruskal- Wallis one way parametric analysis of variance test (H) was used to determine differences in tree abundance between sites, species diversity and tree biomass between sites, among farms and different agroforestry practices, considered significant at p=0.05.A Pearson correlation was used to establish trends and relationships between parameters. This was computed to determine correlation between soil organic carbon (SOC) and tree species diversity between sites and variations between SOC and soil depth. Variation in carbon stocks between farms at different study sites and study areas and variations between the calculated and simulated carbon stocks at the study sites was determined. Genstat version 14 was used for the statistical analysis.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents findings of the study based on the study's specific objectives. The initial findings presented are for tree species abundance, their size class distribution, species richness and diversity. The chapter also contains findings on aboveground biomass (AGB) in farms under different agroforestry practices, soil organic carbon, soil organic matter, bulk density, porosity, Total Nitrogen and SOC: TN ratio. The chapter then discusses the results by comparing similar studies done in other areas.

4.2. Determination of the Tree Abundance and Diversity of Trees Species on Farms Around Kakamega Forest

4.2.1 Species abundance

A total of 1,731 individual trees belonging to 60 different species were sampled in two study sites within the study area on farms around Kakamega Forest. The trees were integrated in crop and livestock production fields as homegardens and hedgerows. Those in homegardens were intercropped with perennial tree crops within the homesteads for production of fruits and nuts, wood, poles and timber, for ornamental purposes and provision of shade and aesthetic value. Trees in homegardens had multilayered canopy, comparable to rainforest such as those found in neighboring Kakamega Forest. Hedgerows were comprised of trees and shrubs planted in rows or maintained in systematic arrangements such as trees on boundaries, live fences, hedges and trees on soil conservation structures such as terraces.

Cupressus lustanica had the highest number of individual trees in the two sites at (22.6%; n=391). This was followed by *Eucalyptus grandis* (11.1%; n=192) and *Markhamia lutea* (11%; n=191) (Figure 4.1).In Kakamega North, the trees with highest number of individuals were *Cupressus lustanica* (26.3%; n=257), *Markhamia lutea* (13.7%; n=134) and *Croton macrostachyus* (11.2%: n=110). In Kakamega South, *Cupressus lustanica* (18%; n=134) recorded the highest abundance of individuals trees inventoried. This was followed by *Eucalyptus grandis* (16.2%; n=122) and *Croton macrostachyus* (10.2%; n=77).

The family Cupressaceae was the most dominant (n=391) followed by Myrtaceae (n=251), while Bignoniaceae (n=222) was the third most dominant. Araliaceae, Asteraceae, Cannabaceae, Caricaceae, Maesaceae, Malvaceae, Olacaceae, Sapindaceae and Solanaceae had the least number of trees each with one individual (n=1). Fifty-three (53) per cent (n=917) of the total individual trees were indigenous while 47% (n=814) were exotic. Forty-seven (47) percent (n=461) of the individual trees in Kakamega North were exotic while 53% (n=517) were indigenous. In Kakamega South, 47% (n=352) were exotic while 53% (n=400) were indigenous. There were differences in the number of indigenous and exotic tree species in the two agroforestry practices and between the study sites. These observed differences were however, not statistically significant (Kruskal-Wallis test: $\alpha = 0.05$; H=6.81; p=0.15) (Table 4.1).

Homegardens had highest abundance at 56% (n=970) as compared to hedgerow at 44% (n=761) of the total tree individuals (Figure 4.2). Homegardens had (n=278) exotic and (n=284) indigenous individual trees in Kakamega North. The majority of the species inventoried in Kakamega south were indigenous (n=226); few (n=182) were exotic. Hedgerow had 183 exotics and 233 individual indigenous trees in Kakamega North and 171 exotic and 174 individual indigenous trees in Kakamega South respectively. Tree abundance was not statistically significant between the two sites (Kruskal-Wallis test: $\alpha = 0.05$; $H=6.43$; $p=0.13$), agroforestry practices per site (Kruskal-Wallis test: $\alpha = 0.05$; $H=6.01$; $p=0.15$) (Table 4.2) and among farms at (Kruskal-Wallis test: $\alpha = 0.05$; $H=6.53$; $p=0.13$) (Table 4.3).

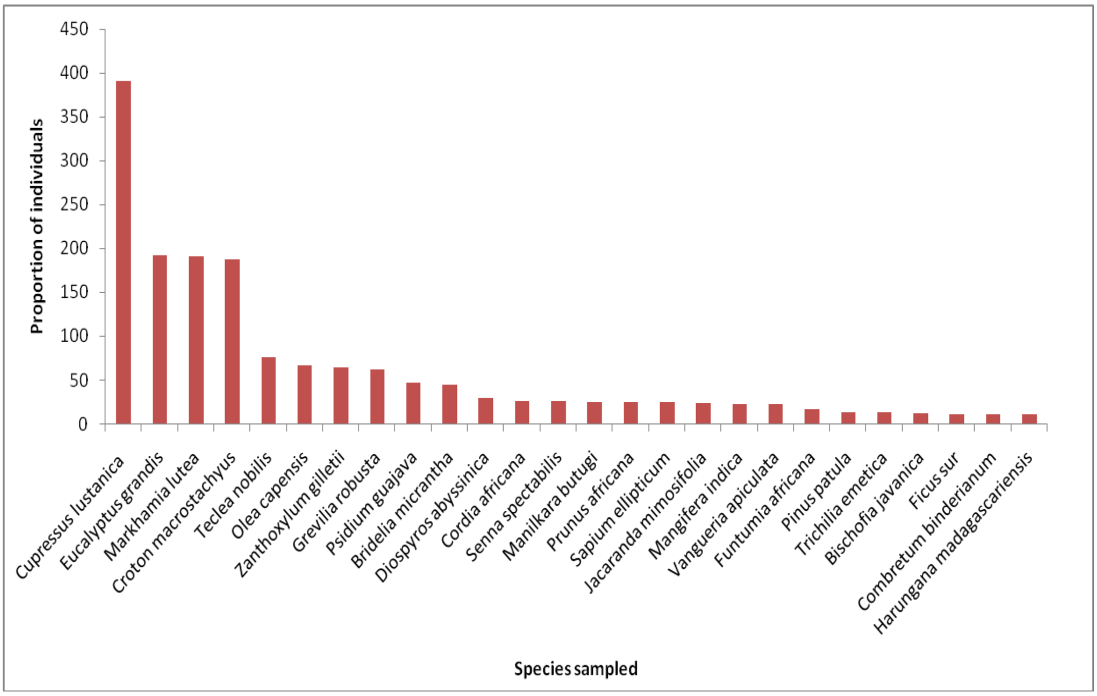

Figure 4.1: Distribution of species with more than 10 individuals per species sampled from the study site

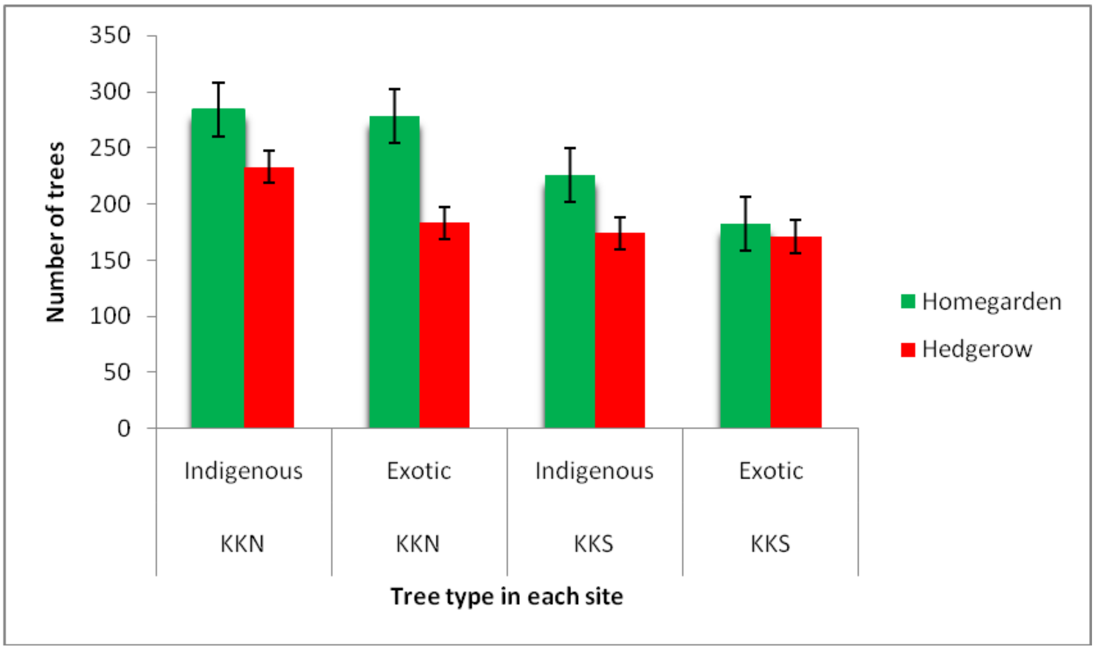

Figure 4.2: Tree abundance in each agroforestry type in each of the site: KKNKakamega North site; KKS-Kakamega South site

Table 4.1: Tree abundance in indigenous and exotic trees on farms, in the agroforestry practices and between sites

Site	Agroforestry	Min	max	SD	Mean±SE	H	p
Kakamega North	Homegardens	4	83	25.83	35.13±6.46a	6.81	0.15
	Hedgerows	2	76	20.31	26.63±5.08a		
Kakamega South	Homegardens	8	89	23.51	25.44±5.88a	6.88	0.13
	Hedgerows	0	68	20.18	21.56±5.04a		

Table 4.2: Abundance between the two agroforestry pracitces in the two study sites

Site	Agroforestry	Min	max	SD	Mean±SE	H	p
Kakamega North	Homegardens	23	152	41.59	70.25±14.70a	6.54	0.19
	Hedgerows	12	127	37.33	50.86± 13.19a		
Kakamega South	Homegardens	21	167	48.39	49.75± 17.11a	6.59	0.11
	Hedgerows	11	108	32.79	42.75± 11.56a		
Overall(two sites)	Homegardens	23	167	41.59	70.25± 14.71a	6.53	0.13
	Hedgerow	12	127	37.33	50.87± 13.19a		

Table 4.3: Variation in abundance, richness, diversity and evenness among farms

Farm	Abundance	Richness	Diversity (H')	Evenness (J)
KKNF1	55.50 a	12.50 a	2.000 abc	0.7700 a
KKNF2	54.50 a	13.00 a	1.915 abc	0.7450 a
KKNF3	52.50 a	13.00 a	1.765 abc	0.6850 a
KKNF4	94.50 a	21.00 a	2.250 bc	0.7550 a
KKNF5	84.00 a	11.50 a	2.005 abc	0.7800 a
KKNF6	55.50 a	17.00 a	2.605 c	0.9250 a
KKNF7	31.50 a	5.00 a	1.185 ab	0.7350 a
KKNF8	56.50 a	7.50 a	1.590 abc	0.8050 a
KKSF 1	22.00 a	5.00 a	1.285 ab	0.8000 a
KKSF 2	69.50 a	16.00 a	1.920 abc	0.8550 a
KKSF 3	119.50 a	19.50 a	2.205 bc	0.7500 a
KKSF 4	27.00 a	11.00 a	1.380 abc	0.7300 a
KKSF 5	33.00 a	12.00 a	2.105 abc	0.8500 a
KKSF 6	34.50 a	4.00 a	0.910 a	0.6200 a
KKSF 7	20.00 a	11.50 a	2.315 bc	0.9600 a
KKSF8	44.50 a	13.50 a	2.255 bc	0.8850 a
p	0.12	0.20	0.12	0.13
S.e.d	40.53	4.070	0.5080	0.1632
L.s.d	85.92	8.627	0.0769	0.3460
SD	39.79	5.67	0.58	0.15
Mean±SE	53.4±7.03	12.1±1.00	1.85±0.10	0.79±0.25
% CV	75.9	33.7	27.4	20.6

Means in the column followed by the same letters are not significantly different at $P< 0.05$ by Duncan post hoc test.

Farmers at the two study sites practiced either homegardens or hedgerow agroforestry practices. The agroforestry practices had both indigenous and exotic trees. Homegardens is a major form of agroforestry practice in western Kenya, where farmers have a long history of maintaining trees around their compounds (Tengnas, 1994). Trees in homegardens had multilayered canopy, comparable to the rainforest, such as that found in neighboring Kakamega Forest. Trees in hedgerows are always planted in some systematic arrangements around or within the farm; they were established as live fences on farm boundaries or to separate homesteads from the other gardens, where they provide benefits such as reduction of wind speed and improvement of microclimate, and supply firewood from occasional pollarding or pruning (Molla and Kewessa, 2015). The primary advantage of these two practices is that they allow carbon sequestration and provision of other ecosystem services without competition between trees and crops, or with minimum competition with crops depending on the spaces between trees and crops in the case of hedgerows (Matteo *et al*., 2016). *Cupressus lusitanica* and *Eucaluptus* species were many in the two sites which is similar to studies by Henri *et al*., (2011). He found out that farms neighboring Kakamega Forest had higher abundance of such trees as a result of their economic value. The presence of high dominance of indigenous trees on farms as compared to exotic could be attributed to change of attitude by the farmers after realizing impact that may be associated with some of the exotic trees.

