ON-FARM TREE SPECIES DIVERSITY, CARBON STOCKS AND SOIL PROPERTIES AS INFLUENCED BY SELECTED *Eucalyptus* spp IN KAKAMEGA-NANDI FOREST ECOSYSTEM

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DECLARATION

This thesis is my original work and has not been presented elsewhere for a degree or any other award.

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SUPERVISORS' APPROVAL

We, the undersigned certify that we have read and hereby recommend for acceptance of Masinde Muliro University of Science and Technology this thesis titled 'On-farm tree species diversity, carbon stocks and soil properties as influenced by selected *Eucalyptus* species in Kakamega-Nandi Forest Ecosystem**'.**

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DEDICATION

To my parents, Mr. Joseph Muigai and Mrs. Ann Gathoni, sister Tabitha, brother Simon and my sons Jaden and Wayne.

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ABSTRACT

On-farm growing of trees has significantly contributed to easing pressure from natural forests in addition to providing extra income to forest-adjoining farming households. There are however concerns that *Eucalyptus* species is becoming the dominant trees in this landscape and may have adverse effects on the environment. This study sought to determine the effects *Eucalyptus* species on the on-farm woody species diversity, carbon stocks and soil properties on farmlands located in the margins of the Kakamega - Nandi Forest Ecosystem. The study targeted farmlands located 0 – 3 km from the forest boundary. It employed a nested experimental design in which the study area was divided into three sentinel blocks. Each block had three sub-blocks, namely: Shamiloli, Mukulusu and Lukala in Kakamega; Makuchi, Makhanga and Blukhombe in Vihiga; and Cheboite, Burende and Mukoyuro in South Nandi. Each sub-block comprised three types of trees stands namely: *Eucalyptus* dominated tree stands, mixed tree stands comprising of *Eucalyptus*, indigenous and exotic trees, and pure indigenous tree stands. The study was carried out along three line transects that traversed the three types of trees stands in each block from the forest edge to farmlands. Stratified systematic sampling was used to assess the extent to which the observed variation in the concentration of *Eucalyptus* trees affected the three variables under investigation (tree species diversity, carbon stocks and soil properties). A sample plot comprised a main plot of 20m by 10m plot for measuring trees with a diameter at breast height (DBH) $\geq$ 10 cm, a sub-plot of 10m by 5m nested within the main plot for measuring saplings and shrubs of DBH less than 10cm. Data was collected on tree species type, stem DBH for trees, tree height, counts of trees, saplings and shrubs. Composite soil samples were collected within the main plot for analysis of soil organic carbon and other physico-chemical properties. The data was subjected to both exploratory and inferential statistical analysis using R Gui Version 4.2.1. Woody species diversity, carbon stocks, and soil properties were subjected to analysis of variance (ANOVA) at 5% significance level to assess their variation with change in the concentration of *Eucalyptus* trees on-farm. Post hoc tests were carried out to determine the source of variation among means using the Ryan-Einot-Gabriel-Welsch Multiple Range Test (REGWQ) at 5% significance level. A total of (N=51) species representing 26 families were recorded. Of these species, (n=8) were encountered in the *Eucalyptus* dominated tree stands, (n=29) in mixed tree species stands and (n=32) in indigenous tree species stands. Among the woody species, mature trees constituted 48.6% while saplings and shrubs comprised 51.4%. Myrtaceae family constituted 50.3% of the woody trees followed by moraceae family with 7.5%. Woody species richness, evenness and diversity were significantly higher in mixed tree stands and indigenous tree stands than in *Eucalyptus* dominated tree stands ($p< 0.05$). Trees in the *Eucalyptus* dominated stands and mixed stands had significantly smaller stem diameter, basal area and above ground biomass than in the adjacent indigenous trees stand ($p< 0.05$). The highest amount of total carbon was observed in the indigenous trees stand. The percentage soil organic carbon in the *Eucalyptus* dominated tree stands and mixed tree stands was significantly lower than in the adjacent indigenous trees stands ($p< 0.05$). The bulk density in the *Eucalyptus* dominated tree stands and mixed tree stands was significantly higher than in the adjacent indigenous trees stands ($p< 0.05$). Phosphorus, Nitrogen and potassium did not vary significantly within the three tree stands ($p> 0.05$). The results suggest that a higher diversity of indigenous trees enhances aboveground carbon stocks and promotes ecosystem conservation.

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LIST OF ABBREVIATIONS AND ACRONYMS

AGB	Above ground biomass
ANOVA	Analysis of variance
BGB	Below ground biomass
DBH	Diameter at breast height
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
IVI	Important value index
KALRO	Kenya Agricultural and Livestock Research Organization
REDD+	Reducing emissions from deforestation and forest degradation and foster conservation, sustainable management of forests, and enhancement of forest carbon stocks
REDD	Reducing emissions from deforestation and forest degradation
SLMP	Sustainable land management programme
SOC	Soil organic carbon
TB	Total biomass
TC	Total carbon
t Cha^{-1}	Tonnes of carbon per hectare
UNFCCC	United Nations Framework Convention on Climate Change

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CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Kenya has witnessed a significant increase in on-farm tree cover over the past decade (Schmitt *et al.,* 2019). More agricultural land has come under either agroforestry or tree plantations during this period than ever before (Agevi etal., 2017; Keya and Rubaihayo, 2013). Whereas farmers have perceived tree planting as an opportunity to cash in on the national wood supply deficit, the situation has emerged as a key enabler of economic growth in the power transmission, construction, pulp and paper, and fuel wood in the national economic sectors (Cheboiwo *et al.,* 2018). There are however emerging concerns that most of the trees that are increasingly occupying the agricultural landscape are exotic species, such as *Eucalyptus*, which are feared to have some adverse effects on the environment, particularly in areas such as Kakamega, Vihiga and Nandi counties ((Agevi *et al.*, 2019; Kuyah *et al.*, 2013).

Although allelopathic effects of *Eucalyptus* trees on other plant species have been demonstrated (Richardson and Rejmánek, 2011), their effects on woody species diversity, below and above ground carbon stocks and soil chemical and physical properties in farmlands are largely unknown. Ordinarily, exotic trees tend to grow faster than indigenous tree species on-farm (Nath *et al.*, 2016). These species' rapid growth rate is expected to result in a higher rate of aboveground carbon sequestration. This is likely to offer an opportunity for farmers to benefit from carbon offset payments for their tree investments within the interim period (Joshi and Palanisami, 2011). However, studies by Laliberte *et al.,* (2010) and (Otuoma *et al.,* 2016) show that native tree species may grow at a slower pace, however, they sequester carbon at a much higher rate than exotic species. These studies suggest that the expansion of *Eucalyptus* trees in farmlands bordering the Kakamega-Nandi Forest Ecosystem could be causing a reduction in carbon stocks. The situation can only be ascertained with empirical data that compare aboveground and below ground carbon stocks of both *Eucalyptus* and native tree species on-farm.

Apart from the likely reduction in carbon stocks due to increase in the concentration of *Eucalyptus* trees in the farming landscape, its potential effects on woody species diversity and soil chemical and physical properties are also unknown (Lorenz and Lal, 2018; Nnenna *et al.*, 2020; Wang *et al.*, 2010). These likely adverse effects of *Eucalyptus* trees are attributable to its allelopathic characteristics, which may lower plant species richness and affect soil organic matter accumulation (Wang *et al.*, 2010). A clear understanding of soil chemical and physical properties, woody species richness and carbon accumulation rates under different native and exotic tree species, including *Eucalyptus* trees, is important to inform the balance between the expansion of eucalypts and environmental safeguards (Madalcho *et al.*, 2019).

The current study sought to compare the variety of woody tree species, above and belowground carbon stocks, and soil chemical and physical properties in farmlands under three different treatments, namely: *Eucalyptus* dominated tree stands (quadrats with *Eucalyptus* trees occupying more than 50%), mixed tree species stands comprising indigenous trees, *Eucalyptus* and other exotic tree species (quadrats with *Eucalyptus* trees occupying less than 50%) and pure indigenous trees stands (control) in the margins of the Kakamega-Nandi Forest Ecosystem, in western Kenya (Muigai *et al*., 2023). The findings of the study are expected to inform agroforestry investment decisions by tree growing households in regard to striking a balance between economic returns and ecological benefits.

1.2 Statement of the problem

Trees growing on-farm have received increased attention in Kenya over the past decade as they significantly contribute to household income and climate change mitigation (De Giusti *et al.*, 2019). Some of the tree species grown however, are exotic to Kenya and are feared to have potential adverse impacts on the environment (Nin-Pratt *et al.,* 2017). One such species is *Eucalyptus* which was introduced in Kenya to drain wetlands and riparian habitats during the construction of the Kenya-Uganda Railway (Wua *et al.*, 2013). Over the years, *Eucalyptus* trees have spread throughout the country and are today the flagship species in some counties (Carnegie, 2015). For instance, it has become the main tree species in farmlands that border the Kakamega-Nandi Forest Ecosystem. Although it has contributed significantly in easing pressure on natural forest ecosystems, there are concerns that it may have had adverse environmental impacts on woody species diversity, carbon stocks and soil properties. Lack of empirical data on its direct impacts has hampered efforts to mitigate against any potential adverse effects. This study provides insight into the long-term effects of *Eucalyptus* species to numerous regions of the country, and furthermore presents opportunities to identify the necessary environmental and social safeguards at a fairly early stage.

1.3 Justification

In an endeavor to attain at least 10% forest cover in Kenya, policy and legal instruments are increasingly recognizing the vital role that trees play in the agricultural landscapes (Ongugo *et al.*, 2017). The Constitution of Kenya 2010 provides for a minimum of 10% tree cover for the country (Kenya, 2013). The 2009 agricultural regulations stipulate that trees must be planted on at least 10% of each acreage (Pocketbook, 2015). Thus, the focus has shifted from whether to plant trees or not on-farm, to how to integrate them with crops within the agricultural landscape. A good choice of tree species offers the opportunity to realize economic gain from agroforestry investments, while providing the much-needed ecosystem services covered under adaptation and mitigation (Egan and Price, 2017). Currently, *Eucalyptus* is the main on-farm tree species being planted in the margins of Kakamega-Nandi Forest Ecosystem (Agevi, 2020; Agevi *et al.*, 2019). Recommendations have been made to substitute these species with native tree species(Kawawa *et al.*, 2016). The findings of the current study are projected to offer insight into the choice of tree species to provide a balance between economic returns and ecosystem benefits as farmer's endeavor to place at least 10% of their farms under trees within agricultural landscapes in the Kakamega-Nandi Forest Ecosystem (Kenya, 2013). The findings contribute to the achievement of the Climate Change Act, 2016 on conservation of carbon stocks in different carbon pools. The findings contribute to attainment of SDG 13 on climate Action in combating climate change. The study contributes to the achievement of the county Climate Change Act: Kakamega, Nandi and Vihiga.

1.4 Objectives

1.4.1 General objective

To determine on-farm woody species diversity, carbon stocks and selected soil properties as influenced by *Eucalyptus* species in the margins of the Kakamega-Nandi Forest Ecosystem

1.4.2 Specific objectives

1. To determine the effect of on-farm *Eucalyptus* species on woody species diversity.
2. To determine the effect of on farm *Eucalyptus* species on above and below ground carbon stocks.
3. To determine the effect of on farm *Eucalyptus* species on selected soil chemical and physical properties.

1.5 Research Hypotheses

H_{o1} *Eucalyptus* species has no effect on on-farm woody species diversity.

H_{o2} The on-farm *Eucalyptus* species has no effect on above and below ground carbon stocks on-farm.

H_{o3} There is no effect on on-farm *Eucalyptus* species on selected soil chemical and physical properties.

1.6 Significance of the study

Most tree species diversity and carbon sequestration studies have concentrated on natural forest ecosystems. Farmlands around the forest margin have received very little attention in this area. As more farms come under agroforestry investments targeting exotic tree species, it is prudent to look at the ecological impacts of such investments.

By comparing the woody species diversity, below and above ground carbon carbon stocks and soil properties under exotic species, mixed, and indigenous tree species, this study contributes significantly to generating knowledge necessary to inform agroforestry interventions regarding balancing between economic returns and environmental safeguards for *Eucalyptus* trees and for any future exotic tree species introductions in farming systems in Kenya.

CHAPTER TWO

LITERATURE REVIEW

2.1 Abundance and diversity of tree species on-farms

There are issues with the low tree species variety in agricultural environments in Kenya (Kindt *et al.*, 2006). The recommended minimum global standard for forest cover is 10% (Pocketbook, 2015). The most detailed analysis of forest cover, “wall-to-wall”, performed in 2013 found that in 2010, 4.18 M Ha, or 6.99% of the Kenyas’ total land area, represented the national forest cover. Based on the national projection from the forest cover data from 2010, the predicted forest cover for 2015 was 7.2%. This is confirmed by the report of Global Forest Resources Assessment in 2015 (Pocketbook, 2015).

The Kenyan government has come up with interventions that will help attain the targeted 10% by the year 2022 as per the Constitutional target using the national land area specified in Article 69 (1) (b) (Kenya, 2013). This comes after efforts to domesticate native tree species as well as other valuable tree crops which may provide more significant co-benefits and enhanced ecosystem services in order to diversify tree cover on agriculture (Klerkx *et al.*, 2013; Rosenstock *et al.*, 2014). Planting of appropriate tree species and fruit tree species such as avocado, mangoes and macadamia on agricultural land using appropriate technologies will help increase the tree cover. According to analysis of land-use change between 1990 and 2015, Kenya lost 311,000 Ha of forestland (Pocketbook, 2015).

Agricultural fields have seen some gains in tree cover while forests have seen a decline (Zomer *et al.*, 2016). Agricultural fields, particularly those in the tropics, are home to a variety of woody trees (Guyassa and Raj, 2013). The forest cover loss is majorly caused by the construction of communities, farms, and other infrastructure (Deribew and Dalacho, 2019). The increase of croplands at the expense of forestland is also explained by the growing reliance on rain-fed agriculture hence the need to promote on farm tree diversity (Nyssen *et al.*, 2009). Tree diversity can be increased using planting material acquired from off-farm or on-farm tree plant sales outlet (Oloo *et al.*, 2013). Farmer-planted trees also occasionally rejuvenate through soil seed banks or through seedling dispersal processes.

The existence of trees on these areas can be attributed to one of three processes: the preservation of trees that were there before farms were built and acceptance after farms were constructed, either by natural forest regeneration or through farmers' deliberate planting of particular trees in chosen locations (Kindt *et al.*, 2006). Most farmers prefer, however, the fast-growing tree species because they have high economic value. The type of trees to plant will depend on the farm's size and how the farmer plans to use them (Agevi *et al.*, 2019; Agevi *et al.*, 2017). In addition to optimizing Soil Organic Carbon (SOC), these trees offer ecosystem services include reducing climate change, enhancing soil fertility, providing habitat for wildlife, and supporting crop production (Lal, 2008). Farmland trees have higher ability to store carbon while also enhancing rural populations' quality of life (Gebrewahid and Meressa, 2020).