4.2.2 Species Richness, Diversity and Evenness

Species richness ranged from 2-52 (Table 4.4) with a mean of 12.06±1.00. Species richness of 2 indicated an area with low number of species represented while an area with species richness of 52 indicated an area with higher representation of species. The highest species richness was in KKSF6 (n=52) and the lowest in KKNF4 (n=2). In Kakamega North, species richness ranged from 5-28 with a mean of 12.4±1.53. Kakamega South had richness ranging from 2-21 with mean of 12±1.46. Species richness in homegardens was higher than hedgerow and ranged from 5-20 (12.63±1.15) as compared to hedgerow which ranged from 2-28 (11.14±1.65) within farms. In Kakamega North, homegardens had the highest richness ranged from 5-20 (12.86±1.79) compared to richness in hedgerow that ranged from 5-28 (12.29±2.88). In Kakamega South, homegardens had the highest species richness which ranged from 6-18(13.86±1.58) while hedgerow ranged from 2-21(11.14±2.5). Species richness did not differ significantly between sites (Kruskal-Wallis test: $\alpha = 0.05$; H=4.87; df=1; p=0.23), among the farms sampled (Kruskal-Wallis test: $\alpha = 0.05$; H=4.23; df=15 p=0.14) and types of agroforestry (Kruskal-Wallis test: α = 0.05; H=4.60; df=1; p=0.13) (Table 4.5).

Shannon diversity index showed that tree diversity was higher in Kakamega north (H´=1.92±0.13) than Kakamega South (H´=1.71±0.16), and in homegardens (H´=1.98±0.14) than in hedgerows (H´=1.65±0.14) (Table 4.6). However, the differences were not significant for the two agroforestry practices in Kakamega North (Kruskal-Wallis test: α = 0.05; H=3.11; df=1; p=0.19), Kakamega South (Kruskal-Wallis test: α = 0.05; H=2.34; df=7; p=0.15) or for the combined (Kruskal-Wallis test: α = 0.05; H=2.45; df=1; p=0.12) (Table 4.7).Shannon index diversity ranged from 0.25-2.7 with a mean of 1.8 ± 0.10. Species diversity in homegardens was higher as compared to hedgerows. It ranged from 1-2.7 with a mean of 1.98± 0.14. The least diversity was in KKNF1 (H´=1) and the highest in KKNF6 (H´=2.7). Hedgerow species diversity ranged from 0.25-2.52 with a mean of 1.74± 0.11. The least was in farm (KKSF6) in Kakamega South (H´=0.25) and highest was in farm (KKNF5) in Kakamega North site (H´=2.53).In Kakamega North, homegardens had diversity ranging from 1-2.7 with mean of 1.96± 0.19. Hedgerow diversity ranged from 0.25-2.5 with mean of 1.86± 0.18. In Kakamega South (KKS), homegardens diversity ranged from 1.2-2.7 with mean of 1.98± 0.23. Hedgerow species diversity ranged from 1.1-2.1 with mean of 1.6± 0.11. Higher diversity in homegardens implied the agroforestry system had high species richness which had proportion of trees evenly represented. The low diversity in the hedgerow is due to tendency of the farmers to plant one type of tree species along the boundary for instance *Cuppressus lusitanica, Grevillea robusta* among others.

Evenness ranged from 0.37-0.98 with mean of (0.79±0.26) with 0.37 indicating farm with low evenness and 0.98 high evenness. In homegardens type of agroforestry, species evenness ranged from 0.58-0.96 (0.78±0.03). Species were evenly distributed in KKSF5 (n=0.96) and KKSF7 (n=0.96). It was less distributed in KKNF5 (n=0.58). Hedgerow on the other hand had evenness value from 0.37-0.98 (0.81±0.04). Farm KKNF5 had the most evenly distributed species (n=0.98) while KKSF6 has the least (n=0.37). In Kakamega North, the farm with most evenly distributed species in homegardens was KKNF6 (n=0.9) and the farm with least distribution of species was KKNF5 (n=0.58) (0.76±0.04). Hedgerow had KKNF5 as farm with most evenly distributed species (n=0.98) and KKNF3 as the least evenly distributed (n=0.51) (0.79±0.05). In Kakamega South, homegardens had KKSF7 as the most evenly distributed in species (n=0.96) while KKSF1 had the least (n=0.72). Hedgerow had KKSF7 as the most evenly distributed (n=0.96) and KKSF6 as the least (n=0.37). There was observed difference in species evenness. However, it was not statistically significant between sites (Kruskal-Wallis test: α = 0.05; H=0.14; p=0.36) and agroforestry practices (Kruskal-Wallis test: α = 0.05; H=2.34; p=0.17) (Table 4.8).

Shannon diversity index showed that tree diversity was higher in Kakamega North than Kakamega south and in homegardens than in hedgerows (Table 4.6). Kakamega North site, which had higher tree diversity, is situated on the part of the Kakamega Forest managed by Kenya Wildlife Service, a state corporation that manages forests and wildlife in Kenya. Farmers in this area have restricted access to the forest, and therefore plant trees in their crop fields to provide benefits that they previously obtained from the forest. There are also several community-based organizations that educate and support tree planting initiatives in the area (Agevi *et al*., 2014). The influence of these organizations, the dispersal of seeds by wind and animals and farmer preference can possibly explain the high number of indigenous trees in Kakamega North compared to Kakamega South. Management regime of Kakamega north could be the reason for high bird and simian diversity that enhances higher dispersal (Althof, 2005).

The activity of dispersal agents has been crucial in establishment and effective colonization of tree species in the Kakamega North landscapes (Howe and Smallwood, 1982).Indigenous trees/multipurpose trees such as *Markhamia lutea*, *Zanthoxylum gilleti*, and *Croton macrostachyus* were the most dominant in terms of biomass. The indigenous trees could also be remnants from the Kakamega Forest as the study site borders it. The exotic trees could have been planted by the individual farmers. Some tree species for instance *Prunus africana*, an important medicinal plant that is proven as a remedy for prostate cancer was evident in both the study sites.

This according to Mpanda *et al*. (2014) is a form of *ex-situ* conservation. Since the tree is listed as Vulnerable by the IUCN (IUCN, 2016) due to its overexploitation in the wild for traditional medicine through debarking, domestication of this tree species could increase their numbers and hence improve their thier status in the world. Furthermore, trees on farm in the study sites and especially in the southern site form an important corridor connecting Kakamega South and Kakamega North forests.

High tree diversity generally ($H' > 1$) in homehardens within the study area compared to hedgerow is consistent with studies such as Henry *et al* (2009) who did their studies in Siaya and Vihiga of western Kenya. This could be attributed to the multipurpose roles the farmers plant the trees for like fruit trees, medicinal purposes among others. Hedgerow had lower diversity as in most cases farmers preffered doing a monospecific types like of *Cupreessus lusitanica*, *Grevillea robusta* among others. These were planted to demarcate land use units farm boundaries, providing firewood among others. The diversity of both homegardens and hedgerows could be related to the gender of the household head and other socio econoic factors, a relationship that may be worth being explored.

4.2.3 Size Class Distribution

The distribution of diameter at breast height (DBH) classes in Kakamega North (KKN) and Kakamega South (KKS) is shown in (Figure 4.3). Trees with DBH ranges of 11-20cm in both sites were the majority (31%). 30% of the total trees inventoried had DBH range of 1-10cm while and trees with DBH range of 21-30cm comprised 20. The DBH distribution is an indication of uneven aged distribution of trees. The trees have different ages in addition to the different management practices farmers employ on the trees. Class 71-80cm, 81-90cm and 91-100cm had 1%. DBH ranged from 3.20- 99.90 cm with mean of 44.69±26.33 for all the trees sampled in the two study sites. Value of 3.2 indicated low DBH while 99.90 highest DBH value. Minimum and Maximum DBH values for homegardens were 3.18cm and 84.34 cm in KKNF1 and KKSF4 respectively. In the hedgerows the values were 3.18cm and 99.94cm in farm KKNF4 and KKSF3 respectively (Table 4.9).

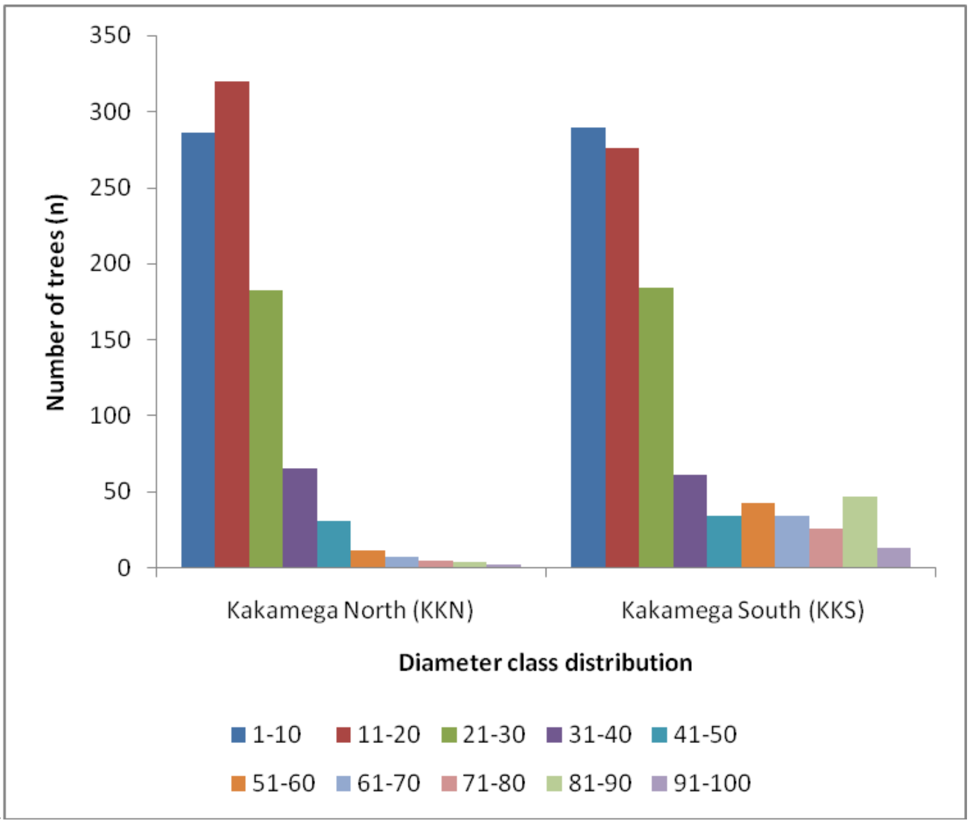

Figure 4.3: Distribution of trees in different size classes of the tress sampled in the two study sites in Western Kenya

Table 4.4: Summary of species abundance, richmess, diversity and evennes per farm, site and agroforestry practice

S/N	Farm	Type of agroforestry	#-number	Richness	Diversity (H´)	Evenness (E)
1	KKNF1	Homegardens	68	15	2.20	0.76
		Hedgerows	43	10	1.80	0.78
2	KKNF2	Homegardens	39	15	2.30	0.85
		Hedgerows	70	11	1.53	0.64
3	KKNF3	Homegardens	37	14	2.27	0.86
		Hedgerows	68	12	1.26	0.51
4	KKNF4	Homegardens	62	14	2.06	0.78
		Hedgerows	127	28	2.44	0.73
5	KKNF5	Homegardens	152	13	1.49	0.58
		Hedgerows	16	10	2.52	0.98
6	KKNF6	Homegardens	80	20	2.70	0.90
		Hedgerows	31	14	2.51	0.95
7	KKNF7	Homegardens	23	5	1.00	0.62
		Hedgerows	40	5	1.37	0.85
8	KKNF8	Homegardens	101	9	1.59	0.72
		Hedgerows	12	6	1.59	0.89
9	KKSF1	Homegardens	33	5	1.16	0.72
		Hedgerows	11	5	1.41	0.88
10	KKSF2	Homegardens	31	13	1.41	0.88
		Hedgerows	108	19	2.43	0.83
11	KKSF3	Homegardens	167	18	2.40	0.83
		Hedgerows	72	21	2.01	0.67
12	KKSF4	Homegardens	21	12	1.41	0.87
		Hedgerows	33	10	1.35	0.59
13	KKSF5	Homegardens	40	16	2.66	0.96
		Hedgerows	26	8	1.55	0.74
14	KKSF6	Homegardens	25	6	1.57	0.87
		Hedgerows	44	2	0.25	0.37
15	KKSF7	Homegardens	28	14	2.53	0.96
		Hedgerows	12	9	2.10	0.96
16	KKSF8	Homegardens	53	18	2.67	0.93
		Hedgerows	36	9	1.84	0.84

Table 4.5: Species richness between sites and agroforestry practices

Site	Agroforestry	min	max	SD	Mean±SE	H	p
Kakamega North	Homegardens	5	20	4.74	12.86±1.79a	4.23	0.14
	Hedgerows	5	28	7.63	12.29±2.88a		
Kakamega South	Homegardens	6	18	4.18	13.86±1.58a	4.60	0.13
	Hedgerows	2	21	6.62	11.14±2.50a		
Overall (two sites)	Homegardens	5	20	4.59	12.63±1.15a	4.87	0.23
	Hedgerows	2	28	6.64	11.14±1.65a		

Max-maximum value of species richness; min-minimum value of species richness; same letters indicate that the mean did not differ significantly (0.05)

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Table 4.6:The diversity of tree species in homegardens and hedgerows found in Kakamega North and Kakamega South

Land use niche	Homegardens (SE)	Hedgerows (SE)	F	Site	p
Kakamega North (KKN)	1.95 (0.19)	1.88 (0.18)	0.03	1.92(0.13)	0.12
Kakamega South (KKS)	1.98 (0.23)	1.62 (0.11)	4.6	1.71(0.16)	0.09
Total	1.98(0.14)	1.65(0.14)			

Table 4.7: Significance difference in species diversity between sites and agroforestry practices

Site	Agroforestry	min	max	SD	Mean±SE	H	p
Kakamega North	Homegardens	1	2.7	0.55	1.96± 0.19a	3.11	0.19
	Hedgerows	0.25	2.5	0.51	1.86± 0.18a		
Kakamega South	Homegardens	1.2	2.7	0.33	1.98± 0.23a	2.34	0.15
	Hedgerows	1.1	2.1	0.64	1.6± 0.11a		
Overall(two sites)	Homegardens	1	2.7	0.57	1.98 ± 0.14a	2.45	0.12
	Hedgerows	1.1	2.5	0.43	1.74 ± 0.11a		

Max-maximum value of species diversity; min-minimum value of species diversity; same letters indicate that the mean did not differ significantly (0.05).

Table 4.8: Equitability index (J) values between sites and agroforestry practices

Site	Agroforestry	min	max	SD	Mean±SE	H	p
Kakamega North	Homegardens	0.58	0.9	0.11	0.76±0.04a	0.12	0.25
	Hedgerows	0.51	0.98	0.51	0.79± 0.05a		
Kakamega South	Homegardens	0.72	0.96	0.08	0.88± 0.03a	0.15	0.17
	Hedgerows	0.37	0.96	0.19	0.74± 0.07a		
Overall(two sites)	Homegardens	0.51	0.98	0.13	0.78 ± 0.03a	0.14	0.36
	Hedgerows	0.37	0.96	0.16	0.81 ± 0.04a		

Max-maximum value of species evenness; min-minimum value of species evenness; same letters indicate that the mean did not differ significantly (0.05).

Table 4.9: Summary of DBH distribution per farm and per each type of the agroforestry

S/N	Farm	Type of agroforestry	Number of trees	Number of species	Dbh (cm)			
					Mean	SD	Min	Max
1	KKNF1	Homegardens	68	15	25.12	2.04	3.18	77.98
		Hedgerows	43	10	15.39	10.58	3.50	39.78
2	KKNF2	Homegardens	39	15	24.93	1.87	5.72	53.78
		Hedgerows	70	11	20.37	12.63	5.09	70.97
3	KKNF3	Homegardens	37	14	20.42	12.79	7.00	73.21
		Hedgerows	68	12	11.15	7.99	3.18	49.70
4	KKNF4	Homegardens	62	14	17.99	1.25	4.77	45.55
		Hedgerows	127	28	19.25	1.09	3.18	91.66
5	KKNF5	Homegardens	152	13	16.74	0.64	3.81	43.60
		Hedgerows	16	10	20.96	2.48	7.63	39.78
6	KKNF6	Homegardens	80	20	21.05	1.44	5.41	58.56
		Hedgerows	31	14	13.68	1.25	5.10	32.14
7	KKNF7	Homegardens	23	5	23.88	2.94	4.14	61.11
		Hedgerows	40	5	14.76	1.05	4.77	31.83
8	KKNF8	Homegardens	101	9	12.11	0.85	4.13	61.74
		Hedgerows	12	6	11.48	1.42	5.73	19.09
9	KKSF1	Homegardens	33	5	14.60	1.40	4.56	45.56
		Hedgerows	11	5	17.62	2.59	5.72	30.23
10	KKSF2	Homegardens	31	13	21.40	1.70	5.28	40.42
		Hedgerow	108	19	19.76	1.19	6.35	99.94
11	KKSF3	Homegardens	167	18	14.40	0.63	5.77	53.46
		Hedgerow	72	21	17.63	1.39	5.28	59.83
12	KKSF4	Homegardens	21	12	25.99	2.90	5.78	84.34
		Hedgerow	33	10	24.82	1.88	5.72	61.10
13	KKSF5	Homegardens	40	16	14.27	1.33	4.46	36.91
		Hedgerow	26	8	18.58	1.91	6.68	39.47
14	KKSF6	Homegardens	25	6	16.77	1.34	5.01	21.54
		Hedgerow	44	2	17.07	0.81	7.32	35.01
15	KKSF7	Homegardens	28	14	34.07	3.24	8.91	79.56
		Hedgerow	12	9	21.03	2.56	7.95	34.04
16	KKSF8	Homegardens	53	18	18.49	1.08	7.32	45.51
		Hedgerow	36	9	21.20	0.97	7.32	39.14

Max-maximum value of DBH (cm); min-minimum values of DBH (cm); KKN-Kakamega North; KKS-Kakamega South.

4.2.4 Relationship between abundance, richness, diversity and evenness

There was a very strong and significant correlation between diversity and evenness and between species richness and diversity. In Kakamega North, correlation between richness and diversity was ($r=0.686$; $p=0.003$) while that between diversity and evenness was ($r=0.702$; $p=0.002$). The increase in species diversity of a site or agroforestry practice was an indicative of high species richness which in turn were evenly distributed (evenness). In Kakamega South, correlation between richness and diversity was ($r=0.787$; $p<0.001$) and that between diversity and evenness was ($r=0.735$; $p=0.001$). In comparing the two sites (north and south), correlation between richness and diversity was ($r=0.740$; $p=0.001$) while that between diversity and evenness was ($r=0.702$; $p=0.001$). Correlation between abundance and diversity was moderate and significant in Kakamega north ($r=0.544$; $p=0.029$), Kakamega south ($r=0.605$; $p=0.013$) and two sites compared ($r=0.579$; $p=0.001$). Correlation between abundance and diversity, abundance and evenness and between richness and evenness in Kakamega North (KKN), Kakamega South (KKS) and between two sites was also significant ($p<0.05$) (Table 4.10).

There was significant and strong correlation between species diversity and evenness and between richness and diversity in the two types of agroforestry systems. Increase in species diversity corresponded to in species richness and evenness. Kakamega North, correlation between diversity and evenness in homegardens was ($r=0.902$; $r=0.002$) while in hedgerows it was ($r=0.0597$; $p=0.01$). In Kakamega South, homegardens had ($r=0.667$; $p=0.002$) while hedgerows had ($r=0.787$; $p=0.021$). In comparing the two sites, homegardens had a correlation of ($r=0.639$; $p=0.008$) while hedgerows had ($r=0.720$; $p=0.002$).Correlation between richness and diversity in homegardens agroforestry was ($r=0.731$; $p=0.001$) and ($r=0.558$; $p=0.005$) in hedgerow in Kakamega North. In Kakamega South, homegardens had (r=0.807; p=0.015) while hedgerow had (r=0762; p=0.028). In comparing the two sites (north and south), homegarden correlation was (r=0.859; p=0.001) and hedgerow had (r=0.665; p=0.005). The correlation between abundance and diversity, abundance and evenness, richness and evenness and abundance and richness was also significant ($p<0.05$) in homegarden and hedgerow types of agroforestry and between the two sites combines (Table 4.11).

Table 4.10: Correlation between variables in the two sites

Variable	Site	R	R^2	df	F	SE	p
Abundance and richness	KKN	0.544	0.296	14	5.87	5.00	0.029
	KKS	0.605	0.366	14	8.08	4.72	0.013
	KKN and KKS	0.579	0.335	30	15.14	4.70	0.001
Abundance and diversity	KKN	0.019	0.000	14	0.005	0.541	0.001
	KKS	0.381	0.145	14	2.37	0.631	0.001
	KKN and KKS	0.281	0.048	30	1.50	0.583	0.001
Abundance and evenness	KKN	0.539	0.291	14	5.73	0.118	0.031
	KKS	0.085	0.007	14	0.10	0.163	0.001
	KKN and KKS	0.306	0.093	30	3.09	0.141	0.001
Richness and diversity	KKN	0.686	0.470	14	12.44	0.394	0.003
	KKS	0.788	0.621	14	22.91	0.420	0.001
	KKN and KKS	0.740	0.547	30	36.27	0.402	0.001
Richness and evenness	KKN	0.047	0.002	14	0.03	0.140	0.001
	KKS	0.370	0.137	14	2.22	0.152	0.001
	KKN and KKS	0.207	0.043	30	1.35	0.145	0.001
Diversity and evenness	KKN	0.702	0.493	14	13.64	0.10	0.002
	KKS	0.735	0.540	14	16.46	0.11	0.001
	KKN and KKS	0.702	0.493	30	29.20	0.11	0.001

KKN-site north of Kakamega Forest; KKS-site south of Kakamega Forest; DF-degree of freedom; SE-standard error mean; r-Pearson correlation coefficient; significant at ($p<0.05$).

Table 4.11: Correlation between variables in the agroforestry practices and sites

Variable	Site	Agroforestry	R	R^2	df	F	SE	p
Diversity and evenness	KKN	Homegardens	0.912	0.833	6	29.83	0.051	0.002
		Hedgerows	0.597	0.357	6	3.32	0.14	0.001
	KKS	Homegardens	0.667	0.445	6	4.82	0.063	0.002
		Hedgerows	0.787	0.619	6	9.73	0.126	0.021
	KKN and KKS	Homegardens	0.639	0.408	14	9.66	0.09	0.008
		Hedgerows	0.720	0.518	14	15.03	0.123	0.002
Abundance and diversity	KKN	Homegardens	0.122	0.015	6	0.09	0.588	0.002
		Hedgerows	0.057	0.003	6	0.02	0.573	0.008
	KKS	Homegardens	0.384	0.147	6	1.04	0.643	0.027
		Hedgerows	0.373	0.139	6	0.97	0.665	0.009
	KKN and KKS	Homegardens	0.160	0.026	14	0.37	0.591	0.001
		Hedgerows	0.239	0.057	14	0.85	0.599	0.001
Abundance and evenness	KKN	Homegardens	0.428	0.183	6	1.35	0.112	0.002
		Hedgerows	0.633	0.400	6	4.00	0.134	0.007
	KKS	Homegardens	0.187	0.035	6	0.22	0.084	0.024
		Hedgerows	0.163	0.027	6	0.16	0.201	0.008
	KKN and KKS	Homegardens	0.381	0.145	14	2.38	0.108	0.001
		Hedgerows	0.360	0.130	14	2.09	0.166	0.001
Richness and diversity	KKN	Homegardens	0.731	0.867	6	38.96	0.216	0.001
		Hedgerows	0.558	0.311	6	2.11	0.476	0.005
	KKS	Homegardens	0.807	0.659	6	11.23	0.411	0.015
		Hedgerows	0.762	0.581	6	8.33	0.464	0.028
	KKN and KKS	Homegardens	0.859	0.734	14	39.25	0.307	0.001
		Hedgerows	0.665	0.443	14	11.12	0.461	0.005
Richness and evenness	KKN	Homegardens	0.718	0.515	6	6.37	0.086	0.045
		Hedgerows	0.234	0.515	6	0.35	0.168	0.003
	KKS	Homegardens	0.609	0.371	6	3.54	0.068	0.000
		Hedgerows	0.237	0.056	6	0.36	0.190	0.004
	KKN and KKS	Homegardens	0.524	0.275	14	5.30	0.100	0.037
		Hedgerows	0.022	0.001	14	0.00	0.173	0.000
Abundance and Richness	KKN	Homegardens	0.166	0.027	6	`0.17	4.745	0.006
		Hedgerows	0.836	0.699	6	13.94	4.213	0.010
	KKS	Homegardens	0.526	0.277	6	2.30	4.573	0.049
		Hedgerows	0.758	0.575	6	8.11	4.578	0.029
	KKN and KKS	Homegardens	0.369	0.136	14	2.20	4.395	0.001
		Hedgerows	0.804	0.647	14	26.67	4.80	0.000

KKN-site north of Kakamega Forest; KKS-site south of Kakamega Forest; df-degree of freedom; SE-standard error mean

4.3. Determine Biomass and Soil Carbon Stocks Under Different Agroforestry Practises in Western Kenya

4.3.1 Above- and Belowground biomass

A total of 13.76±0.37 Mgha^{-1} of aboveground biomass was estimated from the study area using the equation by Kuyah *et al*. (2012). Belowground biomass estimated was 3.45±0.09 Mg ha^{-1}(Figure 4.4), giving total biomass held in live trees on farms to be 17.22±1.65 Mgha^{-1}. This translates to 6.4Mg/ha and 1.6 Mg/ha of carbon in above- and below-ground portions of the trees (Table 4.12). Aboveground biomass estimates determined using the equation by Brown (1997) were consistently higher across the study area, for each of the study sites and in both homegardens and hedgerows than estimates obtained using the equation by Kuyah *et al*., (2012). However, the estimates were closer to those obtained for small trees using the equation by Kuyah *et al* (2012). Kakamega north had significant higher biomass (9.7Mg/ha) ($F=35.03$; $p=0.01$) as compared to Kakamega south (7.51Mg/ha); corresponding to the higher tree density in the north compared to southern part. Similarly, homegardens had significantly higher aboveground biomass (9.85Mg/ha) than hedgerows (7.36Mg/ha) ($F=45.2$; $p=0.001$).