Agricultural fields' diversity of trees and shrubs improves ecological stability by protecting the environment and supplying woody and non-woody products (Abebe *et al.*, 2013). The diversity of tree species and density are influenced by a farm's distance from major roadways (Abebe *et al.*, 2013). Farms close to major roadways typically have fewer tree species because of the highways' improved market access for farmers selling wood products by the roadside and then transport them to merchants and customers in large towns (Arasa-Gisbert *et al.,* 2018). Therefore, closeness to roads has provided wood goods with better market access than actual nearness to local marketplaces (Abebe *et al.,* 2013).

2.2 Tree biomass estimation on farms

Biomass quantification of trees on-farms is getting more attention (Kuyah & Rosenstock, 2015). One can determine a species' capacity to sequester carbon by calculating the rate at which biomass is produced (England *et al.*, 2020). This can also assist in determining a species' production potential or suitability for a particular use, such as the manufacture of charcoal, timber, or firewood (Kuyah *et al.*, 2012). The availability of methods to forecast yield can be used to evaluate the accumulation or loss of biomass over time.

The best method for estimation of tree biomass is the application of allometric equations because it doesn't do any damage. Studies by (Kuyah *et al.,* 2016) observed that at tree breast height diameter (DBH) is substantially linked with its aboveground biomass, accounting for 95% of the difference in aboveground biomass. The studies suggest that DBH is a reliable predictor for farm trees, especially given that its allometric equations are easier to use, less expensive, and more accurate at predicting biomass in agricultural lands. The derivation of equations is done by measuring and fitting tree variables like height, DBH, and crown area, into a suitable allometric equation (Chave *et al.*, 2005). The measurements assist in improving the precision of DBH-based biomass equations. Studies conducted by (Rosenstock *et al.*, 2014) in western Kenya region revealed that adding height, wood density or crown area as tree variables to the biomass equation only slightly altered estimates less than 1.2 Mg, or 1.3% of total biomass, was obtained when the DBH alone was used in the equation. As pointed out by (Kuyah *et al.*, 2016), models published frequently misjudge biomass as a sign that the DBH range must be taken into account when using biomass models. Larger mistakes will be produced when models are applied outside of their DBH range, especially for larger trees. Since the uncertainty in the resulting biomass relies on a tree's size and the species of each individual tree, information on error breakdown is crucial (Kuyah and Rosenstock, 2015).

2.3 Soil organic carbon

As the greatest terrestrial carbon store, soil organic carbon (SOC) also significantly contributes to the global carbon cycle. 3.5% of the carbon stocks on Earth are found in soils, as compared to 1.7% of the atmosphere, 1% is in the biota, 8.9% is in the fossil fuels and 84.9% is in the ocean (Lal, 2008). Depending on how the land is used and managed, soil is either a source (N_2O, CH_4, and CO_2) or a sink (CH_4 and CO_2) of the greenhouse gases (Lal, 1999). Trees will sequester far more carbon if they are planted on degraded or otherwise tree-less land as opposed to replacing natural main or secondary forests, which collect relatively less carbon (Montagnini and Nair, 2004). Forests provide invaluable ecosystem goods and services that provide livelihood support to forest adjacent communities (FAC) (Rönnbäck *et al.*, 2007). Converting forests to agricultural lands can reduce SOC by about 75% (Lal, 2008); additionally, soil fertility falls and land degradation speeds up as SOC stock levels drop. Such SOC losses threaten ecosystem services and may have adverse effects on livelihoods. Increase in human population around forests has, however, exacerbated the pressure on these precious resources. This in turn has resulted in a continuous decline in forest cover hence affecting forests ecosystem health. The prevailing pattern of tropical forest loss in decreasing SOC reserves are linked to deforestation and degradation (Green and Sambrook, 2018). Processes resulting into the sequestration of SOC include humification (formation of humus from biomass), aggregation (formation of organic mineral complexes as secondary particles), biomass is moved into the subsoil by deep roots, followed by the leaching of soil inorganic carbon as bicarbonates into groundwater. (Nath *et al.*, 2015). Attention has however been drawn to trees on farmlands and their contribution to enhancing tree diversity and soil carbon stocks.

Essential nutrients for vegetation development and growth are found in soil, which may contribute to some of the soil creation changes and alteration (Ehrenfeld, 2005; Kardol *et al.,* 2006). Nearly half of the soil organic carbon is stored in the top 30 cm of soil, and mature trees store up to three times as much carbon above ground. The dispersal and connections between on-farm tree diversity and SOC, however, are poorly understood (Toriyama *et al.,* 2015). The complexity of interactions between climatic factors (for instance moisture regime and temperature), edaphic factors (e.g. soil drainage, texture, and parent materials), and management practices applied to the tree species growing in the specific site and soils can affect the quantity and quality of SOC stocks (Nath *et al.*, 2015). Due to altered decomposition conditions, increased carbon input into the soil, or both, variations in land cover and use may result in loss of soil carbon (Gottschalk *et al.*, 2010). Forest ecosystems' ability to store carbon over the long term may be improved by increasing rotation lengths and decreasing thinning severity. To mitigate CO_2 emissions over the long term and thus lessen climate change impacts, a combination of carbon sequestration and bioenergy will be vital when considering the climate change effects. Understanding the potential of these species in carbon sequestration is important despite the fact that carbon sequestration has been researched in some species throughout many different parts of the world(Holmes *et al*., 2017; Shukla, 2012). This helps address how the variation in tree diversity affects aboveground carbon stocks and also to determine the soil organic carbon accumulation rates under different tree species.

2.3.1 Comparing carbon sequestration by *Eucalyptus* with that of other tree species

The greenhouse gas concentration, mainly CO_2, in the air is rising due to development and increased transportation activities (Chavan and Rasal, 2010). Due to the atmosphere's ability to absorb specific heat radiation wavelengths, these are raising the temperature of the atmosphere. Significant concerns about rising carbon emissions in the Kyoto Protocol are addressed (Creutzig *et al*., 2015). Through photosynthesis, forest plantings, natural forests, agroforestry techniques, and other agricultural pursuits serve as carbon dioxide (CO_2) sinks which is and stored as biomass as reported by (Thangata and Hildebrand, 2012). These improves the global climate by lowering the quantity of CO_2 in the atmosphere (Hutyra *et al.*, 2014). Over 80% of the terrestrial in the world stores aboveground carbon in trees, making them an essential part of the global carbon cycle (Govaerts∗ *et al.*, 2009). Through a dynamic exchange of CO2 with the atmosphere, trees play a crucial part in the global carbon cycle. Managing the carbon reserves in terrestrial forests can contribute significantly to global initiatives to combat climate change (Högberg and Read, 2006). Forest ecosystems are very productive and have a large carbon pool, which makes them a key player in the global native carbon cycle (Drake *et al.*, 2011). According to the studies conducted thus far, forest management can efficiently contribute 30 percent of the global effort required across all the sectors to satisfy climate change mitigation objectives (Phelps *et al.*, 2012). In light of growing concerns about global climate changes brought on by an increase in human caused greenhouse gasses emissions, protection of carbon stocks with the existing forests and obtaining new carbon stocks through reforestation and afforestation have become crucial actions to improve the capacity for sequestration of carbon in terrestrial ecosystems hence mitigating the rising atmosphere's carbon dioxide concentration (Lal, 2008). About 1.4% of the world's total usable land (187 million ha) was planted with trees, 64% of this planted area was found outside of the tropics in 2005. Between 1995 and 2005, the area of tropical forest plantations more than doubled, with an average annual growth rate of 8.6%. (Pocketbook, 2015). An efficient method of short-term carbon sequestration, tree plantations are significant timber sources that reduce demand on indigenous forests products (Drigo et *al*., 2017). By accumulating CO_2 in the form of biomass, growing trees may be able to help lower the amount of CO_2 in the atmosphere (Chavan and Rasal, 2010).

Fast-growing poplar short rotation plantations (8 Mg Cha per year) and plantations of *Eucalyptus* (6 Mg Cha^{-1} per year) have the highest net yearly carbon sequestration rates, followed by teak woods that grow only moderately quickly (2 Mg Cha per year) and long rotation forests that grow slowly (1 Mg Cha^{-1} year) (Phelps *et al*., 2012). In comparison to short rotation plantations, longer-rotation trees store more carbon in the forest biomass and product pools over the long term. The overall long-term average carbon stocks in biomass and wood products for slow-growing long-rotation trees were

156 Mg Cha-^{1}, whereas for fast-growing short-rotation trees, they ranged from 101 to 134 Mg Cha^{-1} in which 11–19 Mg Cha-^{1} was contained in wood products. Average net yearly carbon flux ranged between 1 Mg Cha^{-1} for long rotation and slow growing trees, 6–8 Mg Cha^{-1} for quick growing short rotation trees. The carbon pool in soil was greater for short-rotation trees compared to the carbon content of biological biomass (Drake *et al*., 2011). Henry *et al*., (2011) contends that short rotation plantation contributes to reducing greenhouse gasses emission. Forest ecosystems' ability to store carbon over the long term may be improved by increasing rotation lengths and decreasing thinning severity. In order to mitigate CO_2 emissions over the long term and to lessen the climate change effects, a combination of carbon sequestration and bioenergy will be optimum. This helps address how the variation in tree diversity affects aboveground carbon stocks and also to determine the soil organic carbon accumulation rates under *Eucalyptus* stands and indigenous mixed species stands (Li *et al.,* 2010). Trees improve soil quality by holding the soil together by the roots hence preventing erosion especially in steep slopes. SOC differs with soil depths and land-use types (Nath *et al*., 2015; Sapkota *et al*., 2017). Although *Eucalyptus* is a non-native species, they grow more quickly, create more biomass, and make a substantial contribution to carbon sequestration to lessen climate change and global warming, and are therefore viewed as a threat to the wild population (Panneerselvam *et al*., 2019).

2.3.2 Soil organic matter accumulation under *Eucalyptus* tree species

SOC, as the largest terrestrial carbon pool, also plays an important role in the global carbon cycle. Depending on how the land is used and managed, soil can either be a source of greenhouse gases or a sink (Lal, 2008). Eucalyptus is planted as a crop with a short rotation for removing and producing large amounts of biomass, which is consistent with the accepted scientific theory (Bauhus *et al*., 2010). A study by Mensah *et al*., (2016) found that the average soil organic carbon (SOC) under *Eucalyptus* plantation was ranging between 22.6 and 125.2 t/ha. However, it has been discovered that places with eucalyptus have higher amounts of micronutrients than those with crops like tea that are similar in age (Gerland *et al*., 2014). Planting of Eucalyptus for long has been said to increase fertility of soil, despite comparison investigations of the soils beneath Eucalyptus and neighboring grassland showing no substantial changes for trees with a rotation of not less than 10 years (Chen and Zhu, 2019). Studies have shown that the net soil input of eucalyptus through litter fall is probably favorable on damaged hillsides and wastelands (Chauhan *et al.*, 2017).

Eucalyptus is a short rotation tree species since it's grown for a few years with the aim of high biomass production and removal (Rocha *et al*., 2016). *Eucalyptus* trees improve soil quality by holding the soil together by the roots hence preventing erosion. The effect of *Eucalyptus* can be countered by its rotational planting of 10 years (Nickolas *et al.*, 2019).

Organic matter in the soil affects soil's physical and chemical characteristics, which in turn regulate nutrient cycling andhave a substantial effect on the productivity of forests as a result. Given the crucial role that SOM plays in nitrogen cycling, there'sinterest to understand how soil C pools is affected by soil management in the soil (Nkem *et al*., 2007).

2.4 Area presently under *Eucalyptus* in Kenya

The *Eucalyptus* species is in the family Myrtacea. It was first introduced in Kenya in 1902 and since then about 100 species have been planted (Muchiri *et al*., 2006, Githiomi and Kariuki, 2010). Today, eucalyptus has been the frequently planted tree species in the nation, with cultivation taking place over significant geographic and environmental gradients. The area currently under *Eucalyptus* trees is estimated to be 100,000 Ha of which 15,000 Ha have been gazetted and 35,000 Ha under private companies and 50,000 Ha planted by farmers who prefer its trees due to their fast growth, the capacity to resprout and the straightness of its stems, the wide range of soil and climate adaptation, the simplicity of coppicing management, and valuable wood attributes (KFS, 2019). Eucalypts may thrive in a variety of ecological settings, with some thriving in semi-arid regions and others in swampy and marshy places. Eucalypts grows in a various soil type, such as rich loamy soils, barren sands, and dense clays.

South Africa has the most eucalyptus plantations in Africa, covering around 500,000 hectares (Le Maitre *et al.*, 2016). *Eucalyptus* species were introduced to provide wood fuel for the construction of the Kenya-Uganda railway (Mbinga and Cheboiwo, 2009). It is cultivated for various purposes, like building materials, fuel, plywood, poles, firewood, charcoal, essential oils, tannin extracts, the production of plant growth inhibitors and industrial chemical additives (Bayle, 2019). *Eucalyptus* trees can either be fast growing, moderate or slow growing. Despite these benefits there's needed to balance between environmental and economic outcomes hence this research will help make wise choices about how to profitably and sustainably raise the appropriate species.

Additionally, eucalyptus trees are crucial for producing goods that would otherwise come from natural forests. (KFS, 2019). Due to the growing need for wood for carbon sequestration, renewable energy and mitigation of climate change, eucalyptus growth is anticipated to increase (FAO, 2009). It’s crucial to avoid growing eucalypts in environmentally delicate places like wetlands (Sonkoyo, 2009). Since most eucalyptus trees in Kenya are currently produced as investments for financial benefit, this information will help eucalyptus business owners decide which tree species to grow responsibly and successfully. Even though the genus Eucalyptus spans a wide range of ecological circumstances, distinct species can grow in varied altitudes and rainfall patterns. The fact that it is the primary tree species utilized for energy transmission has motivated its planting. The introduction of shorter-rotation, high-yielding species, species through technological innovations between 1997 and 2003 was the result of the government's extensive promotion and support of Eucalyptus spp. growth in response to the rising need for wood. As a result, agricultural forests supported by eucalyptus have grown at a rate that hasn't been seen before in many different configurations across the nation.