The study area was dominated with smaller trees (DBH<30 cm), which constituted about 80% of all the trees enumerated in the study area. Large diameter trees (>90cm)were few in both sites; 14% and 26% of the individuals inventoried in each site, respectively; but held most of the biomass, 73 and 69% respectively. The majority of larger trees were found in hedgerows while homegardens had many small-sized trees. In Kakamega North, over half (66%) of the trees had DBH<20 cm, accounting for 16% of the biomass in the north; trees with DBH range of 50-60cm comprised 1.8% of the all the trees recorded in the site, but stocked most (28%) of the biomass (Figure 4.5a).

Kakamega South had two-third of all the trees recorded with DBH <30 cm and held about a third of the biomass; trees with DBH >60 cm comprised 11% of trees recorded in the south, but stored more biomass (22%) in the area (Figure 4.5 b). In terms of species dominance, biomass was held in species that had large number of individuals. Over 53% of the biomass measured is held in indigenous trees; while only 47% held by exotic species. For example, *Markhamia lutea*, *Zanthoxylum gilleti*, and *Croton macrostachyus* are indigenous and together make up 2.9 Mg of biomass measured. Exotic species with large stocks of biomass were *Eucalyptus grandis*, *Grevillea robusta*, and *Cupressus lusitanica*, which hold a combined 2.1 Mg of biomass.

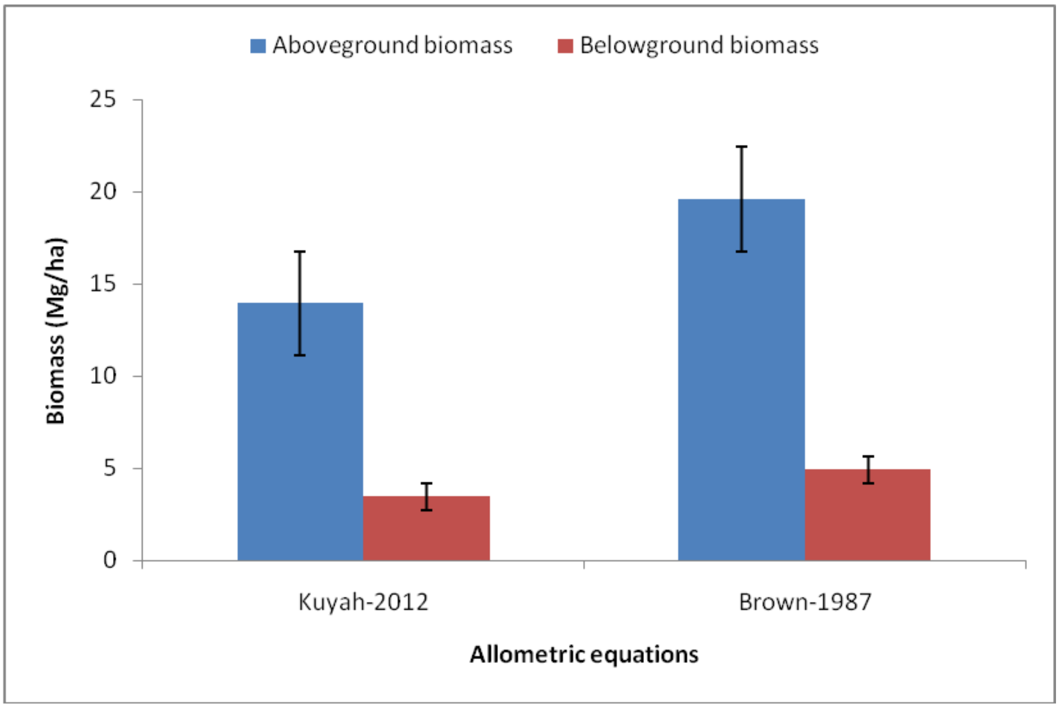

Figure 4.4: Above-and-below-ground biomass estimated using Kuyah et.al., (2012) and Brown, (1997) allometric equations

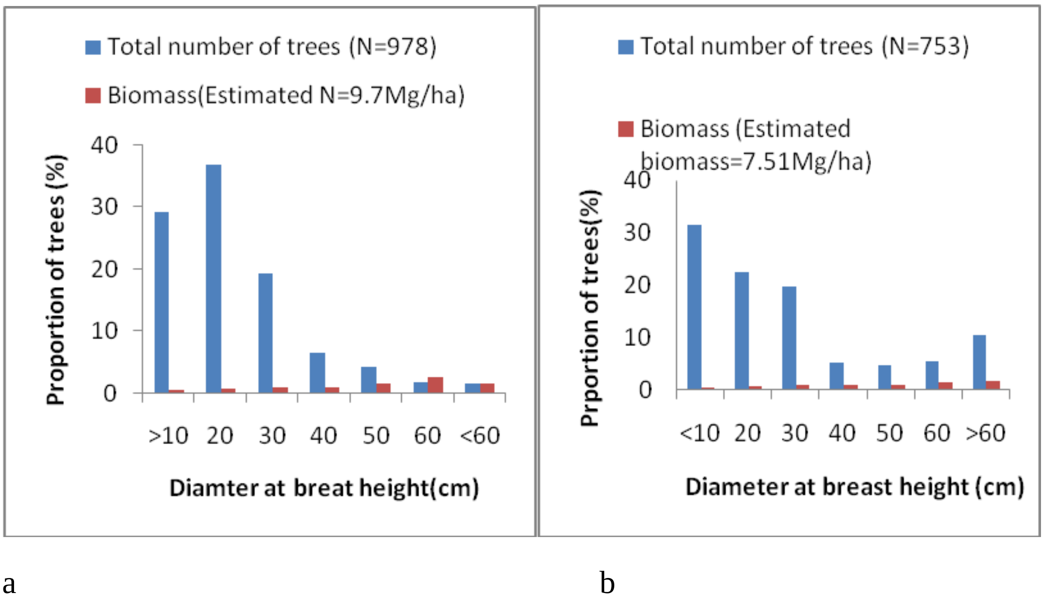

Figure 4.5: Biomass distribution with diameter at breast heigh (DBH) in (a) Kakamega North and (b) Kakamega South

The diversity of tree species in the context of carbon sequestration in smallholder farms depends on the way trees are integrated on the farms. Tree species diversity and biomass carbon stock was higher in homegardens than hedgerows, corresponding to higher tree density compared to hedgerows. Aboveground biomass (7.89±0.75Mgha^{-1}) estimated for homegardens in the study area is within the range of 2-18 Mgha^{-1} for tropical agroforestry systems in wet agro climatic zones with elevations up to 1000 m above sea level (Nair and Nair, 2014). However, these values are higher than 12±0.01, 11.22±0.23, and 9±0.21 Mgha^{-1} reported by Schroth *et al*. (2004), Mattson *et al*. (2015) (12.7MgC//ha), and Kumar *et al*. (2011) (16-36Mg/ha) for homegardens in Sri Lanka and India respectively.

These differences can be attributed to variations in species diversity, tree stand quality, soil fertility and trees management strategies. Homegardens have high species diversity and high carbon storage capacity because of their ability to host multipurpose tree species. For example, fruit trees and other multipurpose tree species scattered in homesteads are commonly used to supply food, fuel wood, fodder, timber and poles that was previously obtained from the neighboring forest. This has an additional climate change mitigation benefit; they help to alleviate the pressure exerted on the natural forest by the surrounding communities, preserving existing carbon stocks (Mattson *et al*., 2015).

Studies quantifying biomass in hedgerows are scarce, and estimates currently range from 1.5-7 Mg/ha for protective agroforestry systems such as windbreaks, shelterbelts, soil conservation hedges such as contour hedgerows, and boundary planting across semi-arid and sub-humid regions (Nair and Nair, 2014). These amounts are lower compared to estimates for trees in homegardens in this study, or trees scattered in crop fields, because of the smaller area occupied by trees in boundaries and hedges can only support a small number of trees (Matteo *et al*., 2016). Interestingly, there is potential to raise carbon stored in smallholder systems in East Africa by about 0.8 Mg/ha of carbon per year through introduction and intensification of hedgerows (Henry *et al*. 2009; Henri *et al*., 2011). Conversely, homegardens would result in about 0.2 – 0.25 Mg/ha of carbon per year, if more trees were introduced, and 0.5-0.6 Mg/ha of carbon if food crops were converted to homegardens (Henry *et al*. 2009). High tree density enhances carbon sequestration in vegetation, although excessively high stand densities can adversely affect tree growth and productivity through competition effects, resulting in lower carbon sequestration (Nair *et al* 2010).

Biomass carbon stored in smallholder farms studied is consistent with estimates given for tropical agroforestry practices (Kumar, 2011). However, the average aboveground biomass carbon stocks estimated in this study is lower than the average 9-11 Mg/ha of carbon (Henry *et al*., 2011) and 17±0.02 Mg/ha of carbon (Kuyah *et al*., 2012) reported for agricultural landscapes of western Kenya. Variations in estimates in the present study and those reported elsewhere e.g. Abebe, (2005), Mattson *et al*., (2015), Agevi *et al*., (2016), Kumar *et al*., (2017) among others can be attributed to management influence, plant diversity, and stand quality. Carbon stocks vary greatly under different biophysical and socioeconomic characteristics, typical of smallholder farms in western Kenya (Kuyah *et al* 2012), and uniform methods of quantification (Nair *et al*., 2010).

Variation in management on individual farms, and the diversity of plants with different growing habits can explain such differences in biomass estimates for agroforestry systems in the region. For example, management practices alter tree growth, and consequently biomass accumulation; this can improve biomass carbon, and contribute to the release of carbon in the vegetation. The study revealed a general trend of increasing biomass carbon with increasing tree size in all practices and at both sites. The majority of large trees were found in Kakamega North and in homegardens indicating that they store majority of biomass carbon stocks. Across the different sites and agroforestry systems, carbon sequestration in the trees was directly related to aboveground biomass production.

Table 4.12: Table of diameter at breast heigh (cm) measured, total tree biomass (above and below) determined in the field using the two equations

Land use	Agroforestry practice	DBH			Tree density (no./ha)		Kuyah *et al* (2012) (Mg/ha)			Brown (1997) (Mg/ha)		
		mean	min	max	#	area(ha)	Above-	Below-	Total-Biomass	Above-	Below-	Total-Biomass
KKN	a. Homegardens	18.52	3.18	18.52	562	3.24	4.31(1.03)	1.07(0.25)	5.38 (1.29)	5.93 (1.32)	1.48(0.98)	7.41(0.67)
	Hedgerows	16.71	3.18	91.66	416	3.24	3.54(1.43)	0.88(0.64)	4.32 (1.22)	5.84 (1.35)	1.46 (0.34)	7.3(0.89)
KKS	b. Homegardens	12.14	2.86	45.56	408	3.24	3.58(1.35)	0.89(0.33)	4.47(1.69)	4.30 (1.38)	1.08 (0.23)	5.38(0.31)
	Hedgerows	19.54	2.63	99.93	345	3.24	2.43(1.72)	0.61(0.43)	3.04 (2.16)	3.53 (1.27)	0.88(0.35)	4.41(0.29)
Total	c. Homegardens	12.53	2.86	79.97	970	6.48	7.89(0.75)	1.96(0.19)	9.86 (0.93)	10.23 (1.56)	2.56 (0.27)	12.79(1.49)
	Hedgerows	17.99	2.63	99.93	761	6.48	5.87(1.35)	1.49(0.34)	7.36 (1.69)	9.37 (1.23)	2.34 (0.19)	11.71(1.10)

#- Number of trees; min-minimum value; max-maximum values for diameter at breast height (cm) values

4.3.2 Soil physico-chemical properties and their influence on organic carbon

4.3.2.1 Soil textural classes

Sand was the dominant soil class compared to the other soil classes at 0-10cm and 10-30cm depth in western Kenya in the two study sites (Figure 4.6). This was followed by clay and silt respectively. Sand showed a decreased with increase in depth. In Kakamega North, it decreased from 62.5±2.55% (0-10cm) to 52.4±2.14% (10-30cm). In Kakamega South, it decreased from 56.3±1.06% (0-10cm) to 51.3±0.77% (10-30cm). Clay and silt increased with increasing depth at both sites. Clay increased from 32.1±2.55 (0-10cm) to 39.5±2.32% (10-30cm) in Kakamega North. In Kakamega South, it increased from 34.6±0.82% (0-10cm) to 37.7±0.5% (10-30cm). Silt increased from 5.35±0.91% (0-10cm) to 8.31±0.74% (10-30cm) in Kakamega north and from 9.1±0.61% (0-10cm) to 11.3±0.62% (10-30cm) in Kakamega south (Table 4.13).