2.5 Socio-economic drivers of planting *Eucalyptus*

Eucalyptus plantations, according to David *et al*. (2014), are one of the ecosystems with the highest growth rates in terms of productivity. *Eucalyptus* is considered an alternative source of livelihood for the under-privileged in most emerging nations (Saxena *et al*., 2018). *Eucalyptus* species have been planted in most areas around the world due to commercial timber products and generation of fiber for industrial products, oil for medicinal and aromatherapy purposes (Khan *et al*., 2020). These trees can be used as construction materials by farmers within the smallholdings (Somboonsuke *et al.,* 2011). They can be used to construct cow sheds and other animal holdings or the farmer's houses. They can also be used as fencing poles to keep off unwanted wildlife within the households or constrict the cattle within the farm. If these trees are well taken care of, they can be sold to power industries for treatment to make electric poles. The tree biomass of these species can be used as fuel within the homesteads or sold to schools, hospitals and other social amenities that use tree biomass in large scale as fuel. The *Eucalyptus* tree leaves can be used as cattle bedding (Munish, 2007). Although *Eucalyptus* tree species has got all these benefits, it's important to consider whether it's the best type of trees to promote positive economic and environmental services to smallholders (Idol *et al.*, 2011). These trees are not only considered beneficial because of their economic return but also due to the low capital and little attention given to them during their growth and bring assured returns (Baird, 2020). Therefore, it is important to carefully weigh the environmental dangers vs potential socioeconomic benefits of planting these trees. Their popularity does not guarantee public acceptance since in agroforestry landscapes their benefits are minimal as compared to pure plantations whose number is less within the study sites. However, when all crops are destroyed by drought *Eucalyptus* trees act as an income source to farmers. It also helps reduce the pressure on natural forests.

Eucalyptus's commercial viability encourages farmers to plant additional trees while simultaneously providing them with justification for doing so. According to studies, three Eucalyptus businesses in Western Kenya that produce transmission poles, construction poles, and firewood are all profitable (Langat, 2015). According to additional research, a hectare of poles and firewood may produce a net surplus of Kshs 540,000 and Kshs 1,000,000 over the course of 8 years, respectively (KFS, 2009). Compared to maize with low to medium production yields (Kshs 88,000), medium yields (Kshs 96,000), and high yields (Kshs 376,000.00), this yield is high (Gil, 2010). This return is comparable to the predicted Ksh. 630,000 returns on tea for the same period (Hohenthal, 2018). The national accounting systems severely underestimate the national income and economic value from woody resources, especially eucalyptus (Simangunsong *et al*., 2017). For instance, current estimates place the input of forest services and products at Ksh. 16.4 billion, or 1% of the GDP of the country (Ninan, 2014). Currently, it is estimated that state commercial plantations generate about Ksh. 460 million in annual revenue (Cai, 2017). Communities and private farmers, who are the main producers of eucalyptus products, are not included in these estimations of income. Excluding non-traded domestic and smallscale industries, it is estimated that the value of pulpwood, short rotation industrial firewood, transmission, sawn wood, and construction poles exceeds Ksh. 1.6 billion (Cai, 2017).

2.6 Interaction of *Eucalyptus* with other tree species

Understanding how *Eucalyptus* species interact with other trees in a mixed plantation will help develop these systems to curtail competition and to further maximize wood production and restoration outcomes. *Eucalyptus* is considered a “thirsty plant” and does well in wet areas (Jackson, 2016). *Eucalyptus* can absorb water from the ground to the level of drying marshy ground (Bayle, 2019). When these trees drain too much water from the ground, they adjust to the water situations to suit their current environment and this gives them an upper hand in survival during ecological instabilities in comparison to other tree species as per studies by Wu and Yu., (2019).

Eucalyptus species has allelopathic effect on other species growing around them and this leads to loss of understory biodiversity hence low species richness (Zhao-hui *et al.*, 2010). Compounds derived from litter or leaves that inhibit the development or growth of other plant species is known as allopathy (Kawawa *et al*., 2016) while in Eucalyptus it occurs through root exudates (Zhang *et al*., 2022). This effect suppresses the tree performance reducing the native species abundance (Vila *et al*., 2011) due to resource use and competition (Hejda *et al.*, 2009). Allelopathy reduces the crops output and in some extreme cases plants die due to water and nutrient competition as per studies by Mukherjee *et al*., (2014) which suggest that *Eucalyptus* due to their capacity to outcompete crops and other vegetation for nutrients and water, they impose considerable environmental costs. Their advantageous water effect is due to possession of deep root systems that aid in competition with other species. Leaching, foliage litter decomposition, volatilization, and root exudation are examples of the ecological mechanisms through which eucalyptus releases its allelopathic compounds into the environment (Fang *et al*., 2009). As per studies by Kawawa *et al*., (2016), the allelopathic effect of eucalyptus causes a reduced survival rates native tree growth performance grown nearby; as a result, it is necessary to look for mixed plantations with high tolerance to the allelopathic effect, such as Markhamia lutea and Diospyros mespiliformis (Kwawa *et al*., 2016). According to a study by *Tang et al*., (2007), tree seedlings and saplings make up the majority of the understory species in a eucalyptus plantation.

2.7 Application of environmental safeguards in farming systems

Over the past ten years, the concept of a worldwide scenarios to encourage the lessening of carbon emissions caused by forest degradation and deforestation (REDD +) has acquired significant push (UNFCCC, 2014) interms of reducing global warming while also maintaining indigenous rights, tropical forests (important for biodiversity), and local populations' livelihoods (good for people). There are rising worries that REDD+ may worsen poverty in communities near forests by limiting forest resources and access to land, particularly for people who rely on natural resources for livelihood (Chhatre *et al.*, 2012). Commentators have pointed out that these different standards do not concur (Arhin, 2014), and that their approaches range from actively attempting to improve people's livelihoods and welfare to proactively preventing and mitigating negative effects (a "risk-based approach") (Roe *et al.*, 2013). Social protection in a REDD+ project involve figuring out who may lose out as a result of the effort and how this loss should be made up. Concerns have been raised about the procedure for evaluating social protections and allocating benefits in REDD+ initiatives, which has been linked to local elite capture (Pascual *et al.*, 2014); this raises the possibility that the process intended to protect the poor's interests will be undermined and may make social inequality worse. "If REDD is to disrupt business as usual and to benefit local populations," Ribot and Larson (2012), "safeguard measures must not simply preserve rights, but also build, strengthen, and guarantee rights". It is encouraging that the Paris Agreement explicitly recognizes the need to uphold and advance human rights, particularly those of vulnerable people, while addressing climate change.

The safeguards strategy, which is designed to reduce any potential bad effects of a program or project, is frequently referred to as a "do-no-harm approach" (Hall, 2007). Doing no harm should not be the only goal of safeguards. Safeguards should aim to increase ecological and social well-being where they are employed if they are to efficiently affect the incomes of some of the unfortunate people living in communities that depend on forests and ensure improvement of livelihoods and social welfare are achieved.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

The chapter provides a comprehensive description of the methods used to carry out this study. The study area, study design, data collection and data analysis are all covered.

3.2 Study area

The study was conducted in the margins of the Kakamega-Nandi Forest Ecosystem. It covered farmlands located between 0-3 km from the forest boundary of Kakamega, Kibiri and South Nandi forests within Kakamega, Vihiga and Nandi counties respectively. Assessment sites within the margins of Kakamega Forest included Shamiloli, Mukulusu and Lukala. Assessment sites around Kibiri Forest included Makuchi, Makhanga and Blukhombe. Assessment sites surrounding South Nandi Forest included Cheboite, Burende and Mukoyuro as shown in Figure 3.1. The study sites were farms where sustainable land management (SLM) project interventions funded by GEF through MMUST studentship of 2018 were being implemented within Kakamega, Vihiga and Nandi counties.

The climate in and around Kakamega Forest is hot and wet, with an annual rainfall of 1,500 - 2,000 mm and a dry season between December and March (Agevi *et al.*,2016; Agevi *et al.*, 2019). It has a temperature mean minimum range of 11^{o} to 21^{o} C and a temperature mean maximum range of 18 to 29^{o} C (Althof, 2005; Otuoma *et al.*, 2016). The area is located between 0^{o} 16’ N and 34^{o} 45’ E. The soils in Kakamega are classified as Acric Ferrasols (Fa) (Akenga *et al.*, 2014). More than 400 plant species, including 112 woody species; 300 bird species, and 7 indigenous primate species live in the adjacent woodland (Agevi *et al.*, 2019). The forest's vegetation included primary woods that had been disturbed, secondary forests in various phases of development, mixed indigenous plantations, and monoculture plantations with both indigenous and exotic species (Adhiambo *et al.*, 2019; Tsingalia and Kassily, 2009). The forest sustains a population of about 280,000 people who reside nearby and depend on it for timber, firewood, pasture, twines and vines, native fruits and vegetables (Mutegi *et al*., 2017).

It is located West of Kapsabet Town and east of Kakamega Woodland, at 0^o and 0^o15^oN and 34^o45^o and 35^o07^oE, respectively, is the location of South Nandi Forest (Njunge and Mugo, 2011). It's situated between a tropical afro-montane forest and a tropical rainforest. The western portion of the forest extends into the Rift Valley at an elevation of about 2,000 m above sea level, and the eastern portion extends into the Kakamega rainforest at an elevation of 1,700 m above sea level, which is what causes the change (Otuoma and Ongugo, 2013). As altitude rises, species characteristics gradually shift from tropical rainforest to tropical afro-montane woodland (Bird Life International, 2013). The average annual rainfall in the region is between 1,600 and 2,000 mm, and the average temperature is 19^o C (Williams and Middleto, 2008). There are granitic and basement rocks beneath the gently undulating terrain, which weather to form deep, well-drained soils. 2013's Bird Life International. Kakamega forest is situated in the Kimondi and Sirua rivers' upper catchment areas, which unite downstream to form the river Yala, which empties into Lake Victoria (Mitchell *et al*., 2006). More than 86 natural woody species can be found there. The most prevalent of these species include *Strombosia scheffleri, Croton megalocarpus, Macaranga kilimandscharicum, Tabernaemontana* *stapfiana, and Celtis africana* (Njunge and Mugo, 2011). With over 60 different bird species, the forest is designated as an important bird area (Fergus, 2013). 371 persons per km2 reside within 0–3 kilometers of the forest boundary and depend on it for firewood, honey, pasture, building materials, herbal medicine, and native fruits and vegetables, according to the 2019 human population census (Kenya National Bureau of Statistics, 2019).

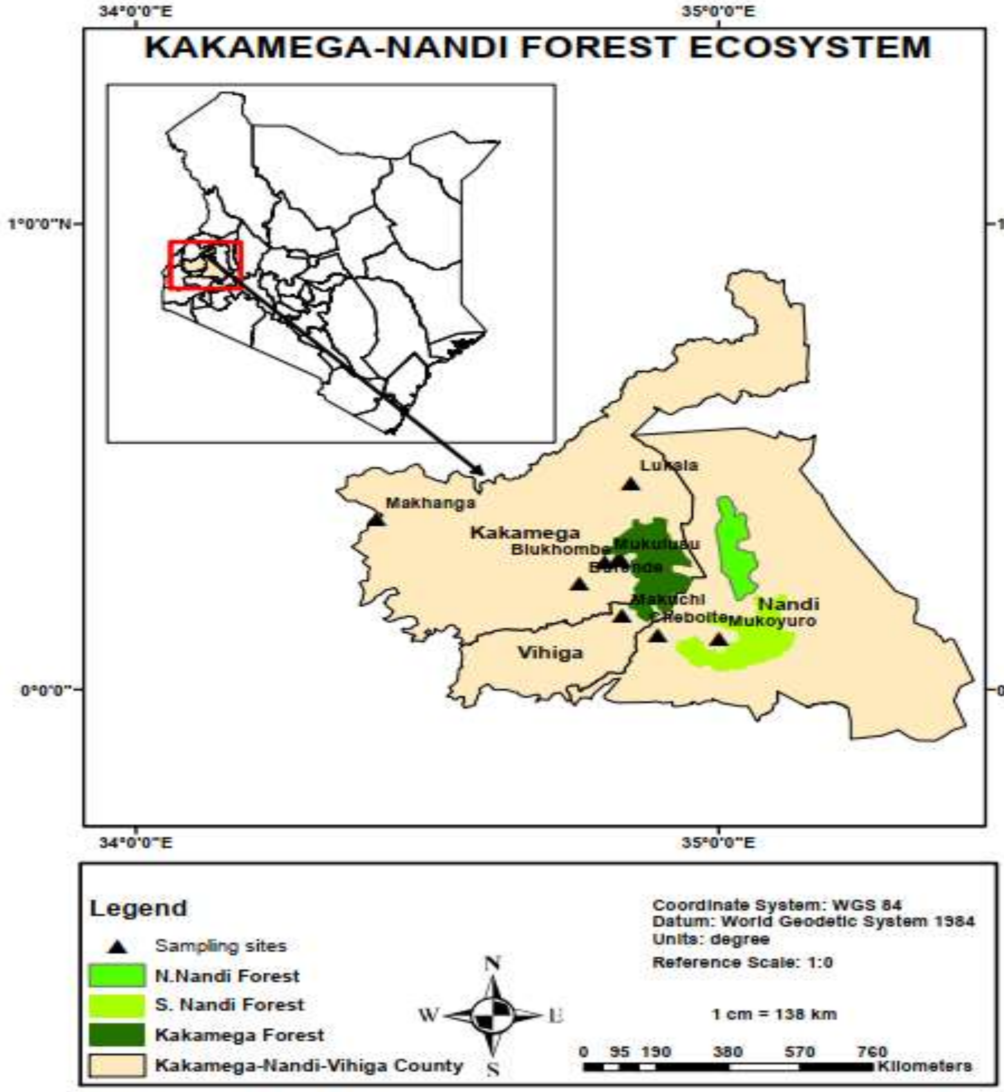

Figure 3.1: Study area showing Kakamega-Nandi Forest ecosystem, Kenya (Researcher, 2019)

Kibiri Forest ecosystem is in Vihiga County and has an annual mean rainfall of 1,800-2,000 mm and an average temperature of 18.9 - 20.9°C. It is located between 1,300 and 1,800 meters above sea level. Tree planting has a long history in the area, dating back to the 1940s, when Eucalyptus species were introduced to reverse rampant deforestation and provide scarce forest materials for domestic use (Shimamoto *et al*., 2004). Trees are estimated to occupy 30% of the land area with *Eucalyptus* being dominant with its main products being construction poles, timber, and firewood (Warner, 1997). The average individual land holding is 0.05 hectares (Ekabten, 2017).