There was significant difference in sand ($F=7.34$; $p=0.0001$), clay ($F=10.43$; $p=0.006$) and silt ($F=11.51$; $p= 0.004$) in soil depth classes of 0-10cm and 10-30cm in the study area. There was significance difference in sand ($F=0.548$; $p=0.04$) and silt ($F=0.35$; $p=0.04$) between the two sites at 0-10cm depth. Clay did not show significant difference ($F=3.66$; $p=0.104$). At 10-30cm depth, there was no significance difference in sand ($F=3.28$; $p=0.55$) and clay ($F=2.31$; $p=0.32$) between the two sites. Silt showed significant difference between the two sites ($F=1.26$; $p=0.006$).

Sand exhibited a strong significant negative relationship with clay at 0-10cm depth in Kakamega North ($r=-0937$; $p=0.001$) and Kakamega South ($r=-0.821$; $p=0.013$). As the sand content was decreasing with depth, there was a corresponding increasing in clay content with depth. At 10-30cm depth, the two variables showed a strong negative significant relationship in Kakamega North ($r=-0.948$; $p=0.000$). In Kakamega South, sand showed negatively moderate insignificant relationship with silt ($r=-0.639$; $p=0.088$) and with clay ($r=-0.600$; $p=0.116$) at 0-10cm depth. There was insignificant negative relationship between sand and silt ($r=-0.174$; $p=0.684$), clay and silt($r=-0.181$; $p=0.669$) in Kakamega North at 0-10cm and between clay and silt ($r=-0.058$; $p=0.582$) in Kakamega South at 10-30cm. There was a low insignificant positive relationship between sand and silt($r=0.085$; $p=0.841$) in Kakamega North at 10-30cm and between clay and silt ($r=0.084$; $p=0.842$) in Kakamega South at 0-10cm (Table 4.14).

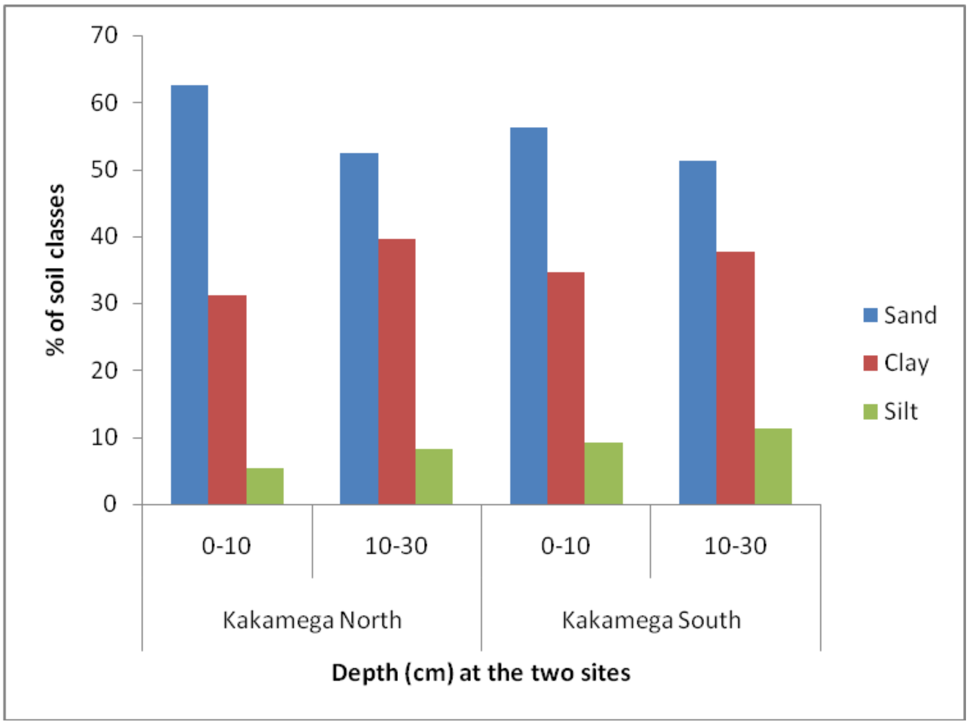

Figure 4.6: Representation of different soild classes (%) in the two study sites at 0-10cm and 10-30cm

The soils in the two study sites were slightly acidic both in the upper (0-10cm) and in the inner soil layers (10-30cm). Soils within Kakamega Forest and its environments according to Musila, (2007) are acidic and mostly nutrient poor. Low pH suggests that the tree species in the study sites may have acidified the soil to a greater extent by producing more organic acids during litter decomposition (Acheamfuor *et al*., 2014). Noble *et al*. (2000) attributed the low pH to continuous nutrient uptake by trees and other plants within the agroforestry systems. The decomposition of high organic matter in the study area coupled with parent material weathering by the trees could also be another attribute according to Sharma *et al*., (2011). The low pH values of the soils in the study sites could possibly also be due to the intensive application of nitrogen fertilizers during cultivation. This could also be attributed to the addition of litter by trees and plant residuals to the soils. This in turn adds more organic carbon into the soils (Mattson *et al*., 2015; Tanveera *et al*., 2016). In addition, the oxidation of nitrogen and sulphur could have resulted in an intensified decomposition of soil organic matter leading to a reduction in the soil pH (Bahrami *et al*., 2010).

Soil classes in both the sites were dominated by sandy clay loam soil classes in the 0-10cm depth and sandy clay classes in the deep soil layers (10-30cm). Soil types of Acric ferrasols which are dominant in the study area (USDA, 1990) are dominated mostly by sand. The amount of sand decreased with increase in soil depth. The high level of sand in both the two study sites is an indication that soils in both sites originate from the same parent material. Clay increased with increase in soil depth. Differences in the chemical, biological and otherphysical properties of the soils are due to differences in land-useand management practices, position and climate rather thaninherent differences in the soils (Sharrow and Ismail, 2007).

Table 4.13: Summary of the physico chemical characteristics at 0-10cm and 10-30 cm depth in the two study sites

Site	Depth (cm)	Textural classes (%) Sand	Clay	Silt	BD(gcm^{-3})	Porosity (%)	pH	EC (ds/vol)
Kakamega	0-10	62.5±1.56	32.1±1.26	5.6±0.91	1.12±0.047	57.7±1.8	5.56±0.08	0.09±0.13
north	10-30	52.4±1.11	39.5±1.11	8.1±0.74	1.26±0.024	51.5±1.5	5.45±0.15	0.08±0.001
Kakamega	0-10	56.3±1.06	34.6±0.82	9.1±0.61	1.04±0.005	60.7±2.12	5.53±0.1	0.09±0.001
south	10-30	51.3±0.77	37.5±0.5	11.3±0.62	1.22±0.005	53.9±2.16	5.55±0.12	0.07±0.009

Table 4.14: Pearson correlation between soil classes in the two study sites at 0-10cm and 10-30cm

Site	Depth	Variables	n	r	p
Kakamega North (KKN)	0-10	sand + clay	8	-0.937	0.001
		sand+ silt	8	-0.174	0.684
		clay+ silt	8	-0.181	0.669
	10-30	sand + clay	8	-0.948	0.000
		sand+ silt	8	0.085	0.841
		clay+ silt	8	-0.397	0.330
Kakamega South (KKS)	0-10	sand + clay	8	-0.821	0.013
		sand+ silt	8	-0639	0.088
		clay+ silt	8	0.084	0.842
	10-30	sand + clay	8	-0.600	0.116
		sand+ silt	8	-0.764	0.027
		clay+ silt	8	-0.058	0.582

r- Pearson coefficient correlation; significant at ($p<0.05$)

4.3.2.2 Bulk density and Porosity

Bulk density increased with depth from 1.08±0.15gcm^{-3} to 1.24±0.12gcm^{-3} at 0-10cm and 10-30cm respectively. Porosity on the other hand decreased from 59.20±1.4% to 52.83±1.31%at 0-10cm and 10-30cm respectively. There was no significant difference in bulk density in Kakamega North and Kakamega South at 0-10cm ($F=0.880$; $p=0.560$) and 10-30cm ($F=1.053$; $p=0.466$). Porosity also showed no significant difference in the two sites at 0-10cm (F=0.971; p=0.361) and 10-30cm (F=0.867; p=0.388). There was a strong negative correlation between bulk density and porosity at 0-10cm (r= -0.99; p=0.0001) and 10-30cm (r= -0.95; p=0.0001). In Kakamega North, bulk density correlated negatively with porosity at 0-10cm (r= -0.99; p=0.0001) and 10-30cm (r =-0.87; p=0.003). In Kakamega South, there two parameters also correlated negatively at 0-10cm (r= -0.99; p=0.0001) and 10-30cm (r= -0.99; p=0.0001) (Table 4.13).

There was a significance difference in soil bulk density (SBD) between Kakamega North and Kakamega South (p<0.05). The difference in bulk density between sites according to Nath, (2014) could be due to difference in the soil texture, amount of organic matter in the soil surface, porosity, amount of nutrients between sites and with depth and constituent minerals. The levels of bulk density were consistent with other studies (Nath, 2014); Leifield *et al*., 2005 and Rawls *et al*., 2005).

Bulk density however increased with increase in depth in both the study sites (Table 4.13). Soils with high sand content tend to have a higherbulk densitydue to high specificgravity of quartz and principal component of sand (USDA, 2008). High bulk density in the top soil as compared to the sub soil was as a result of high organic carbon in top soil (Kassa *et al*., 2017). Soil bulk density (ρb) describes the spatial arrangement of the solid particles that compose soil matrix, providing an indication of basic soil quality index (Chan, 2005). It provides valuable information relating to porosity, compaction, and penetration resistance of soil (Horns, Way and Rostek, 2003). Bulk density typically increases with soil depth since subsurface layers are more compacted and have less organic matter, less aggregation, and less root penetration compared to surface layers, therefore contain less pore space. High sand content in the upper soil layers than the subsequent layers also explains the high bulk density difference with depth.

Bulk density is dependent on soil organic matter, soil texture, the density of soil mineral (sand, silt, and clay) and their packing arrangement. High organic matter in the top soil surface decrease soil bulk density (Chan, 2005). This was the reason for the negative correlation between organic matter and soil bulk density in the study sites. The bulk density bears an inverse relationship with the soil organic matter (White, 1987). Similar results hane been reported many researchers (Morisada, Ono, and Kanumata, 2004; Leifeld, Bassin and Fuhrer, 2005 ; Perie and Ouimet, 2007; Sakin, 2012). Porosity trend decreased with depth (0-10cm and 10-30cm) in the two study sites. It negatively correlated with bulk density. According to Rawls, Nemes and Pachepsky, (2005), soil organic matter which affects both bulk density and porosity can stimulate soil aggregation, which lowers bulk density (ρb), increases porosity.

There was a negative correlation between porosity and clay content but a positive one between sand and porosity in the two study sites. Kakamega South recorded higher organic matter stocks than Kakamega North (Figure 4.6). The stocks however decreased with increase in depth.. The higher organic matter in the upper soil surface layers explains the increase in bulk density with depth.The variation between sites and depth is attributed to differences in soil texture, bulk density, constituent minerals among others (Nath, 2014).

Table 4.15: Correlation between bulk density (gcm^{-3}) and porosity at 0-10cm and 10-30cm

Site	Overall		Kakamega North		Kakamega South	
Depth(cm)	0-10	10-30	0-10	10-30	0-10	10-30
R	-0.99	-0.95	-0.99	-0.866	-0.99	-0.99
R^2	0.9801	0.906	0.999	0.786	0.999	0.999
Adj R	0.999	0.899	0.999	0.751	0.999	0.999
F	138.08	134.45	12.28	22.09	28.72	28.11
P	0.0001	0.0001	0.0001	0.003	0.0001	0.0001

R-Pearson coefficient correlation; Correlation is significant at ($p<0.05$)

4.3.2.3 Soil pH and Electrical Conductivity (EC)

Soils were acidic at both sites in the study area and at both depths. Soil pH decreased with depth in Kakamega north from 5.56 to 5.45 and in Kakamega south from 5.55 to 5.53. This could be attributed to the soil variations in the soil texture with increase in the soil depth. Electrical conductivity showed a decrease with increase soil depth in both the sites. The decrease in soil electrical conductivity indicated that the levels of salts were deceasing with increase in soil depth which exhibited the soils becoming more acidic with increase in soil depth. Soil pH differed significantly with electrical conductivity between 0-10cm and 10-30cm depth in both Kakamega north and south (Table 4.16). Soil electrical conductivity is a measure of salinity of the soil.

Table 4.16: Variation in pH and Electrical Conductivity (ds/vol) in the two study sites at 0-10cm ad 10-30cm depth

Site	**Kakamega north**				**Kakamega south**			
Depth	**0-10cm**		**10-30cm**		**0-10cm**		**10-30cm**	
Variables	pH	EC ds/vol	pH	EC	pH	EC	pH	EC
M	5.56	0.09	5.45	0.08	5.55	0.09	5.53	0.08
SE	0.08	0.013	0.15	0.001	0.17	0.01	0.16	0.009
SD	0.022	0.037	0.44	0.032	0.474	0.031	0.045	0.026
min	5.23	0.04	4.75	0.05	4.77	0.05	4.88	0.04
max	5.91	0.16	5.93	0.13	6.11	0.13	6.08	0.11
CV (%)	0.33	46.25	8.08	40	8.57	34.44	0.81	32.5
Multiple R	0.146		0.460		0.855		0.719	
R^2	0.021		0.212		0.731		0.517	
F (pH and EC)	0.13		1.61		16.34		6.44	
P (pH and EC)	0.0001		0.0001		0.007		0.044	

M-mean; SE-Standard error; SD-Standard deviation; min-Minimum values for pH and EC; max-Maximum values for pH and EC; EC-Electrical Conductivity; CV-Coefficient of variation

4.3.3 Relationship between soil texture, bulk density, porosity, soil pH and electrical conductivity

Bulk density showed a low insignificant negative correlation with sand in Kakamega North at 0-10cm depth (r=-0.32; p=0.434). At 10-30cm depth, it was not significant (r=0.65; p=0.08). In Kakamega South, the correlation was moderately positive and significant at 0-10cm (r=0.488; p=0.22). The correlation was not significant at 10-30cm (r=0.626; r=0.097). Relationship between bulk density and clay positive was positive but not significant in Kakamega North at 0-10cm (r=0.164; r=0.694). It was strongly positive and significant at 10-30cm depth (r=0.796; r=0.018). In Kakamega South, it was moderately negative but not significant at 0-10cm (r=-0.5; r=0.207) and strongly negative and significant at 10-30 cm (r=-0.711 r=0.048). Silt correlated moderately but not significant with bulk density at 0-10 cm (r=0.449; r=0.265) and 10-30cm (r=0.621; r=0.101) in Kakamega North. In Kakamega South, it was negative but not significant at 0-10 cm (r=-0.177 p=0.694) and at 10=30 cm (r=-2.88; r= 0.621).

There was low positive insignificant correlation between bulk density and pH at 0-10 cm (r=0.280; r=0.501), 10-30 cm (r=0.158; p=0.708) in Kakamega North and at 0-10 cm (r=0.244; p=0.560) in Kakamega South. At 10-30cm, the correlation was negative and insignificant (r=-0.129; p=0.760). Electrical conductivity strongly and negatively correlated with bulk density at 0-10 cm (r=-0.676; p=0.066) in Kakamega North while it lowly but negatively correlated at 10-30cm (r=-0.342; p=0.408) in Kakamega South. The relationship was positive insignificant at 10-30 cm (r=0.133; p=0.753) in Kakamega North and at 0-10 cm (r=0.037; p=0.931) in Kakamega South.

The relationship between porosity and sand was negative but not significant at 10-30cm (r=-0.524; p=0.183) in Kakamega North, at 0-10cm (r=-0.485; p=0.228) and (r=-0.628; p=0.095) in Kakamega North. The increase in the sand particles which are large in space tried to fill the airspace and pores within the soil and hence reducing porosity. The correlation was positive at 0-10 cm (r=0.320; p=0.439). Clay moderately correlated with porosity at 10-30cm (r=0.663; p=0.073) in Kakamega North, 0-10 cm (r=0.504; p=0.202) and strongly but significant at10-30 cm (r=0.719; p=0.044) in Kakamega South. The correlation was negative at 0-10 cm (r=-0.165; p=0.696). Silt also correlated negatively and significantly at 0-10 cm (r=-436; p=0.028) but not significant at 10-30 cm (r=-0.566; p=0.143) in Kakamega North. It was positive but not significant at 0-10cm(r=0.167; p=0.692) and at (r=0.204;

p=0.629) (table 4.17). The difference in the porosity and soil structure of the soil affected the water holding capacities in the area. The variation in the parameters is attributed to the fertility of the soil, soil type, vegetation cover and diversities.

Table 4.17: Pearson correlation coeffiecient between variables in the two study sites at 0-10cm and 10-30cm

Parameter		Kakamega North (KKN)		Kakamega South (KKS)	
		0-10cm	10-30cm	0-10cm	10-30cm
BD and sand	r	-0.32	0.65	0.488	0.626
	p	0.434	0.08	0.22	0.097
BD and clay	r	0.164	-0.796	-0.500	-0.711
	p	0.694	0.018	0.207	0.048
BD and silt	r	0.449	0.621	-0.177	-0.208
	p	0.265	0.101	0.694	0.621
Porosity and sand	r	0.320	-0.524	-0.485	-0.628
	p	0.439	0.183	0.223	0.095
Porosity and clay	r	-0.165	0.663	0.504	0.719
	p	0.696	0.073	0.202	0.044
Porosity and silt	r	-0.436	-0.566	0.167	0.204
	p	0.028	0.143	0.692	0.629
Bd and pH	r	0.280	0.158	0.244	-0.129
	p	0.501	0.708	0.560	0.760
Db and EC	r	-0.676	0.133	0.037	-0.342
	p	0.066	0.753	0.931	0.408

r- Pearson correlation coefficient; BD- bulk density; EC-electrical conductivity; significant at ($p<0.05$).

4.3.4 Soil organic carbon (SOC) stocks

Total soil organic carbon (SOC) stocks in the study areas were 14.91Mg Cha^{-1}. Kakamega South had higher soil organic carbon stocks compared to Kakamega North (Figure 4.7). Carbon stocks decreased with increase in depth in both sites (Table 4.16). The decrease in the soil organic carbon with increase in soil depth could be attributed to the decrease in the soil organic matter with increase in soil depth as presence of organic matter in the upper soil layers is an indicative of soil organic carbon. There was significant difference in the amount of SOC stocks at 0-10cm and 10-30cm in Kakamega North ($F=3.30$; $p=0.005$) and in Kakamega South ($F=0.633$; $p=0.0001$).

Soil organic carbon stocks were higher in Kakamega north than in Kakamega south (Figure 4.5). Levels of organic carbon stocks recorded however were within range similar ranges within agroforestry studies like those by Nair *et al*., (2010), Nair, (2012) and Negash, (2015) among others. The quantities were however lower than those in studies by Nair *et al*., (2010) and more than studies by Amezquita *et al*., (2005). The variations are attributed to the differences in agroforestry practices in the area of study. Variation between systems, ecological regions, and soil types, always give a general trend of increasing soil carbon sequestration in agroforestry when compared to other land-use practices, with the exception of forests (Perie and Ouimet, 2007; Kassa *et al*., 2017).

The soil organic stocks however decreased with increase in depth. The difference in the organic carbon stocks could be due to variation in bulk density between the sites which according to Leifeld, Bassin and Fuhrer (2005) highly correlates with organic carbon stocks. The turnover rate of fine roots decreases with increase in depth, which in turn affects the organic matter input in deep soil layers. This contributes to decline in the soil organic carbon with depth increase (Nayar and Sastry, 1987). The higher organic carbon stocks and more so in the upper soil layers could also be attributed to variation in tree abundance and diversity between the two sites which increases organic matter through litter fall.

Tree diversity results has been shown to increase in root productivity and hence, high carbon stocks in the upper soil layers (Henry *et al*., 2009; Meinen, Hertel and Leuschner, 2009; Henry *et al*., 2011). The high level of organic matter in the upper surface explains the decrease in the amount of organic carbon stocks with depth. High turnout of leaf litter on the soil surface increased the organic matter in the top soil. Those inputs can help to stabilize soil organic matter (SOM) and decrease biomass decomposition rate and SOM destabilization, improving SOC stocks (Stefano and Jacobson, 2017). Soil organic carbon may also vary depending on the biophysical and socio-economic characteristics of the system parameters (Nair and Nair, 2014). Mpanda *et al*., (2014) noted that variations might be linked to the differences in soil types while Lal, 2004a) attributed the same to environmental variables, management regimes, elevation and climate (Soto-Pinto *et al*., 2010). Trees like *Grevillea robusta* which were found within the study area within the agroforestry practices have the ability of nitrogen fixation. This may cause higher biomass production changes.

In addition microbial decomposer community composition under N-fixing trees may result in greater retention of relatively stable SOC ctocks in soils (Resh, Binkley and Parrotta, 2002). Soil organic carbon plays a vital role in the global carbon cycle, forming large carbon pools with long residence times (Negash, 2015). The high carbon stocks influenced by these agroforestry practices also mean that they have a significant carbon sequestration and a climate change mitigation effect, complementing the adjacent Kakamega Forest. Although the ability of soils to accumulate carbon is generally related to characteristics that are little influenced by management, such as texture (clay soils typically accumulate more carbon than sandy soils), some management practices can influence soil carbon sequestration, particularly the insertion of trees in agricultural systems. Soils in various sites studied by Takimoto, Nair and Nair, (2008) in the African Sahel were not markedly different among each other in terms of their characteristics such as pH, bulk density, and particle size, such that variations in their carbon contents seemed to be related to the influence of trees.

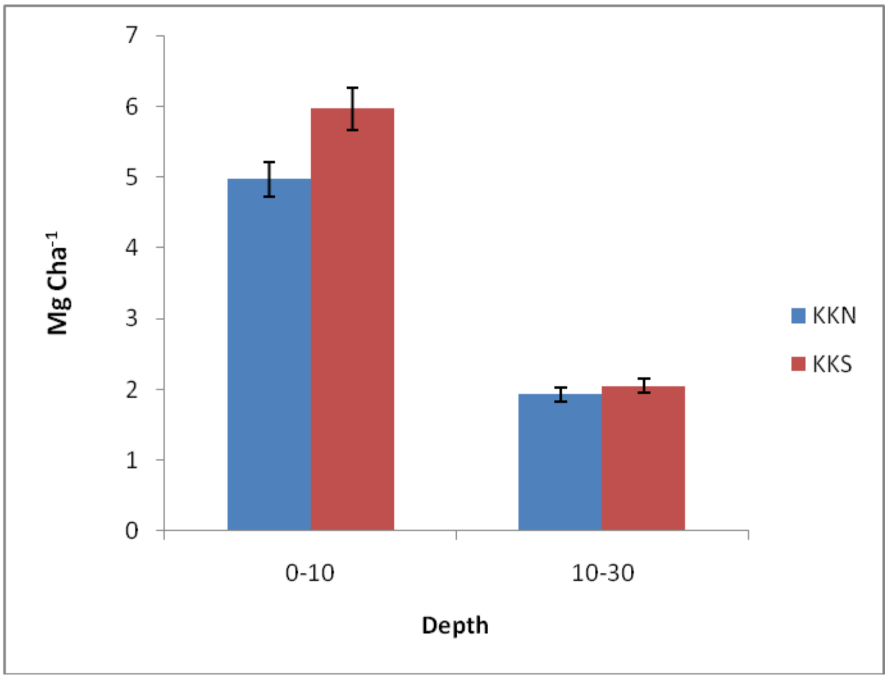

Figure 4.7: Amount of soil organic carbon (MgCha^{-1}) in Kakamega North (KKN) and Kakamega South (KKS) at 0-10cm and 10-30cm depth

Table 4.18: Summary of soil organic carbon stoks, soil organic matter, total nitrogen socks and SOC: TN

Site	Depth(cm)	SOC	SOM	TN	SOC:TN
Kakamega	0-10	0.62±0.1	1.07±0.01	1.67±0.07	0.36
north	10-30	0.24±0.03	0.42±0.05	0.74±0.04	0.33
Kakamega	0-10	0.74±0.05	1.28±0.08	2.12±0.16	0.36
south	10-30	0.26±0.02	0.44±0.03	1.30±0.16	0.23

4.3.4.1 Relationship between Soil Organic Carbon (SOC) stocks with tree abundance and diversity

There was a negative insignificant correlation between soil organic carbon stocks and tree abundance in homegardens (r= -0.177; p=0.675) and hedgerows (r= -0.246; p=0.558) in Kakamega North. In Kakamega South, the relationships were also negatively insignificant (homegardens; (=-0.407; p=0.317); hedgerows; r=-0.461; p=0.250). The correlation between tree diversity and soil organic carbon varied between the two sites (north and south). In Kakamega north, the correlation was negative and insignificant in homegardens (r=-0.243; p=0.563) and in hedgerows, positive and insignificant(r=0.095; p=0.823). In Kakamega South, homegardens had moderately positive insignificant correlation (r=0.488; p=0.220) and negative in hedgerow type of agroforestry (r=-0.330; p=0.425) (table 4.19). The variation in the soil organic carbon with tree abundance and diversity is attributed to the difference in the litter fall production, age of the trees which contribute to litter fall. Young trees potential to contribute to litter fall is reduced as leaves are intact. As the trees age, then their potential to contribute to litter fall then increases significantly.