3.3 Study design

A reconnaissance visits to the study sites revealed that a 3 km transect from the forest edge into the farmlands traversed indigenous forest (control), mixed species stands comprising indigenous trees, *Eucalyptus* and other exotic tree species (quadrats with *Eucalyptus* trees occupying less than 50%); and *Eucalyptus* dominated stands (quadrats with *Eucalyptus* trees occupying more than 50%) as one moved further into farmlands (Muigai *et al*., 2023). The study selected stratified systematic sampling to assess the extent to which the observed variation in the concentration of *Eucalyptus* trees affected the three variables under investigation (tree species diversity, carbon stocks and soil properties). The research was conducted in three sentinel blocks, namely Kakamega, Kibiri, and Nandi, as well as a control within the forest. Each of the sentinel blocks comprised three sub-blocks which are the micro-catchments where sustainable land management (SLM) project interventions were being implemented within the three counties (Kakamega, Nandi and Vihiga). In each sub-block, assessment was carried out in *Eucalyptus* dominated woodlot, a pure indigenous tree stands and mixed stand of *Eucalyptus*, indigenous and other exotic trees. A sample plot consisted of a 20m by 10m main plot for assessing trees with DBH ≥10 cm. Saplings and shrubs were evaluated in 5m by 10m subplots. Counts per quadrat along the transects were averaged and scaled up to hectare area for each site to provide a range of estimated stem abundance in units of ha^{-1}. A nested experimental design was used in the study (Otuoma *et al*., 2016). Sub-plots were nested within the main plot and main plots were nested within blocks.

The transects passed through farmlands, water catchments and along river lines. In each sub-blocks assessment entailed use of line transects to assess these parameters. Sample points were located systematically along a transect (Buckland *et al*., 2012). Three transects were laid within the 3 kilometers length and a 40 m width of a block, consisting of 5 quadrats per transect of 200 meters apart.

3.4 Data collection

3.4.1 Tree species abundance

All trees in the plots were inventoried, with the diameter at DBH, species name, and number per plot recorded on a data sheet. With the help of a taxonomist and a reference collection of woody tree species found in and around Kakamega Forest, the species name was determined (Tsingalia and Kassily, 2009).

3.4.2 Diameter at Breast Height (DBH) and height

A diameter tape was used to measure the stem DBH at a height of 1.3 meters from the ground. A Varnier caliper was used to measure the diameter of smaller trees, such as saplings and shrubs. A Suunto clinometer was used to measure the height of the trees. The global database http://db.worldagroforestry.org/wd was used to obtain wood densities for tree species. For some species, wood density was obtained from related studies in the same area as well as other places with climatic circumstances and tree species that are similar to those of the study area (Pandey and Pokhrel, 2021).

3.4.3 Soil Sample Collection

A soil auger was used to collect soil samples. Four soil samples were taken from the main plot and placed in a bucket before being thoroughly mixed to form a sample from which a composite sample of 0.5kg was placed in a brown paper. The top and subsoil samples were taken from the plot's center, and the other three were taken at 120^{o} angle intervals at depths of 0-15 cm and 15-30 cm, respectively. A data sheet was used to record all the information.

3.5 Field measurements

This sub section presents how data was processed and analyzed for tree species diversity, above and below ground biomass, total tree biomass and carbon and selected soil properties.

3.5.1 Tree species diversity

For further processing, the data were entered and managed in a Microsoft Excel worksheet. The number of different woody species was used to calculate species richness. The Shannon Wiener index was used to calculate the diversity of tree species (Konopiński, 2020) expressed as:

Equation: 3.1

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

Where: Σ is the sum, pi is the quantity of individual species divided by the total number of species, ln represents natural log, and - is a negative that when multiplied by the equation yields a positive value as the index.

The diversity of trees and shrubs was measured using an inventory of all woody species larger than 2cm in DBH in the sample plot (Negash, 2013). Species richness (S), Importance Value Index (IVI), equitability/evenness (J), Basal Area (BA), and species dominance using the Simpson dominance index (Cd) are all measures of species richness (Krebs, 1978; Magurran, 1988) were estimated using the following formula:

Species richness (S) was calculated by;

Equation: 3.2

$$S=\sum ni$$

Where ni is the number of species in a community.

Equation: 3.3

$$H' = -\sum(pi)xln(pi)/\ln s$$

Where S represents the number of species, H' represents the Shannon diversity indices, and Pi represents the proportion of individuals found in the ith species.

Equation 3.4

$$Basal\,area = \pi r^2$$

Where π=3.142; r is the radius of individual tree

The Importance Value Index (IVI) was calculated for each woody species in the treatments as follows:

Equation 3.5

$$IVI = RA + RBA + RF$$

Where IVI is the Importance Value Index, RA; relative abundance, RBA; relative basal area, and RF; relative frequency.

The Jaccard index is the proportion of species in the two sites' total species list; that is, a Eucalyptus dominated woodlot, a pure indigenous tree stands, and a mixed stand of Eucalyptus, indigenous, and other exotic trees that is common to both sites. It was calculated as:

Equation: 3.6

$$SJ = \frac{C}{(a + b + c)}$$

Where SJ denotes the similarity index, c denotes the number of species shared by the two sites, and a and b denote the number of species unique to each site.3.6.2 Carbon stocks.

3.5.2. Aboveground biomass (AGB)

Above ground biomass (AGB) was estimated using non-destructive sampling and allometric equations developed by Kuyah for trees on farms Kuyah *et al*., (2012b).

Equation 3.7

$$AGB = 0.091 \times (DBH)^{2.472}$$

Where, AGB is the above ground biomass and DBH diameter at breast height.

While for tropical forest trees (Chave *et al*., 2005) was selected by;

Equation 3.8

$$AGB = \rho \times e^{\left(-1.499+(2.148\times\ln D)+\left(0.207\times(\ln D)^2\right)-\left(0.0281\times(\ln D)^3\right)\right)}$$

Where, e is the constant 2.71828 for the exponential function, D is DBH and ρ is the specific wood density (grams cm^{-3}). Individual tree biomass estimates in kg per tree were obtained using diameter measurements and allometric equations.

3.5.3 Below ground biomass (BGB)

A root-to-shoot ratio of 0.26 was used to calculate the below ground biomass (IPCC, 1996).

Equation 3.9

$$BGB = AGB \times 0.26$$

3.5.4 Total Tree Biomass (TB) and Carbon stocks

The total tree biomass was calculated by adding aboveground biomass to belowground biomass. Estimates of tree biomass were added together to obtain plot-level estimates in mega grams per hectare Mg C ha^{-1}. The biomass estimates were converted to carbon using the IPCC's default carbon fraction in wood value of 0.46. (IPCC, 2010).

Tree biomass estimates were added together to obtain farm/plot level estimates in Mega grams per hectare Mg C ha^{-1}.

Equation 3.10

i. $$TB = AGB + BGB$$

ii. $$TC = TB \times 0.46$$

Where, TB is total biomass, AGB; above ground biomass; BGB below ground biomass TC; total carbon.

3.5.5 Laboratory soil analysis

The elements were analyzed after the soils were dried at room temperature and sieved using a 2mm mesh size sieve and the coarse fragments (>2 mm) weighed.

3.5.5.1 Soil organic carbon

The Walkley-Black method was used to analyze soil organic carbon (Walkley–Black, 1934). A mixture of soil and 5 ml of aqueous $K_2Cr_2O_7$ was treated with 7.5 ml of concentrated H_2SO_4. The heat of dilution increased the temperature enough to cause a significant, but not complete, oxidation by the acidified dichromate. Using ferrous sulphate, residual dichromate was back titrated. To calculate the amount of easily oxidizable organic carbon, the difference in added FeSO4 was compared to a blank titration.

The percentage carbon is given by the formula:

Equation 3.11

$$\%C = M \times \frac{(V_1 - V_2)}{W} \times 0.30 \times CF$$

Where M represents the molarity of the $FeSO_4$ solution (from blank titration), V1 represents the volume (mL) of FeSO4 required in blank titration, V2 represents the volume (mL) of FeSO4 required in actual titration, W represents the weight (g) of the oven-dried soil sample, and CF represents the correction factor. The CF compensates for incomplete oxidation by being the inverse of the recovery. The Walkley-Black method was used to analyze soil organic carbon (Walkley–Black, 1934), demonstrated as:

Equation 3.12

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

Where SOC = soil organic carbon stock (t Cha1), C = laboratory determined soil organic carbon concentration (g kg^{-1}), = soil bulky density (g cm^{-3}), D = soil depth of sampled soil layer (cm), frag =% volume of coarse fragments/100, and 100 = is a conversion factor to tones of Cha^{-1} (Carbon per hectare).

The SOC stock values for the two layers (0-15 cm and 15-30 cm) were added together to yield the total SOC stock for the 0-30 cm layer.

3.5.5.2 Soil pH

Potentiometric (Laqua HORIBA, Model F-72G) analysis was used to determine the pH of soil in a 1:1 suspension of soil and water (Czinkota *et al.*, 2002). 15 g of the soil sample was placed in two extraction cups with lids. 30 ml of deionized water was added and gently swirled to create a soil slurry. The cups were removed 30 minutes before the pH was measured. The pH meter was calibrated using pH 7 and pH 4. The soil slurry was gently swirled while measurements were taken to the nearest 0.01 and standard buffer concentrations were rechecked every 10 to 12 samples.

3.5.5.3 Soil bulk density

The bulk density of the soil was obtained using the core sampling method (Blake *et al*., 1986). Soil was excavated with a soil auger, a core ring was installed, and the soil at the ends was cut with a knife. The soil was then dried in an oven at 105^0 Celsius for 24 hours before being weighed. The bulk density was obtained by dividing the mass of dry weight of soil (g) by the volume of soil (cm^3).

3.5.5.4 The soil porosity

The soil porosity, (*f*) was calculated using the formula:

Equation 3.13

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

where, f is porosity, ρs is taken as 2.65g cm^3 which represents the particle density and ρb is the bulk density (Danielson and Sutherland, 1986).

3.5.5.5 Soil texture

To determine soil texture, the hydrometer method given by (Okalebo *et al*., 2002) was used. The soil samples were placed into a 0.5-mm fine screen to separate the sand fraction after dispersing the sodium pyrophosphate solution, and the clay and silt fractions were poured into a sedimentation cylinder. The USDA soil textural triangle was then used to compute the clay content.

Figure 3.2. The soil textural triangle can be used to classify soils according to their particle size distribution (Okalebo et al. 2002).

3.5.5.6 Nitrogen content

The micro-Kjeldahl method was used to analyze the nitrogen content (AOAC, 1990). The elements were analyzed after the soils were dried at room temperature and sieved. 3g digestion mixture ($K_2SO4 + CuSO_4\text{-}5H_2O$) was added to 5 ml of treated soil solution into a Kjeldahl flask and kept on flame until it was clear (greenish-blue) and then continued heated for five more minutes. The solution was cooled, diluted to 15 ml with 10(N) NaOH to under neutralize. The flasks were chilled in ice water, then was wiped outside, and attached to a distillation apparatus. 100 ml conical flask was fixed with 10 ml boric acid and 2 drops of methyl red at the receiving end. 30 ml of distilled water was added to the boric acid solution in the conical flask to make the receiving end of the funnel dip into boric acid solution.5 ml 10 (N) NaOH from the side tube was added into the Kjeldahl flask to over neutralize the solution. The flask was heated for distillation till 20 ml of solution remained. The receiver conical flask was drawn down and heating stopped and when distillation stopped the end of the receiving funnel was washed. The contents of the conical flask were titrated with 0.1 (N) HCl and the volume of HCl used noted. A blank was run without soil and the value from titration figure reduced.

The following formula is used to determine the nitrogen content in the sample material expressed in N%:

Equation 3.14

$$\%N = (a - b) \times v \times \frac{100}{1000} \times w \times al \times 1000$$

Where v = total volume at the conclusion of the analytical method, w = weight of the dried sample, and al = aliquot of the solution taken. Where a = concentration of N in the solution, b = concentration of N in the blank.

3.5.5.7 Soil phosphorus

The Olsen method was used to analyze the phosphorus content of the soil (Olsen *et al*., 1954). For 30 minutes, a 1gram scoop of air-dried soil and 20 milliliters of 0.5 molar sodium bicarbonate ($NaHCO_3$) solution were shaken together. Blue color was developed in the filtered extract with 10 mL molybdate-ascorbic acid reagent and measured at 880 nm with the Brinkman PC 900 probe colorimeter. Phosphorus (P) levels in the soil were measured in parts per million (ppm).

3.5.5.8 Potassium

Atomic Absorption Spectrophotometry (AAS Shimadzu, 7000) series was used to analyze the soil exchangeable potassium (David, 1960). For K determination to be within the flame photometer and atomic absorption spectrophotometer's detectable range, the soil extract solution A was diluted ten (10) times. Soil extract solution A was diluted by pipetting 5 ml of it into a 50-ml volumetric flask. The mark was treated with 1 ml of a 26.8% lanthanum chloride solution that had been diluted with 1M NH4OAc extraction solution. To determine K or to measure K, this solution was sprayed into the flame of an atomic absorption spectrophotometer or flame photometer. To calibrate the instruments, the standard working solutions were measured.

3.6 Statistical analysis

Using R Gui software version 4.2.1, all the above data were subjected to analysis of variance (ANOVA) at the 5% significant level to determine possible variations in woody species diversity, aboveground carbon stock, and soil organic carbon in Eucalyptus dominated woodlots, mixed tree stands, and indigenous tree stands. Variances in species diversity and tree biomass between farm sites were considered significant at $p<0.05$ using ANOVA. The Ryan-Einot-Gabriel-Welsch Multiple Range Test (REGWQ) was used in post hoc tests to determine the source of variation among means at the 5% significance level (Krull and Craft, 2009; Sokal and Rohlf, 2012; Holt *et al*., 2013).

CHAPTER FOUR

RESULTS

4.1 Introduction

This section presents the results of the study. It is organized in three parts namely, species composition and stand structure, carbon stocks, soil chemical and physical properties.

4.2 Effects of *Eucalyptus* trees on woody species diversity

4.2.1 Woody species richness

A total of 51 woody species representing 26 families were recorded. Of these, 8 species (15.4%, n=133) were encountered in *Eucalyptus* dominated tree stands, 29 species (55.8%, n=193) were recorded in mixed tree species stands, while 32 species (61.5%, n=143) were in indigenous tree species stands. Mature trees constituted 48.6% (n=228), while saplings and shrubs comprised 51.4% (n=241) of the woody species recorded. The plant family Myrtaceae had the highest number of woody plants at 50.3% (n=236) followed by Moraceae with 7.5% (n=35).

Analysis of Importance Value Indices (IVI) of woody species indicated that *Eucalyptus grandis* (Myrtaceae) was the most dominant woody species 93% in the study area followed by *Bischofia javanica* Phyllanthaceae (17.45%) and *Ficus sur* Moracea (14.44%) in descending order. Analysis of the IVI of woody species across respective treatments, showed that *Eucalyptus* species was also the most dominant species (93%) in *Eucalyptus* dominated tree stands followed by *Harungana madagascariensis* (2.3%) and *Persea americana* (2.1%) (Table 4.1). In mixed tree stands, the most dominant woody species were *Eucalyptus* species (43.2%), *Zanthoxylum gilletii* (10.2%) and *Grevillea robusta* (8.8%) (Table 4.1). In indigenous tree stands, the most dominant woody species were *Bischofia javanica* (17.4%), *Ficus sur* (14.4%) and *Antiaris toxicaria* (11.0%) (Table 4.1).

Table 4.1: The most dominant woody species in *Eucalyptus* dominated tree stands (EDTS), mixed species tree stands (MTS) and indigenous species tree stands (ITS) in Kakamega-Nandi Forest Ecosystem, as recorded by importance value index (IVI).

Treatment	**Woody species**	**IVI**
Eucalyptus dominated tree stands	*Eucalyptus grandis*	92.97
	Harungana madagascariensis	2.29
	Persea americana	2.06
	Bridelia micrantha	0.69
	Croton macrostachyus	0.65
	Zanthoxylum gilletii	0.49
	Grevillea robusta	0.49
	Markhamia lutea	0.49
Mixed species tree stands	*Eucalyptus grandis*	43.21
	Zanthoxylum gilletii	10.24
	Grevillea robusta	8.79
	Croton macrostachyus	5.42
	Solanum mauritanum	4.14
	Maesopsis eminii	3.39
	Vitex keniensis	2.68
	Markhamia lutea	2.64
	Cupressus lusitanica	2.50
	Bischofia javanica	2.13
Indigenous species tree stands	*Bischofia javanica*	17.43
	Ficus sur	14.44
	Antiaris toxicaria	11.02
	Psidium guajava	10.37
	Funtumia africana	9.49
	Spathodea campanulata	4.89
	Trilepisium madagascariense	3.94
	Solanum mauritanum	3.72
	Polyscias fulva	2.45
	Dracaena fragrans	2.15

(Dalitz, 2011)

Increase in the density of *Eucalyptus* trees led to a significant reduction in tree diversity Figure 4.1.

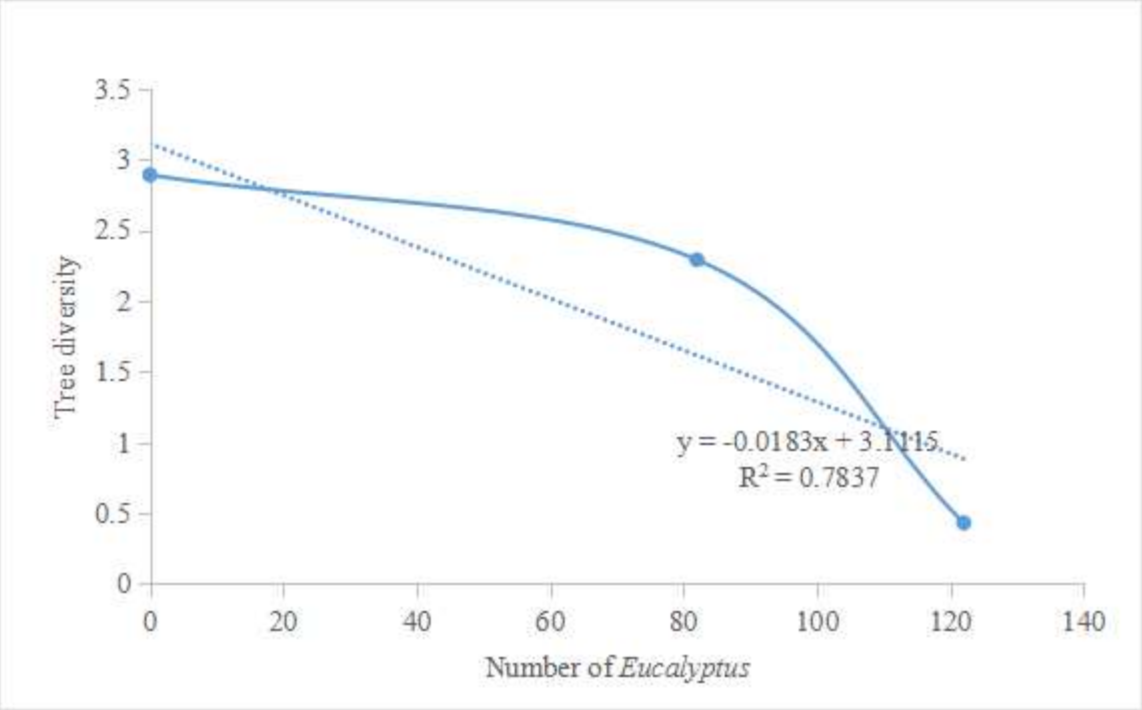

Figure 4.1: Effect of increase in density of *Eucalyptus* species on the tree diversity within the treatments.

4.2.2 Woody species diversity

The Shannon diversity index in the three treatments ranged between (H′=0.43) and (H′=2.89) (Table 4.2). The diversity index was higher in the indigenous tree stands (2.89) followed by mixed tree species stands (2.29). *Eucalyptus* dominated tree stands had the lowest diversity index (0.43). The Shannon diversity index in the *Eucalyptus* dominated tree stands ranged between (H′=0) and (H′=0.72). The Shannon diversity index in the mixed tree stands ranged between (H′=0.94) and (H′=2.30). The Shannon diversity index in the indigenous tree stands ranged between (H′=0) and (H′=2.24).

Table 4.2: Woody species richness, abundance and diversity in *Eucalyptus* dominated tree stands (EDTS), mixed tree species stands (MTS) and indigenous tree species stands (ITS) in the Kakamega-Nandi Forest Ecosystem.

Treatment	**Richness**	**Abundance**	**Shannon**
Eucalyptus dominated tree stands	1.89±0.35a	13.67±3.00	0.43
Mixed tree species stands	6.56±1.06b	21.44±4.63	2.29
Indigenous tree species stands	6.67±0.73b	15.78±3.65	2.89
p	0.00519	0.346	0.011

Different letters indicate significant differences across treatments at $p < 0.05$.

4.2.3 Woody species similarity indices

Jaccard similarity indices ranged between 11.1% and 22.2% (Table 4.3). This indicated that woody species within the three treatments were largely dissimilar. Nonetheless, mixed trees stands (MTS) and indigenous trees stands (ITS) had a relatively higher similarity index (22.2%) which implied that the two vegetation types probably shared more woody species than *Eucalyptus* dominated tree stands. Similarly, mixed trees stand appeared to share relatively more woody species with *Eucalyptus* dominated tree stands (15.6%) than the case between indigenous trees stands and *Eucalyptus* dominated tree stands (11.1%) (Table 4.3).

Table 4.3: Jaccard similarity indices for *Eucalyptus* dominated tree stand (EDTS), mixed trees stand (MTS) and indigenous trees stand (ITS) in the Kakamega-Nandi Forest Ecosystem.

	Eucalyptus dominated tree stand	Mixed trees stand	Indigenous trees stand
Eucalyptus dominated tree stand	1		
Mixed trees stand	0.15625	1	
Indigenous trees stand	0.1111	0.2222	1

4.2.4 Woody stand structure

4.2.4.1 Stem density

Stem density ranged between 50 stems/ha and 200 stems/ha. The mean stem density in *Eucalyptus* dominated tree stands was 128, whereas it was 125 in mixed tree species stands. In the indigenous tree species stands the mean stem density was 126 see (table 4.4). The variation was not statistically insignificant ($p > 0.05$) among the three treatments. The species with the highest and lowest stem density in *Eucalyptus* dominated tree stands is *Eucalyptus* species and *Markhamia lutea* while in the mixed tree species stands was *Eucalyptus grandis* and *Bischofa javanica* and indigenous tree species stands was *Bischofa javanica* and *Dracaena fragrans* in the Kakamega-Nandi Forest Ecosystem.

Table 4.4: Stem density, DBH, tree height and basal area (Mean ± SD) of *Eucalyptus* dominated tree stands (EDTS), mixed tree species stands (MTS) and indigenous tree species stands (ITS) in Kakamega-Nandi Forest Ecosystem.

Treatment	**Stem density (Ha$^{-1)}$**	**DBH**	**Height**	**Basal area**
Eucalyptus dominated tree stands	127.82±6.52	10.91±0.80b	11.00±0.66	1.60±0.26b
Mixed tree species stands	124.61±5.41	12.23±0.69b	12.58±0.64	1.90±0.20b
Indigenous tree species stands	125.52±6.29	17.69±1.65a	14.08±1.00	5.50±0.93a
p	0.0925	0.044	0.0925	0.0174

Different letters indicate significant differences across treatments at $p < 0.05$.

4.2.4.2 DBH and height distribution

The overall tree DBH size classes ranged from 2 cm to 87.9 cm across the different treatments. The DBH classes of woody species within specific treatments ranged between 2 - 59.5, 2 - 49 and 2 - 87.9 cm in the *Eucalyptus* trees dominated stand, mixed tree stand and indigenous tree stand respectively (Figure 4.2). The mean tree DBH was 10.9 cm, 12.2 cm and 17.7 cm in the *Eucalyptus* trees dominated stand, mixed tree stand and indigenous tree stand respectively. There was no significant variation ($p > 0.05$) in tree DBH between *Eucalyptus* dominated tree stands and mixed tree species stands. There was a significant difference ($p = 0.0456$) in tree DBH between *Eucalyptus* dominated tree stands, mixed tree species stands and indigenous tree species stands in the Kakamega Nandi Forest Ecosystem (Table 4.4). The tree species with the highest DBH in EDTS, MTS and ITS were *Eucalyptus grandis, Maesopsis eminii and Ficus sur* respectively. Trees with DBH ranges of 0.1-10 cm in the study sites were the majority (51.4%) while 80.1-90 cm were the least (1.1%).

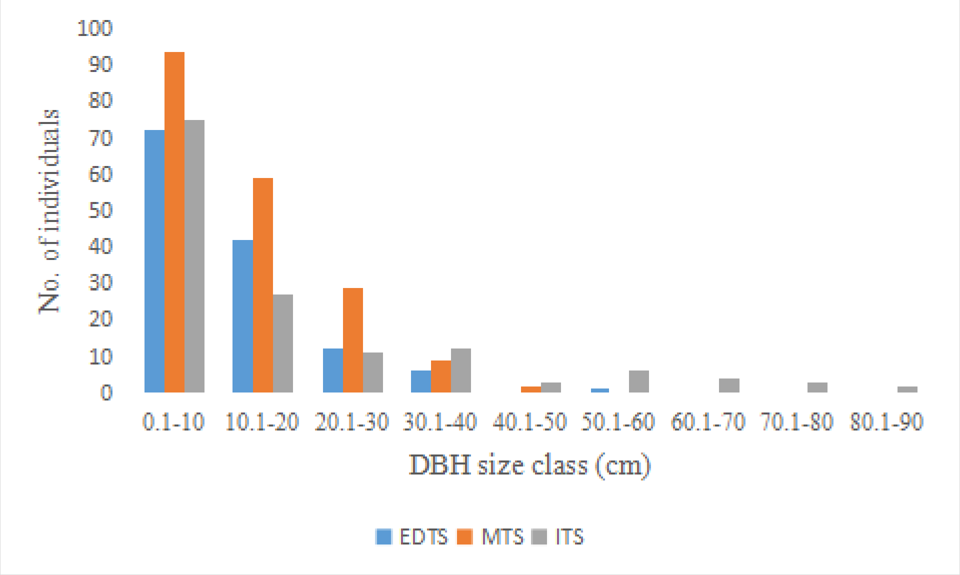

Figure 4.2: Diameter at breast height class (cm) distribution of woody species encountered in the *Eucalyptus* trees dominated stand, mixed tree stands and indigenous tree stand.

The results show that as an individual's DBH and height increase, the number of individuals decreases (Figure 4.3). The diameter class distribution of these trees exhibited a negative exponential or inverted 'J' distribution pattern. This implies that most of the species had the greatest number of individuals in the low DBH and height size classes, with a gradual decrease in the high DBH and height size classes. The overall tree heights range was between 1.5 m and 61 m. The tree heights of woody species ranged between 1.5 m and 31.5 m, 1.4 m and 42.5 m and 1.6 m and 61 m in the *Eucalyptus* trees dominated stand, mixed tree stand and indigenous tree stand respectively (Figure 4.3). There was no significant difference ($p > 0.05$) in tree height among *Eucalyptus* dominated tree stands, mixed tree species stands and indigenous tree species stands in the Kakamega Nandi Forest Ecosystem (Table 4.4). The tree species with the highest height in EDTS, MTS and ITS were *Eucalyptus* species, *Maesopsis eminii and Antiaris toxicaria* respectively.

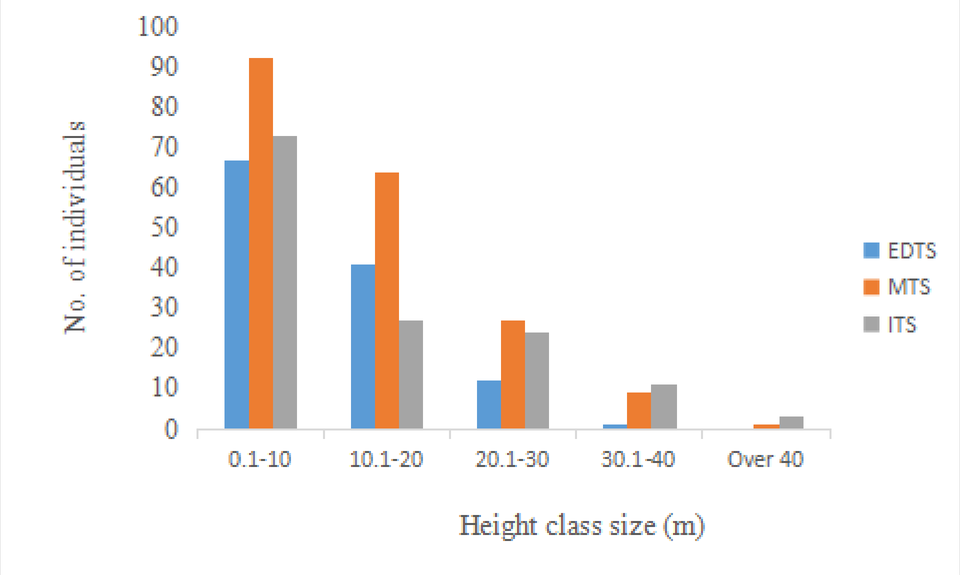

Figure 4.3: Height class (m) distribution of woody species encountered in the *Eucalyptus* trees dominated stand, mixed tree stands and indigenous tree stand.