Table 4.19: Pearson correlation between soil organic carbon and diversity and abundance

Parameters	Agroforestry type	KKN			KKS		
		n	R	p	n	r	p
SOC and Abundance	Homegardens	8	-0.177	0.675	8	-0.407	0.317
	Hedgerows	8	-0.246	0.558	8	-0.461	0.250
SOC and diversity	Homegardens	8	-0.243	0.563	8	0.488	0.220
	Hedgerows	8	0.095	0.823	8	-0.330	0.425

r-Pearson correlation coefficient; KKN-Kakamega North, KKS-Kakamega South

4.3.5 Soil Organic Matter (SOM) stocks

Total Organic Matter (TOM) estimated in the study area was 25.7Mgha^{-1}. Most of the organic matter was concentrated in the top soil profile within the 0-10cm (18.8Mgha^{-1}) and decreased with increase in depth at 10-30cm (6.87Mgha^{-1}) (Figure 4.8). Kakamega South had slightly more organic matter at 0-10cm (10.27Mgha^{-1}) compared to Kakamega North (8.56Mgha^{-1}) at the same depth. This could be attributed to the high species abundance and diversity of trees in north which contributed to high litter fall. The difference was however not statistically significant (F=1.13; p=0.306). At 10-30cm depth, it was also not significant between Kakamega North (3.33Mgha^{-1}) and Kakamega South (3.54Mgha^{-1}) (F=0.184; p=0.675). There was however, a significance difference in the amount of organic matter between 0-10cm and 10-30cm in Kakamega north (F=11.59; p=0.004) and Kakamega South (F=100.25; p=0.000) (Table 4.20). The high moisture in the upper soil layers could also be as a result of high amounts of rainfall experienced in the region which increases soil moistures and especially in the upper soil layers. This promotes high biomass production which provides more residues, and thus more potential food for soil biota (Mollison and Slay, 1991). The difference in vegetation type, soil type and soil organism could also contribute to the difference in the amount of organic matter.

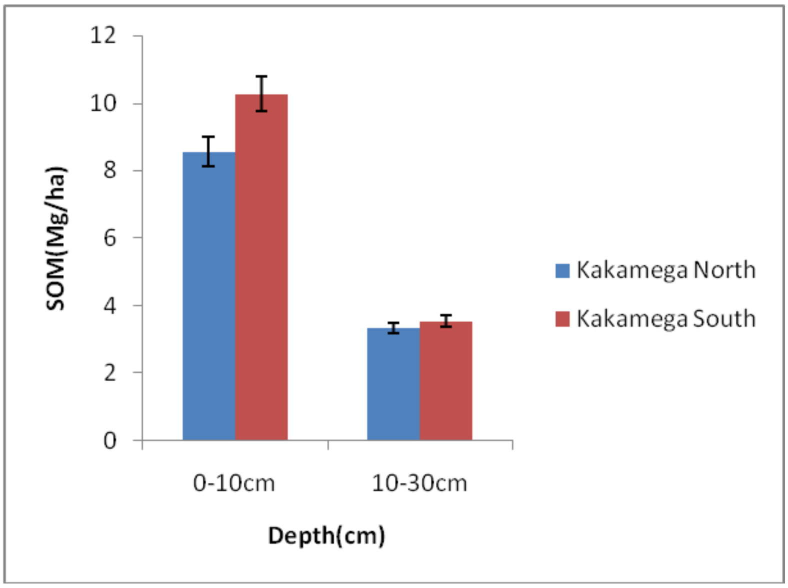

Figure 4.8: Amount of soil organic matter (SOM) in the two study sites at 0-10cm and 10-30cm

Table 4.20: Soil organic matter (SOM) among farms, between sites and depth

	Kakamega North (KKN)		Kakamega South (KKS)	
Depth (cm)	0-10	10-30	0-10	10-30
mean	1.07	0.42	1.284	0.44
SE	0.19	0.05	0.077	0.034
SD	0.52	0.14	0.22	0.096
Cl (95%)	0.44	0.12	0.18	0.08
F	11.59		100.25	
p	0.004		0.000	

SE-standard error; SD- standard deviation; Cl-confident level (95%); significant at ($p<0.05$)

There was a moderate positive significant correlation between soil organic matter (SOM) and soil organic carbon (SOC) at 0-10cm ($r=0.596$; $p=0.119$) and at 10-30cm depth ($r=1$; $p=0.000$). The positive correlation implied that as the amount of soil organic matter increased, it in turn resulted to a corresponding increase in the amount of organic carbon in both sites and with change in soil depths. The correlation between soil organic matter (SOM) and tree abundance was negative and insignificant in homegardens (r= -0.177; p=0.6750) and hedgerows (r= -0.246; p=0.558) in Kakamega North. In Kakamega South, homegardens had (r=-0.407; p=0.317) and hedgerows(r=-0.461; p=0.250). Correlation between tree diversity and soil organic matter varied between the two sites (north and south). In Kakamega North, the correlation was negative and insignificant in homegardens (r=-0.243; p=0.563) and positive and insignificant in hedgerows (r=0.095; p=0.823). In Kakamega South, homegardens had moderately positive correlation (r=0.488; p=0.220) and negative in hedgerows type of agroforestry (r=-0.330; p=0.425) (Table 4.21).

Table 4.21: Pearson correlation between soil organic carbon and diveristy and abundance

Parameters	Agroforestry practice	KKN			KKS		
		n	r	p	n	r	P
SOC and Abundance	Homegardens	8	-0.177	0.675	8	-0.407	0.317
	Hedgerows	8	-0.246	0.558	8	-0.461	0.250
SOC and diversity	Homegardens	8	-0.243	0.563	8	0.488	0.220
	Hedgerows	8	0.095	0.823	8	-0.330	0.425

r-Pearson correlation coefficient; KKN-Kakamega North, KKS-Kakamega South

4.3.6 Total Nitrogen (TN)

The Total Nitrogen (TN) determined in the study area was 46.69MgN ha^{-1}. Kakamega North (KKN) had 16.69MgN ha^{-1} while Kakamega South had 27.37MgN ha^{-1}. Farm KKSF4 had the highest nitrogen stocks (4.2MgN ha^{-1}) while KKSF1 had the least nitrogen stocks (1.6MgN ha^{-1}). There was a decrease in the amount of nitrogen stocks with soil depth in both sites. In Kakamega North, nitrogen stocks decreased from 13.34±0.79MgN ha^{-1}(0-10cm) to 5.98±0.04MgN ha^{-1}(10-30cm). In Kakamega South, nitrogen stocks decreased from 16.95±0.16MgN ha^{-1}(0-10cm) to 10.42±0.156MgN ha^{-1}(10-30cm). There was a significance difference in the amount of nitrogen stocks among farms in Kakamega North (F=4.78; p=0.021) and in Kakamega South (F=-4.253; p=0.030). There was a significant difference in the amount of nitrogen stocks with soil depths between the two sites at 0-10cm (F=6.4; p=0.024) and 10-30cm (F=11.08; p=0.005). Nitrogen stocks also differed between 0-10cm and 10-30cm depth in Kakamega North (KKN) (F=105.66; p=0.0001) and Kakamega South (F=12.92; p=0.003) (Table 4.22).

Table 4.22: Total Nitrogen (Mg Nha-1) between sites, depth and among farms

Sites	**Kakamega North (KKN)**		**Kakamega South (KKS)**	
Depth(cm)	**0-10**	**10-30**	**0-10**	**10-30**
mean	1.67	0.74	2.12	1.30
SE	0.79	0.04	0.16	0.16
SD	0.22	0.12	0.45	0.46
CV (%)	13.17	16.22	22.23	35.38
Cl	0.19	0.38	0.10	0.38
F	105.66		12.92	
p	0.000		0.003	
	Farms(North)		Farms(South)	
F	4.78		-4.253	
p	0.021		0.030	
	0-10cm(N and S)		10-30cm(N and S)	
F	6.4		11.08	
p	0.024		0.005	

SE-standard error; SD-standard deviation; CV-coefficient of variation (%); Cl-confidence level (95%); N-North; S-south; significant at (p<0.05).

Total nitrogen stocks were higher in the Kakamega South than in the Kakamega North in the study area. The levels however decreased with increase in depth in both sites. High levels of nitrogen in southen part could be attributed to more nitrogen fixing trees compared to the northern part.According to Kassa *et al*., (2017), the nitrogen fixing trees like the Gruvillea *robusta*play a significantrole in supplying organic matter, organic carbon and nitrogen to the soil.The inherent ability to fix the atmospheric nitrogen and the association with symbiotic bacteria and mycorrhizal fungi lead to organic carbon and nitrogen accumulation in the biomass of trees. These findings of this study are consistent with those of Abegaz and Adugna, (2015) and

Nsabimana *et al*., (2008). In addition, it could be as a result of agricultural activities such as mixed cropping in the southern part that led to addition of nitrogen in the soils. Leaf litter fall is also a major contributor of nitrogen and organic carbon in the top soils as compared to the sub soils.As nitrogen stocks decreased with depth, clay increased with depth in both the study sites. According to Cote *et al*., (2000), the net nitrogen mineralization decreases when the clay amount increases in the soil. McLauchlan, (2006) explains that when clay amounts increase in soil, aggregate amounts increase dramatically and the potential net nitrogen mineralization decreases and thereby decreasing the amount of nitrogen in the soil. Abera and Belachew, (2011) reported a decreasing trend oftotal nitrogen to be due to decline in humus with depth.

4.3.6.1 Soil organic carbon (SOC) and Total Nitrogen (TN) ratio

The ratio of Soil organic carbon to Total Nitrogen (SOC: TN) at 0-10cm depth for Kakamega North and Kakamega South was 0.36±0.56 and 0.36±0.02 respectively. For 10-30cm depth, the ratio was 0.33±0.04 and 0.23±0.05 for Kakamega North and Kakamega South respectively. There was no significant difference in the ratio between the two sites at 0-10 cm ($F=0.0001$; $p=0.992$) and 10-30cm ($F=2.66$; $p=0.125$). In comparing the ratio between the two depths in each site, Kakamega North did not show significant differences in the ratio at 0-10 cm and 10-30 cm ($F=0.280$; $p=0.605$). Kakamega South exhibited a significant difference at 0-10 cm and 10-30 cm ($F=6.18$; $p=0.026$). There was a strong positive insignificant correlation between soil organic carbon (SOC) and total nitrogen (TN) in Kakamega North ($r=0.638$; $p=0.089$) and in Kakamega south at 0-10 cm ($r=606$; $p=0.111$). At 10-30cm depth, there was a weak positive correlation but not significant in Kakamega North ($r=0.147$; $p=0.728$) and in Kakamega South ($r=0.035$; $p=0.935$) (Table 4.23).

Table 4.23: Soil Organic carbon (SOC) and total Nitrogen (TN) between sites and depth (cm) and correlation between soil organic carbon (SOC) and total Nitrogen (NT) between sites and depth (cm)

	Kakamega North (KKN)		**Kakamega South (KKS)**	
Depth(cm)	**0-10**	**10-30**	**0-10**	**10-30**
mean	0.36	0.33	0.36	0.23
SE	0.56	0.04	0.02	0.05
SD	0.16	0.104	0.07	0.133
CV (%)	44.44	31.52	19.44	57.83
Cl (95%)	0.13	0.08	0.06	0.111
F	0.280		6.18	
p	0.605		0.026	
r	0.638	0.147	0.606	0.035
p	0.089	0.728	0.111	0..935

SE-standard error of the means; SD-Standard deviation; CV-coefficient of variation (%); Cl-confidence level (95%); r-Pearson coefficient correlation; significant at ($p<0.05$).

Carbon stocks had a strong relationship with nitrogen stocks. Both carbon stocks and nitrogen stocks were higher in the 0-10cm depth. This is an indication of their strong relationship (Table 4.20). The high concentration of these parameters could be attributed mostly to presence of leguminous trees like *Grevillea robusta*, *Albizia gummifera* which play a significant role in supplying organic carbon, organic matter and nitrogen in the soils (Kassa *et al*., 2017). SOC: TN ratios serve as an indicator of stability and examine the effects of abiotic factors such as climate, temperature and rainfall as well as texture on SOC stocks and accumulation. High values for these parameters are also due to high precipitation as alluded to by Callesen *et al*., (2007) and Sakin, (2012). This is in agreement with high precipitation experienced in these areas due to the rainforest that neighbours the study area.

The high nitrogen values and carbon in the surface soils is attributed to cultivation/farming techniques which add these elements into the soil in addition to humus and leaf litter fall (Yimer, Ledin and Abdelkadir, 2007).In general, the surface layer (0-10cm) stored more nitrogen than did the subsurface layer (10-30cm), probably because, according to White (2006), microorganisms and organic residues are more plentiful in the surface layer than they are in the lower strata. Furthermore, up to 95% of the nitrogen in the soil is found in organic forms which are mostly found in the upper soil layers. The C: N ratios found in this study are similar to those found by Batjes, (1996) and Batjes and Dijkshoorn, (1999) among others.

4.4 Simulate biomass and soil carbon stocks in agroforestry practises in Western Kenya in the next 50 years using CO2FIX model.

4.4.1 Biomass carbon sequestration

The total simulated biomass carbon in the study area for 50 years was 916.8±78.89Mg C ha^{-1}. Northern part had higher biomass (477.2± 44.2 Mg C ha^{-1}) compared to southern part (439.6± 33.7 Mg C ha^{-1}). This is due to higher tree abundance and diversity in the northern part as compared to the southern part. Homegardens had higher simulated biomass as compared to hedgerow in the two study sites (Table 4.24). The biomass was distributed between indigenous and exotic trees that acted as cohorts in the CO2FIX model. Indigenous trees recorded higher biomass than exotic trees because of their high stem density. In both the study sites, the biomass carbon stocks largely declined at age of 25 years due to thinning-harvest of trees which greatly reduced biomass.

Table 4.24: Mean simulated biomass compartments C stocks (+SD, Mg C ha^{-1})

Niche	Homegardens		Hedgerows	
	Indigenous	**Exotic**	**Indigenous**	**Exotic**
Kakamega North	126.7±43.9	120.3±38.3	119.6±39.12	110.63±38.5
Kakamega South	117.4±32.2	109.6±41.1	`106.8±31.5	105.8±33.5

4.4.2 Soil Carbon Sequestration

Average simulated soil organic carbon (SOC) stocks from litters and decomposition fractions are shown in table 4.25. The net simulated carbon was almost similar in both the study sites and in both cohorts. The average simulated carbon stocks for homegardens were slightly higher than that of hedgerows. The difference was however not statistically significant (F=11.21; p=0.32). Among the decomposable fractions, humus 1 and humus 2 contributed to the highest carbon inputs in percentage. This was followed by coarse woody litter holocellulose. Long-term simulated total biomass carbon stocks in the study area were (rotation age of 50 years) 437.1±12.89Mg C ha^{-1}. They are higher than those reported worldwide 12–228 Mg C ha^{-1} (Albrecht and Kandji, 2003) and that reported in Ethiopia (Negash and Kanninen, 2015).

Kakamega North recorded the highest simulated biomass carbon compared to Kakamega South. This was due to higher tree species abundance and diversity in north as compared to south. This indicates that trees play important role in carbon sequestration within agroforestry systems. The amount of carbon stored in the biomass depends on the tree density (number of trees ha^{-1}), species composition and the rotation age, tree species selection and management intensity, and site condition (soil, topography, rainfall), among others, (Kaonga and Bayliss-Smith, 2012; Mbow *et al*., 2014).

Average simulated SOC stocks in the agroforestry systems (916.11±89.89 Mg C ha^{-1}) were higher than those reported for other agroforestry systems in other study areas (Oelbermann *et al*., 2007; Dossa *et al*., 2008; Negash and Kanninen, 2015). The higher soil carbon stocks in the agroforestry systems can be attributed to the higher of proportion trees and associated coarse litter and humus inputs. The total carbon stocks declined, and then levelled off afterwards after 10 years. This is due to high soil respiration at the early period of plant recruitment in the agroforestry systems. This was consistent with the land use history of the study area where the three agroforestry systems established on deforested land, and intensification of the agricultural land uses centuries ago (Negash and Achalu, 2008). The soil carbon stock also increased with increased biomass carbon stock in the homegardens and hedgerow cohorts. This suggests that any biomass removal activities like pruning and thinning should be encouraged after 10years. The ratio of SOC to biomass in agroforestry systems depends on type of agroforestry practice, land-use history, the composition of tree species and rotation age, elevation, climate, soil type and silvicultural management (Soto-Pinto *et al*., 2010).

Table 4.25: Mean simulated soil carbon stock inputs (±SD Mg C ha $^{-1}$) in the two agroforestry practices

Soil carbon inputs	North				South			
	Homegardens		Hedgerows		Homegardens		Hedgerows	
	Indigenous	Exotic	Indigenous	Exotic	Indigenous	Exotic	Indigenous	Exotic
Non-woody litter	7.5±2.8	7.5±4.3	7.5±2.8	7.3±4.3	7.5±2.8	7.2±2.5	7.1±2.1	7.9±3.4
Fine woody litter	6.4±3.2	6.4±3.1	6.4±3.2	7.4±3.0	7.4±2.1	5.9±3.9	7.4±3.8	6. 4±3.5
Coarse woody litter	13.2±15.6	19.4±11.54	13.2±15.6	17.4±11.0	11.2±2.1	20.4±10.6	15.2±9.6	19.4±5.9
Soluble compound	3.1±1.2	3.1±2.9	3.1±1.2	3.1±2.9	3.4±1.2	3.4±2.0	3.6±1.8	3.9±2.4
Holocellulose	11.0±4.5	10.4±4.0	15.0±4.5	9.4±3.7	12.0±3.3	11.0±4.2	13.0±4.3	8.4±3.1
Ligninin	7.9±3.1	7.5± 5.2	7.9±3.1	8.5± 2.1	7.2±2.9	7.1± 2.0	6.9±3.8	9.5± 2.4
Humus 1	23.1±9.1	20.1±5.2	22.1±9.1	20.9±3.5	22.5±6.6	21.1±3.3	23.1±9.8	21.9±3.0
Humus 2	28.2±1.7	23.2±6.1	24.2±1.7	21.2±6.1	27.2±1.1	20.9±2.1	22.2±1.6	23.2±6.5
Total	100.4±36.2	97.6±22.1	99.4±36.2	94.6±22.1	98.4±36.2	97.0±19.2	98.4±31.6	99.1±19.1

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the conclusions and recommendations for further research in the related study.

5.2 Conclusions

1. Shannon wiener diversity showed that species diversity was higher in Kakamega North (KKN) (H'=1.92±0.13) compared to Kakamega south (KKS) (H'=1.71±0.16).
2. Agroforestry systems surrounding Kakamega Forest (Homegardens and hedgerow) stocked on average 13.96±1.23Mg/ha aboveground biomass (6.33±0.57Mg/ha of carbon); much of this biomass was held in homegardens about 7.78±0.64 Mg/ha while hedgerows stock about 5.97±0.46Mg/ha.
3. Total soil organic carbon estimated in the study area was 14.91$MgCha^{-1}$With Kakamega south recording higher soc than Kakamega north. The amount however decreased with depth. The variation was occasioned by a number of factors like tree species density, Ph, soil organic matter, texture, bulk density and porosity.
4. The simulated biomass carbon sequestration for the next 50 years was 916.8±78.89$MgCha^{-1}$. The northern part of the study site had more of the biomass as compared to the southern part. This was attributed to higher tree abundance and diversity which if maintained through replacing the cut ones and maintaining farm sizes.

5.3 Recommendations

1. Tree diversity on farmlands should be emphasized than monoculture type of tree planting as this enhances more carbon stocks on farms.
2. There is need to recommend and advocate for planting of indigenous trees as they store biomass for longer period of time in addition to championing sustainable land management practices which help to increase the potential of soils to store carbon.
3. There is need to investigate how tree harvesting is likely to alter c sequestration potential of trees.

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APPENDICES

Appendix 1: Data Sheet

<table>
<tr><td colspan="2">Date:</td><td colspan="2">Start time:</td><td>End time:</td></tr>
<tr><td colspan="5">Crew:</td></tr>
<tr><td colspan="3">Plot ID:</td><td colspan="2">Plot area (m^2):</td></tr>
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Appendix 2: Letter for Providing Climatic data for the Project

MINISTRY OF ENVIRONMENT, NATURAL RESOURCES AND REGIONAL DEVELOPMENT AUTHORITIES

State Department of Natural Resources

Telegrams: "NATURE", Nairobi
Telephone: Nairobi 2730808-Ext. 1276
Fax : 0254-20- 2734722
Email : sleek@environment.go.ke
Website : www.sleek.environment.go.ke

NHIF BUILDING, 13thfloor
RAGATI ROAD
P.O. BOX 30126-00100
NAIROBI

Ref: DENR/EMC/47/12/01

Date: 14th November, 2016

The Director
Kenya Meteorological Department
P. O. Box 30259 – 00100
Nairobi

RE: REQUEST TO PROVIDE RESEARCH DATA TO SLEEK SCHOLARSHIP PROGRAM AWARDEE

The System for Land-based Emissions Estimation in Kenya (SLEEK) is a program being delivered by the Government of Kenya through the Ministry of Environment, Natural Resources to develop an emissions estimation system.

The program has provided scholarships to selected students from various government institutions to pursue Masters and PhD studies in Kenyan public universities up to 2018 to build their scientific capacity in areas relevant to the program. The scholarship Program will also support the sustainability of the SLEEK program by ensuring the relevant capacity to run and maintain it is available in Kenya.

As a partial requirement for their studies, the students are required to carry out study research and would therefore need specific historical datasets, specific equipment and laboratory access for data collection and analysis respectively.

KMD is a partner institution within the SLEEK program. Therefore we request for research support in form of access to available datasets, equipment and access to laboratories as needed by scholarship recipients.

I wish to confirm that **Mr. Humphrey Agevi** is one of the awardees sponsored under the System for Land based emission estimation in Kenya (SLLEK) scholarship program. He is a **PhD student at Moi University pursuing PhD in Environmental Biology** and currently at the data collection and analysis stage of his study.

Mr. Agevi has expressed the need to access the following **climatic data to facilitate his research (rainfall, temperature, humidity and sunshine) for Kakamega and areas around Nandi North and South Forests form 1985 to current.**

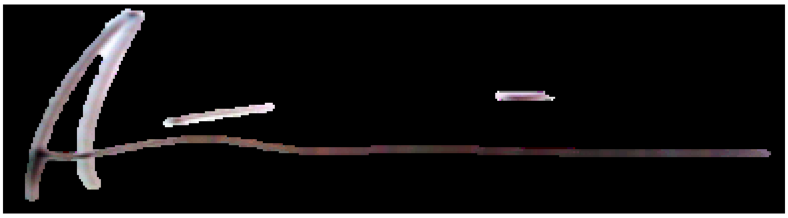
This letter is to kindly request that KMD assist the student to access the said data. We look forward to continued collaboration within the SLEEK program.

Ali Mwanzei
Ag. PROGRAMME COORDINATOR, SLEEK

Appendix 3: Letter of offer for the SLEEK Scholarship

1271 Avenue of the Americas, 41st Floor• New York, NY 10020, USA • Tel: +1 (212) 348-8882
• Fax: +1 (917) 720-0275

Humprey Agevi,
Masinde Muliro University of Science and Technology (MMUST),
P.O. Box 190-50100,
Kakamega.
Dear Mr. Agevi,
RE: CONDITIONAL OFFER FOR THE SLEEK SCHOLARSHIP AWARD
Following you application for the SLEEK Scholarship Award Program, I am pleased to inform you that the SLEEK Scholarship Selection Committee has considered you for a PhD partial scholarship.
This scholarship will be administered from **University of Nairobi**.
Please ensure that you liaise with the underlisted SLEEK contact person at the university:
Dr. Onwonga
Mobile number: 0725828254
Email: richard.onwonga@uonbi.co.ke
Kindly forward your admission letter from Moi University, a letter from your university Head of Department stating the status of payment (remaining fee balance) and a letter fromyour employer stating full time release for the period of the scholarship; on or before **31stJuly 2015** to the said contact person for onward transmission to CCI for scholarshipprocessing.Further details on the Scholarship award and conditions thereof will be communicated to you
by Clinton Foundation.
Kind regards,



Jackson Kimani
Regional Director