4.2.4.3 Basal area

Tree basal area ranged between 0.03 m^2/ha and 60.69 m^2/ha. Indigenous tree species stands had the highest mean basal area, while *Eucalyptus* dominated tree stands and mixed tree species stands had the lowest (Table 4.4). The variation in basal area was not significant between *Eucalyptus* dominated tree stands and mixed tree species stands but differed significantly ($p < 0.05$) to those of indigenous tree species stands in the Kakamega Nandi Forest Ecosystem.

The mean tree basal area was 1.6, 1.90 and 5.50 m^2/ha in the *Eucalyptus* dominated tree stands, mixed tree species stands and indigenous tree species stands. It ranged between 0.03 and 27.81 m^2/ha, 0.03 and 18.86 m^2/ha and 0.03 and 60.69 m^2/ha in the *Eucalyptus* dominated tree stands, mixed tree species stands and indigenous tree species stands in the Kakamega-Nandi Forest Ecosystem.

4.3 Effects of *Eucalyptus* trees on tree biomass carbon stocks

The aboveground biomass carbon ranged between 0.10 and 110.82 Mg C ha^{-1}, between 0.10 and 68.58 Mg Cha^{-1} between 0.50 and 512.84 Mg Cha^{-1} in the *Eucalyptus* trees dominated stand, mixed trees stand and indigenous trees stand respectively. The above ground biomass carbon in the *Eucalyptus* dominated tree stands and mixed trees stands was significantly lower than in the adjacent indigenous trees stands ($p=0.0143$) (Table 4.5). The belowground biomass carbon ranged from 0.03 to 28.81 Mg C ha^{-1}, 0.03 to 17.83 Mg C ha^{-1} and 0.01 to 133.344 Mg C ha^{-1} in the *Eucalyptus* trees dominated stand, mixed trees stand and indigenous trees stand respectively. The below ground biomass carbon in the *Eucalyptus* dominated tree stands and mixed trees stands was significantly lower than in the adjacent indigenous trees stands ($p=0.0143$) (Table 4.5). The mean carbon estimated in the treatments was 2.62 Mg C ha^{-1}, 3.09 Mg C ha^{-1} and 19.05 Mg C ha^{-1} in the *Eucalyptus* trees dominated stands, mixed trees species stands and indigenous tree species stands respectively (Table 4.5). The carbon estimated total carbon in the treatments ranged between 0.06 and 64.23 Mg C ha^{-1}, 0.06 and 39.75 Mg C ha^{-1} and 0.03 and 297.24 Mg C ha^{-1} in the *Eucalyptus* trees dominated stands, mixed tree species stands and indigenous tree species stands respectively. The total carbon in the

Eucalyptus dominated tree stand and mixed trees stand was significantly lower than in the adjacent indigenous trees stand (p=0.0143) (Table 4.5).

Table 4.5: Above ground biomass, below ground biomass, total biomass and total carbon (Mean ± SD) of *Eucalyptus* dominated tree stand (EDTS), mixed trees stand (MTS) and indigenous trees stand (ITS) in Kakamega-Nandi Forest Ecosystem.

Treatment	AGB Ha^{-1}	BGB Ha^{-1}	TC Ha^{-1}
Eucalyptus dominated tree stand	4.54±0.95b	1.18±0.25b	2.62±0.55b
Mixed trees stand	5.33±0.61b	1.39±01.07b	3.09±0.35b
Indigenous trees stand	32.87±6.76a	8.55±1.76a	19.05±3.92a
p	0.0143	0.0143	0.0143

Different letters indicate significant differences across treatments at $p < 0.05$.

Increase in the density of *Eucalyptus* trees led to a significant reduction in carbon stocks ($Cha^{-1}Mg$) ($F_{(1,\ 15)} = 27.198$; $p < 0.001$). However, the regression model for the relationship showed a fairly weak positive correlation (Figure 4.4).

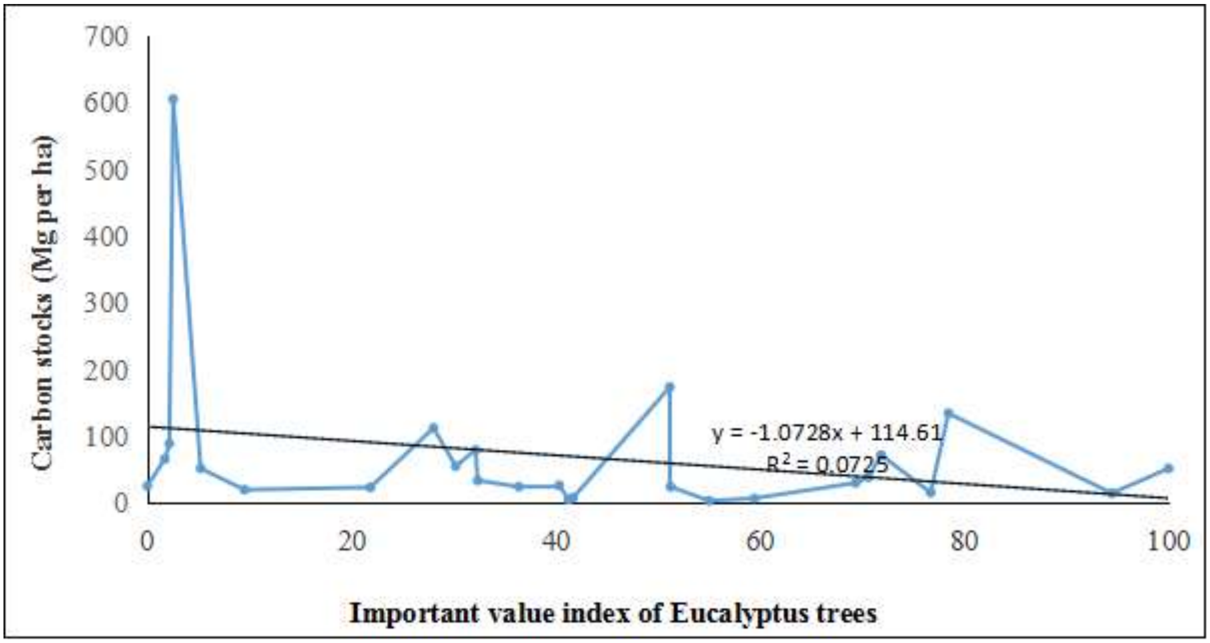

Figure 4.4: Effect of increase in density of *Eucalyptus* species on above and belowground carbon stocks within the treatments.

4.4 Effects of *Eucalyptus* trees on soil organic carbon stocks

The SOC in the treatments ranged between 26.24 and 50.75 Mg C ha^{-1}, 29.00 and 58.25 Mg C ha^{-1} and 42.19 and 107.36 Mg C ha^{-1} in the *Eucalyptus* trees dominated stands, mixed tree species stands and indigenous tree species stands respectively. The mean SOC carbon (depth 0-15 cm) estimated in the treatments was 38.57 Mg C ha^{-1}, 44.65 Mg C ha^{-1} and 81.87 Mg C ha^{-1} was significantly higher in indigenous tree species stands than in the *Eucalyptus* trees dominated stands and mixed tree species stands (Table 4.7). The mean soil organic carbon (depth 15-30 cm) estimated in the treatments was 54.01 Mg C ha^{-1}, 41.57 Mg C ha^{-1} and 61.31 Mg C ha^{-1} in the *Eucalyptus* trees dominated stands, mixed tree species stands and indigenous tree species stands respectively was not significantly different. The percentage SOC in the indigenous tree species stands (0-15 cm and 15-30 cm) was significantly higher than in the adjacent *Eucalyptus* dominated tree stands and mixed tree species stands within the different depths (Table 4.7).

The increase in the density of *Eucalyptus* trees led to a significant reduction in soil carbon stocks Mg C ha^{-1} (Figure 4.5).

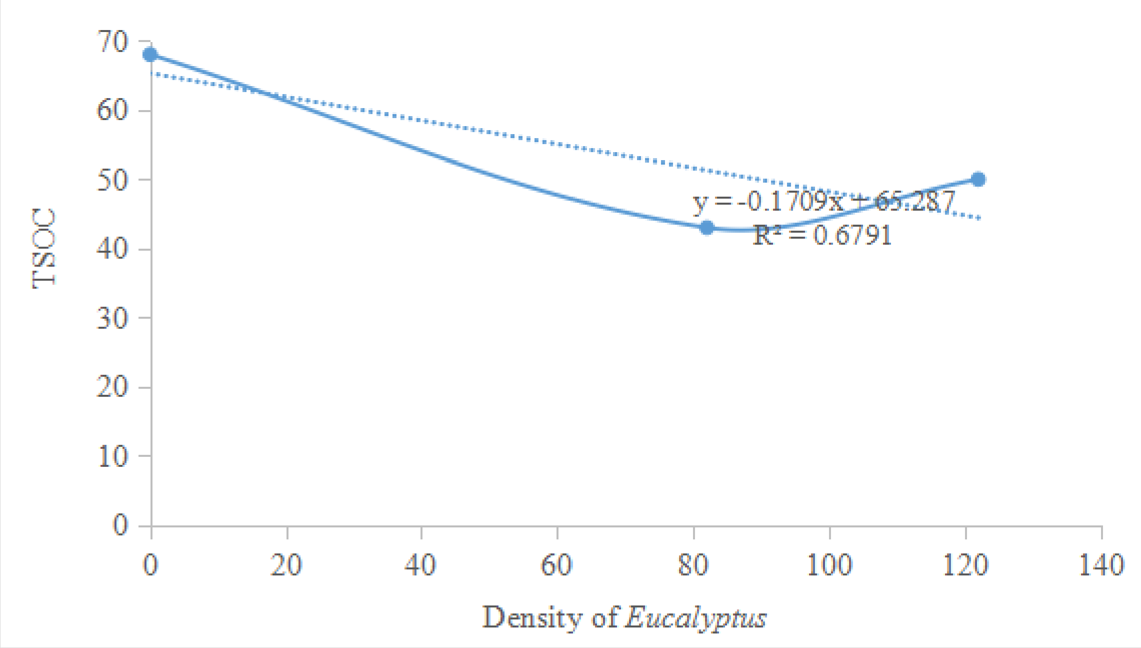

Figure 4.5: Effect of increase in density of *Eucalyptus* species on above and belowground carbon stocks within the treatments.

4.5 Effects of *Eucalyptus* trees on soil chemical and physical properties

4.5.1 Soil texture

The percentage of sand, silt and clay ranged between 22 and 56, 16 and 36 and 28 and 58 respectively. The percentage sand, clay and silt did not vary across the *Eucalyptus* trees dominated stand, mixed trees stand and indigenous trees stand (p= 0.394, 0.709, 0.247) respectively (Table 4.6).

The percentage sand, silt and clay did not vary across the *Eucalyptus* trees dominated stand, mixed trees stand and indigenous trees stand ($p > 0.05$) (Table 4.6). The results of the particle size analysis revealed that the soil under EDTS was clayey, with sand, clay, and silt contents of 22%, 58%, and 20% respectively, while the soils under MTS were found to be sandy clay loam, with sand, clay, and silt contents of 56%, 28%, and 16% respectively, and the soils under ITS where clay loam, with sand, clay, and silt contents of 32%, 38%.

Table 4.6: Soil texture (0-30 cm) (Mean ± SD) of *Eucalyptus* dominated tree stand (EDTS), mixed trees stand (MTS) and indigenous trees stand (ITS) in Kakamega Nandi Forest Ecosystem

Treatment	Sand	Clay	Silt
Eucalyptus dominated tree stands	35.33±5.58	41.00±5.63	23.67±2.33
Mixed trees stand	41.00±4.97	37.33±3.33	21.67±1.82
Indigenous trees stand	32.00±3.32	41.43±1.89	27.29±6.99
P	0.394	0.709	0.247

4.5.2 Nitrogen

The soil total nitrogen ranged between 1.31 and 13.73 Mg ha^{-1}. The soil total nitrogen and percentage nitrogen in all the treatments was not significantly different within the 0-15cm and 15-30cm depths (Table 4.7).

4.5.3 Phosphorus

The soil phosphorus ranged between 1.68 and 25.42 ppm. There was no significant difference in phosphorus concentration in soils of the three treatments (p= 0.079) (Table 4.7).

4.5.4 Potassium

The soil potassium ranged between 136.05 and 893.51 ppm. There was no significant difference in potassium concentration in soils of the three treatments (p= 0.06) (Table 4.7).

4.5.5 Soil pH

The soil pH ranged between 4.61 and 6.44 pH and significantly varied across the *Eucalyptus* trees dominated stand, mixed trees stand and indigenous trees (p= 0.002) (Table 4.7).

4.5.6 Porosity

The soil porosity ranged between -0.19 and -0.00. Porosity levels varied significantly across the treatments (p= 0.002). The indigenous trees stand had the highest porosity. Porosity decreased with increase in soil depth (Table 4.7).

4.5.7 Bulk density

The soil bulk density ranged between 1.00 and 1.49. There was a significant difference in bulk density across the treatments (p= 0.002). The indigenous trees stand had the lowest soil bulk density. Likewise, as depth increased, bulk density rose (Table 4.7).

Table 4.7: Soil physical and chemical properties (0-15 cm and 15-30 cm) (Mean ± SD) of *Eucalyptus* dominated tree stands (EDTS), mixed tree stand (MTS) and indigenous trees stand (ITS) in Kakamega-Nandi Forest Ecosystem.

Treatment	Depth	TSOC	TN	PH	EC	%C	%N	P ppm	K ppm	Porosity	Bulk density
EDTS	0-15 cm	38.57±3.478b	6.07±9.99	5.37±0.11b	0.04±0.00a	1.84±0.15b	0.74±0.44	10.30±2.11	237.70±27.35	0.438±0.00d	1.490±0.00a
	15-30 cm	54.01±6.96b	7.67±2.14	5.34±1.13a	0.36±0.00b	2.89±1.15b	0.35±0.09	7.33±2.58	208.45±15.16	0.436±0.00d	1.494±0.00a
MTS	0-15 cm	44.65±3.16b	3.47±0.62	5.97±0.12a	0.05±0.01a	2.17±0.17b	0.17±0.03	12.77±2.71	417.91±82.37	0.48±0.00c	1.38±0.00b
	15-30 cm	41.57±3.54b	5.59±1.14	5.95±0.12b	0.05±0.05b	1.96±0.17b	0.26±0.05	8.70±1.61	373.91±55.88	0.47±0.00c	1.41±0.00b
ITS	0-15 cm	81.87±10.60a	8.21±0.94	5.75±0.14b	0.10±0.02b	4.91±0.53a	0.51±0.07	4.47±1.64	395.74±64.97	0.59±0.02a	1.10±0.04d
	15-30 cm	61.31±24.22b	6.09±1.73	5.60±0.21b	0.05±0.01b	3.00±0.35a	0.341±0.09	4.14±1.14	323.45±91.71	0.55±0.01b	1.19±0.06c
p		0.19	0.479	0.002	0.0010	0.013	0.443	0.079	0.06	0.002	0.002

Different letters indicate significant differences across treatments at $p < 0.05$.

CHAPTER FIVE

DISCUSSION

5.1 Introduction

This section comprises the discussion of this study. It is organized in three parts namely, woody species diversity, above and below carbon stocks and soil chemical and physical properties.

5.2 Effect of *Eucalyptus* trees on woody species diversity

Increase in density of Eucalyptus tree led to a significance reduction in tree diversity. This may have been caused by the fact that there were other few tree species where *Eucalyptus* trees dominated. The fast rate of growth of *Eucalyptus* trees may have ensured that the trees grow fast at the expense of other woody species due to water and nutrient competition. The results of the study suggest that increase in the concentration of *Eucalyptus*, as illustrated by IVI and regression analysis, leads to lower woody species diversity. The phenomenon is likely caused by the effects of allelopathy (Qui *et al*., 2018). *Eucalyptus* species has allelopathic effect on other species growing around them and this leads to loss of understory biodiversity hence low species richness due to soil nutrient and water leading to competition (Zhao-hui *et al*., 2010, Wang *et al*., 2010, McMahon *et al*., 2019). This effect suppresses the tree performance by reducing the native species abundance (Vila *et al*., 2011) due to resource use and competition (Hejda *et al*., 2009). Allelopathy reduces the crops output and in some extreme cases it kills the entire plant due to water and nutrient competition as by Mukherjee *et al*., (2014) which suggest that, because of their capacity to outcompete crops and other vegetation for nutrients and water, eucalyptus imposes significant environmental costs.

The high number of *Eucalyptus* trees was due to their advantageous water and mineral uptake and is due to possession of deep root systems that aid in competition with other species (Zharo *et al*., 2007, Hamer *et al*., 2016, Holster *et al*., 2017). Allelopathic effect of *Eucalyptus* leads to decline in native tree survival and growth performance species grown around it hence need to look for mixed plantation with high tolerance to the allelopathic effect like *Markhamia lutea* and *Diospyros mespiliformis* as per studies by Kawawa *et al*., (2016). Exudates from the roots of *Eucalyptus* trees have an allelopathic influence on the growth of seedlings and young trees (Abdelmigid and Morsi, 2017, Song *et al*., 2019).

The woody tree species IVI of this study shows that *Eucalyptus* is the only species whose dominance was able reach 92.97%. A finding by Dos *et al*., (2008) shows that *Eucalyptus* trees had the highest IVI of 51.4%. According to a different study by Berhanu *et al*., (2002) on on-farm tree inventories, *Croton macrostachyus* (104%), *Acacia abyssinica* (45%), *Cordia africana* (36%), *Ficus vasta* (26%) and *Eucalyptu*s (11.9%) had the highest IVI values. *Eucalyptus* has a high IVI rating owing to their high relative density and frequency (Agidie *et al*., 2013). IVI value is a significant measure that reflects the ecological importance of species in a particular environment, according to (Zegeye *et al*., 2006). It is used in determining which species should be prioritized for conservation (Zegeye *et al*., 2006; Tadele *et al*., 2013; Berhanu *et al*., 2016). Species with high IVI values require low conservation effort, while those with low IVI values require high conservation effort. As a result, the majority of the woody species in the treatments had low IVI (10%) values and thus required conservation priority.

Reduced woody species diversity may compromise environmental safeguards, including reduced biological diversity and ecosystem services, such as pollination (Rai and Singh 2020). The Shannon index in this study's treatments ranged from 0.43 to 2.89, which was lower than in other studies (H'= 3.016-3.28 and 1.76-2.71) (Mekonnen *et al*., 2014; Eyasu, 2020). These results confirm the FAO's (1993) report that wild forests typically have more biodiversity than plantations of *Eucalyptus* species because natural ecosystems have a broader variety of species than plantations of Eucalyptus species. The high diversity in the forest for tree species is also because forests are protected areas with limited access and experience less loss than non-protected areas such as farms (Wade *et al*., 2020). However, anthropogenic sources of indigenous or exotic planting material (planted or grafted), typically produced on-farm or off-farm by tree nurseries, can be used to increase tree species diversity in *Eucalyptus* dominated tree stand (Oloo *et al*., 2013).

The Jaccard similarity index results show a greater dissimilarity of woody species between treatments. This is because of farmers introducing exotic trees for a variety of reasons, such as economic benefits in the *Eucalyptus* dominated tree stand and mixed tree stand, and thus keeping the accessible native woody species in the indigenous tree stand (Mensah, 2016; Eyasu, 2020). This is most likely due to their larger economic role (Talemos and Sebsebe, 2014) and the ecological requirement of the species' life strategy (Neelo et al., 2015).

The present mean woody species density for the three treatments was greater than those reported by Yitebitu, (2009) in southern Ethiopian and Yakob et al., (2014) at 78 trees ha^{-1} and 113 trees per hectare respectively was lower than what was stated for Arbegona as (705 trees ha^{-1}) by Muktar, (2006). The tree density of the treatments was within the range of what was reported in the southern Ethiopian agroforestry system (86-1082 trees ha^{-1}) (Tesfaye, 2005). Aboveground carbon stock was found to be strongly influenced by stand basal area (Mensah 2016).

The results show that as the DBH and height of the individual increased, the number of individuals reduced. This agrees with the findings of other studies that compared farm trees to natural forests (Gebrehiwot and Hundera, 2014; Eyasu, 2020). The diameter class distribution of these trees exhibited a negative exponential or inverted 'J' distribution pattern. This implies that most of the woody species with the lowest densities of individuals were of low DBH and height, while the size classes with the highest densities of individuals were gradually decreasing (Gebrehiwot and Hundera, 2014; Fashing and Gathua, 2004; Feyera and Denich, 2006). This shows that the woody species' tree populations are healthier because of the treatments (Tesfaye, 2005).

5.3 Effect of Eucalyptus trees on tree soil organic carbon/biomass carbon stocks

Increase in the density of *Eucalyptus* trees led to a significant reduction in carbon stocks. This may have been caused by the fact that there were other intervening factors that contributed to the recorded reduction in carbon stocks. For instance, the fast rate of growth of *Eucalyptus* trees may have ensured that their carbon stocks do not go too low compared to that of other woody species. Similarly, some of the woody species that were being replaced by *Eucalyptus* may not have been huge in size hence may not have necessarily had the largest carbon stocks.

Most of the understory species in a *Eucalyptus* plantation comprises of tree shrubs and saplings, this translates to low tree carbon due to small DBH, **t**his is in tandem with a study by Tang *et al*., (2007). Because of their small DBH, the increase in *Eucalyptus* trees resulted in a decrease in carbon stocks. Eucalyptus tree species grow quickly, but their proximity to roads, which has improved market access for wood products (Abebe *et al*., 2013), may lead to mature tree harvesting.

Despite the saplings being the majority not all of them grow to maturity because of the allelopathic effect from some of the larger species for instance, the *Eucalyptus* species which were the most abundant in the *Eucalyptus* dominated tree stand in study area (Agevi *et al*., 2019). Due to the growing need for wood for carbon sequestration, renewable energy, and climate change mitigation, *Eucalyptus* growth is anticipated to increase (Nkem *et al*., 2007; FAO, 2009).

The findings showed that compared to forest stands with smaller basal areas, those with larger basal areas had a considerably higher aboveground carbon storage. The results imply that the basal area contribution was attributed to stem DBH since stand basal area is a function of both stem DBH and stem density, the latter of which had been demonstrated to have negligible effect on aboveground carbon stock. This finding is consistent with the results of Chaturvedi *et al*., (2011), Omeja *et al*., (2011) and Ifo *et al*., (2014), who found that large trees, despite being less abundant, often store more aboveground carbon than smaller trees, which are typically much more abundant in tropical forest stands. According to Omeja *et al*., (2011), older tree stands have larger trees and thus increased biomass and basal area. The lower tree carbon in the on-farm study sites could be ascribed to the fact that most of the trees in these sites are mainly exotic like the *Eucalyptus* species and are known to have a lower carbon sequestration capability as likened to the native species (Meunpong *et al*., 2010). The low tree carbon among on-farm trees could be attributed to low soil fertility that affects tree growth (Oelbermanna *et al*., 2004) in a study in India's North-Western Himalayas, which discovered low biomass carbon stock as linked to variations in soil fertility, species diversity, strategies on management of trees, tree stand quality, structure, age and carbon concentration in various components.

Although increased carbon sequestration in vegetation is facilitated by high tree densities, overly dense stands may negatively affect tree growth and production due to competing effects, resulting in carbon sequestration decrease (Nair *et al*., 2010). As demonstrated by researchers such as Kuyah *et al*., (2012), Chave *et al*., (2005), DBH alone was used in the study to determine plant biomass. Agevi *et al*., (2019) also found it to be satisfactory when estimating biomass unlike including total tree height.

The results of tree biomass carbon of this study, *Eucalyptus* dominated tree stand were lesser than those by Kuyah *et al*., (2013). According to estimates in agricultural landscapes in Western Kenya the living tree biomass with *Eucalyptu*s predominance stores 11.71 Mg Cha^{-1} (Henry *et al*., 2009), (86.6 Mg C ha^{-1}), (Kuyah *et al*., 2013), (16 Mg C ha^{-1}), (Dimobe *et al*., 2018) and (Oeba *et al*., 2018) (85.012 Mg C ha^{-1}). When compared to the other study sites on the farmland, the indigenous tree stand had the highest carbon concentration. This high biomass could be attributed to higher tree density and relatively large tree sizes (Kuyah *et al*., 2014). Increased species diversity increased carbon storage Ruiz *et al*., (2011), as seen in the Indigenous tree stand. Otuoma *et al*., (2016) stated a significant variation in aboveground carbon stock, which they attributed to stand age variation. Omeja *et al*., (2011) demonstrated that older tree stands contain larger trees, resulting in an increase in biomass.

Species biodiversity (i.e., Shannon) was also identified as a factor that impacted on carbon stocks (Baishya *et al*., 2009). Although increased carbon sequestration in vegetation is facilitated by high tree densities, overly dense stands may negatively affect tree growth and production due to competing effects, resulting in decreased carbon sequestration (Nair *et al*., 2010). The biomass carbon stock under indigenous tree stand (9.05 Mg C ha $^{-1}$ in this current study was lower than previously reported in North East India (Brahma *et al*., 2018; Nath *et al*., 2021). The native trees in the tropics have the largest biomass C storage of any terrestrial ecosystem ranged from 30 to 255 Mg C ha^{-1} (Brahma *et al*., 2018; Olorunfemi *et al*., 2019). The average aboveground biomass carbon stocks calculated in this work inside the *Eucalyptus* dominated tree stands and mixed tree stands were less than the averages reported for agricultural landscapes in western Kenya, which were 9 Mg Various estimations provided elsewhere and in the current study, for example, (Abebe *et al*., 2013; Agevi, 2020; Agevi *et al*., 2017; Kumar and Mutanga, 2017; Mattsson *et al*., 2015), can be ascribed to plant diversity, management influence, and stand quality, among others. Furthermore, management practices, the age of the trees and human and natural disturbances all effects the aboveground and belowground carbon stored (Tilahun *et al.*, 2016). The study suggested a broad pattern of rising biomass carbon with growing tree size across all treatments. Native tree stands hold most of the biomass carbon stores because many large trees were found there.

SOC of acrisols has been reported to range between 37 Mg C ha^{-1} and 106 Mg C ha^{-1} globally, with an average of 51 C Mg ha^{-1} for the upper 30 cm layer (Omoro *et al*., 2013), the results of this study were within the range. On the contrary, the study's findings show that SOC is significantly lower in tropical forests than the worldwide organic soil carbon and nitrogen data (WOSCN) mean densities (minimum of 114 Mg C ha^{-1}). According to Kamoni *et al*., (2007) in Kenya different SOC data have been reported which may be clarified by differences in soil type, climatic conditions, and land use type because agricultural systems are known to store less SOC than forested systems (Mensah, 2016). Increase in density *Eucalyptus* trees led to a lower percentage carbon in the present study. This could imply that Eucalyptus tree litter is less easily incorporated into soil (Chapla and Campos, 2010; Kawawa *et al*., 2016) than other tree litter, thereby reducing the amount of C stored in the soil and living biomass.

The lower percentage of carbon in the *Eucalyptus* dominated tree stand and mixed tree stands soil maybe due to differences in plant litter decomposition rates under indigenous tree stands vegetation (Demessie *et al*., 2012). Mensah (2016) discovered that the average soil organic carbon under Eucalyptus plantation ranged from 22.6 to 125.2 t/ha. The high SOC observed in indigenous tree stands could be attributed to the dense vegetation cover, which accumulated C via higher litter returns, resulting in high SOC (De Kovel *et al*., 2000). This can also be accredited to the high diversity (Fang *et al*., 2009) in the ITS treatment.

The low carbon concentration on the *Eucalyptus* dominated tree stand and mixed tree stands is attributed to land disturbance during cultivation and harvesting of crops among other land use systems (Kamoni *et al*., 2007). The forest soils (indigenous tree stands treatment) on the other hand are less disturbed hence there is high carbon accumulation taking place (Omoro *et al*., 2013). The low carbon concentration in the *Eucalyptus* dominated tree stand and mixed tree stands soils as compared to the indigenous tree stands soils could was also associated with the fact that more of the trees were mainly exotic species on those treatment which have low carbon sequestration capacity as compared to the indigenous trees which are known to have a higher carbon sequestration capacity (Omoro *at al*., 2013).

The research sites' soil carbon stocks were within the ranges stated for agroforestry soil C (13 to 300 Mg C ha^{-1}) and soil carbon (28.2 to 98.9 Mg C ha^{-1}) in southern Ethiopian traditional agroforestry land use by Kumar and Nair (2021) and Demessie *et al*., (2013). The SOC stocks for agroforestry lands in Central India that were previously published, which were 27 Mg ha^{-1} in upper 60 cm soil layer (Swamy and Puri, 2005). The mixed tree stands and indigenous tree stands treatments' top soils exhibited high carbon concentrations, which dropped as soil depth increased. The large accumulation of SOC stocks was caused by the high quantities of litter-fall and other vegetative biomass (Kassa *et al*., 2017). Crop management techniques including crop rotation and crop residual retention help to increase SOC reserves in the topsoil layers (Raffa *et al*., 2015).

5.4 Effect of *Eucalyptus* trees on soil properties

The total nitrogen concentrations found in the treatments did not differ significantly (P >0.0 5). Alemie, (2009) found out that soil total nitogen concentrations decreased in Eucalyptus spp. plantations in Ethiopia, which contradicts the findings of this study. As a result, the insignificant total nitrogen concentration observed in the *Eucalyptus* tree stand soils likened to the mixed tree stand and indigenous tree stands soils was unexpected in this study. Other tree species were present in the treatments, which could explain why the amount of total nitrogen was not statistically different. Another study found that combinations of non-leguminous monoculture Eucalyptus species plantations and N-fixing tree plantings cycled more N and P through litter fall (Binkley and Stape, 2004). The rate of plant decomposition has an impact on the amount of nitrogen in soils (Cao *et al*., 2010). Demessie *et al*., (2012) reported that Eucalyptus spp. produces low nutrient concentration litter that decomposes slowly to release low nutrient concentrations, and N mineralization from Eucalyptus litter would have been significantly slower. The high rates of uptake of soil nutrient by plants was another explanation offered by Tererai *et al*., (2014) for the low total available N in Eucalyptus spp. plantings in South Africa. When compared to *Eucalyptus globulus* tree monocultures, according to Forrester *et al*., (2006), the addition of *Eucalyptus globulus* to *Acacia mearnsii* increased the amount and pace at which N and P were cycled through aboveground litter fall. The high levels of nitrogen in the EDTS and MTS could be attributed to the presence of some nitrogen-fixing trees in the sites. Nitrogen-fixing trees, according to Kassa *et al*., (2017) and Agevi (2020), play a crucial role in giving the soil organic matter, nitrogen and organic carbon. The accumulation of nitrogen and organic carbon in tree biomass is caused by the ability to fix atmospheric nitrogen and the connection with symbiotic bacteria and mycorrhizal fungi. The topsoil layer had a high numerical TN concentration than the subsoil layers though not statistically different (Nsabimana *et al*., 2008). Leaf litter fall and and animal droppings could be the reason of the high nitrogen accumulation on the top soil (Abegaz and Adugna, 2015).

Eucalyptus trees dominated stand and mixed trees stand had higher mean P than indigenous trees. Studies by Mensah (2016) who found that the available P concentration in the Eucalyptus plantation compared to the soil in the natural Forest, was much lower contradicts with results of this study. The low pH value could have caused a higher amount of soil accessible P to be fixed or absorbed, which could have resulted in the significantly lower available P measured for the indigenous tree stands soil (Mensah, 2016). *Eucalyptus* species have a stronger ability to immobilize phosphorus, making it unavailable to plants (Aweto and Moleele, 2005). According to Tening *et al*., (2013), when soil pH falls below 5.5, the availability of soil trace nutrients such as aluminum increases to levels unsuitable for the growth of most plants. Additionally, soil soluble phosphorus tends to form insoluble compounds with aluminium and iron in acidic soils, hence inaccessible to native plants. These results are consistent with observations made by Tening *et al*., (2013), the amount of inorganic phosphorus present in soil under *Eucalyptus* spp. plantation decreased with age. Other studies, however, demonstrate that, at both the 0–10 and the 10–20 cm depths of soil in Botswana, soil under Eucalyptus spp. plantations contained less readily available phosphorus than did forest (Aweto and Moleele 2005). Additionally, Alemie (2009) noted that in Ethiopian Eucalyptus spp. plantings within 2 cm of soil depth, accessible phosphorus concentrations were in the very low range (5 mg kg^{-1}). Most of the people in these areas work in agriculture as their primary occupation. Phosphorus fixation in soils may have contributed to the low amounts of phosphorus in the forest. Understanding the relationship between soil characteristics and P-fixation is crucial for the efficient application of phosphorus fertilizer on a range of soils in the western part of Kenya since the soils in this region often have low levels of accessible phosphorus (Tening *et al*., 2013). Phosphorus is found in soils with pH levels ranging from 6.5 to 8.0, which are slightly acidic to moderately alkaline. The soil in the forest were acidic. Manganese, Aluminium and Iron ions limit P availability in soils because of their solubility in soil to form acid compounds. This explains why acidic soils and moderately alkaline soils are deficient of P. Tening *et al*., (2013) and Furey and Tilman, (2021) found that P-fixation capability associated favorably with clay content and pH and negatively with organic carbon and accessible P in several soil strata taken from a soil profile in this area. *Eucalyptus* trees dominated stand and mixed trees stand had higher mean potassium than indigenous trees. This contradicts the outcomes of Aweto and Moleele (2005), who discovered cation of a lower exchangeable nutrient (magnesium, calcium, and potassium). According to the Eucalyptus species, soil nutrients are immobilized in their standing biomass quicker than they can be recycled back into the topsoil, leading to a gradual loss of the soil's exchangeable base over time. Posada and Schuur, (2011) found lower concentrations of exchangeable bases in *Eucalyptus* species plantations in Senegal and northern Nigeria, respectively. Potassium (K) content availability in the soil is influenced by a variety of factors such as soil structure, texture, pH, and organic matterThe indifference in K content in the study sites could be because their soils originate for the same parent rock and undergo the same weathering process as they experience the same climatic conditions (Deepthy and Balakrishnan, 2005). The study area also has same vegetation cover thus the same organic matter that could be influencing its K concentration in the soil.

The outcomes of this study agree with the findings of Musila, (2007) which states that soils within Kakamega Forest and its environments are acidic and mostly nutrient poor.

Kakamega Forest and its environs fall under the tropical rain forest ecosystems and their soils are characterized by low soil pH (Pereira *et al*., 2013). Low pH suggests that the study locations' tree species may have further acidified the soil by creating additional organic acids during the decomposition of their leaves (Sharma *et al*., 2011). In agroforestry systems and forests, Acheamfuor *et al*., (2014) connected low pH to ongoing nutrient uptake by trees and other plants. The excessive use of inorganic fertilizers during farm agriculture may also be to blame for the low pH values of the soils on the farms in the study areas. Additionally, it's possible that nitrogen and sulfur oxidation hastened the breakdown of organic matter in the soil, causing the pH to drop (Bahrami *et al*., 2010).

The pH of the soils under *Eucalyptus* dominated tree stand was significantly lower than that found in mixed and indigenous tree stand. The bases released by litter decay can help to prevent acidification (Mensah, 2015). This implies that as soil interchangeable bases decrease, so does soil pH, and vice versa. According to Aweto and Moleele (2005), Eucalyptus species immobilize soil exchangeable bases, particularly calcium, resulting in low soil pH. Honeck *et al*., (2011), most nutritional components are present in soil with a pH between 5.5 and 6.5, implying that the MTS and ITS soils were more fertile with greater plant nutrient availability than the EDTS soil. These findings are also consistent with the findings of Furey and Tilman, (2021), who discovered that in Botswana, soil pH beneath Eucalyptus camaldulensis was substantially lower than soil beneath native Acacia Forest at both the 0–10 cm and 10–20 cm soil depths. Similar findings were made by Leifield *et al*., (2005), who found that soil pH in Zimbabwe's original savanna woodland was higher than that in Eucalyptus grandis plantations.

Rawls *et al*., (2005) asserts that the acidity of the soil under Eucalyptus species is expected to rise over time. Porosity levels varied significant across the treatments ($p < 0.05$). The indigenous trees stand had the highest porosity.

Soil bulk density provides useful information about soil porosity, compaction, and penetration resistance (Horns and Fleige., 2003). Soil organic matter affects both porosity and bulk density by stimulating soil aggregation, which pulls down bulk density and escalates porosity (Rawls *et al*., 2005).

The *Eucalyptus* dominated tree stands soil had a significantly higher bulk density than the mixed tree stands and indigenous tree stands soils. The bulk density of soil is used to assess soil health and compaction (Furey and Tilman, 2021). A lower soil bulk density indicates that the soil is less compacted and can hold more water, whereas a higher soil bulk density signifies that less water is stored in the soil at field capacity (Kakaire *et al*., 2015). In a Brazilian soil with *Eucalyptus* spp. plantations, Ravina, (2012) found a higher soil bulk density of 1.24 g cm^{-3} compared to 0.66 g cm^{-3} in native forest (0-15 cm). The bulk density of fertile natural soils ranges from 1.1 to 1.5 g cm^{-3} (Kolay and Kolay, 2002). The study results supported those of Aweto and Moleele (2005), who indicated that *Eucalyptus* spp. plantations increased soil bulk density more than natural forest because the soil bulk densities in both the *Eucalyptus* dominated tree stands and indigenous tree stands soils were within this range. The difference in bulk density among treatments could be because of the amount of organic matter on the soil's surface, porosity, the amount of nutrients presents at different depths, and the minerals that make up the soil all differ, the bulk density values were consistent (Nath, 2014). Because subsurface layers are more compacted, have less organic content, aggregate, and root penetration, and have fewer pores than surface layers, bulk density normally rises with soil depth. The significant bulk density variation with depth is explained by the increased sand content in the upper soil layers. High soil organic carbon content leads to reduced soil bulk density at the topsoil surface (Chan, 2006). Similar findings about the soils in a plantation of *Eucalyptus* spp. were made by Alem *et al*., (2010). Both the upper (0-15cm) and inner soil layers of the treatments' soils were slightly acidic (15-30cm).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This chapter presents the study's conclusions and recommendations for future research.

6.2 Conclusions

For this study, it has been established that:

Objective 1; Increase in density of *Eucalyptus* trees led to a reduction in tree species diversity; leads to loss of other forms of biodiversity.

Objective 2; Increase in density of *Eucalyptus* trees on farms led to a reduction in carbon stocks; loss of capacity to offset carbon payments - farmers who have planted *Eucalyptus* trees get less carbon credit.

Objective 3; Increase *Eucalyptus* trees' density led to a significant decrease in percentage carbon, pH and porosity.

-Increase in density of *Eucalyptus* trees led to a significant increase in bulk density.

- Soil percentage nitrogen, phosphorus and potassium were not significantly affected by increase in density of *Eucalyptus* trees.

6.3 Recommendations

The following recommendations were derived from our study:

1. Tree diversity on farmlands should be emphasized rather than monoculture type of tree planting as this enhances more carbon stocks on farms (store biomass longer).

2. Although *Eucalyptus* species is a great economic gain, planting it should be done with environmental and social safeguards in mind.
3. Reducing the exploitation of litter resources can help increase soil carbon densities and nutrients.

The following recommendations for future studies:

1. Future studies on tree species diversity of farms further away from forest boundary.
2. Future studies on carbon trading on farms adjacent to the forest boundary.
3. Future studies should consider measuring the water table within the Kakamega-Nandi Forest Ecosystem and assess the environmental and social safeguards if any.
4. Future studies on *Eucalyptus* tree species' effects on water sources.
5. Future studies on farmers' views on the environmental impacts of *Eucalyptus* species on farms.

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APPENDICES

APPENDIX 1: DATA SHEET

ASSESSMENT OF FLORAL DIVERSITY IN KAKAMEGA-NANDI FOREST ECOSYSTEM

DATASHEET 1: FLORAL DATA WITHIN A SAMPLE PLOT

County………………………………Sub- County………………………………

Location……………………………… Sub location………………………………

Macro catchment**……………………………...**

Transect number.……………………… Sample plot number……………..........................

Plot GPS coordinates: UTM………………………Plot elevation (m): ……………………

Percentage slope …………………………………………………

FLORAL SURVEY DATA COLLECTION SHEET

A.

<u>AIN PLOT</u>

Main plot (20m by 10m) for assessing trees with (DBH ≥ 10 cm)					
Tree no.	Tree species name	Local name	Total height (m)	DBH (cm)	Remarks

B.SUB-PLOT 1

Sub-plot 1: (10m by 5m) for assessing tree saplings, lianas and shrubs within a DBH = 2 cm - 9.99 cm and at least 1.5 m height)					
Tree no.	Tree species name	Local name	Total height (m)	DBH(cm)	Remarks

APPENDIX II

ASSESSMENT OF SOIL PHYSICAL AND CHEMICAL PROPERTIES IN KAKAMEGA_NANDI FOREST ECOSYSTEM

County…………………………………Sub county……………………………

Location…………………………… Sub location……………………………

Macro catchment**……………………………...**

Transect no.…………………………. Sample plot No……………........................

GPS coordinates: ……………………………Elevation (m): ……………………

Percentage slope …………………………………………………

Date collected..

APPENDIX III

Appendices

Table 4. 8: Accumulated analysis of variance of an unbalanced design using R Gui regression

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ Species richness	9	26238.8	2915.4	6.00	<.001
Residual	22	10685.8	485.7		
Total	31	36924.6	1191.1		

Table 4. 9: Above ground carbon stocks Accumulated analysis of variance – overall (all sites)

Change	d.f.	s.s.	m.s.	v.r.	F pr.
+ IVI	25	349073	13962.9	25.66	<.001
Residual	6	3264.7	544.1		
Total	31	352337.7	11365.7		

Table 4. 10: Woody species, family and relative abundance within the treatments; that is *Eucalyptus* dominated trees stand, mixed trees stand and indigenous trees stand (n = 133, n=193 and n = 143) respectively.

S/N	Woody species	Family	RA (%) EDTS	RA (%) MTS	RA (%) ITS
1	*Alangium chinese*	Cornaceae			0.70
2	*Albizia grandibracteata*	Fabaceae			0.70
3	*Albizia gummifera*	Fabaceae			0.70
4	*Antiaris toxicaria*	Moraceae			7.69
5	*Bischofia javanica*	Phyllanthaceae		2.07	16.78
6	*Blighia unijugata*	Sapindaceae			0.70
7	*Bridelia micrantha*	Phyllanthaceae	0.75		1.40

8	*Celtis gomphophylla*	Cannabaceae			0.70
9	*Clausena anisata*	Rutaceae			0.70
10	*Croton megalocarpus*	Euphorbiaceae			1.40
11	*Dracaena fragrans*	Asparagaceae			2.80
12	*Ficus exasperata*	Moraceae			2.80
13	*Ficus sur*	Moraceae		1.04	9.79
14	*Funtumia africana*	Apocynaceae		0.52	11.19
15	*Craibia brownii*	Rubiaceae			2.10
16	*Lantana camara*	Verbenaceae			1.40
17	*Maesopsis eminii*	Rhamnaceae		1.04	0.70
18	*Manilkara butungi*	Sapotaceae			0.70
19	*Margaritaria discoidea*	Phyllanthaceae			0.70
20	*Markhamia lutea*	Bignoniaceae	0.75	3.11	2.10
21	*Oncoba spinosa*	Salicaceae			0.70
22	*Persea americana*	Lauraceae	1.50		0.70
23	*Polyscias fulva*	Araliaceae			2.80
24	*Psidium guajava*	Myrtaceae		1.55	11.89
25	*Sapium ellipticum*	Euphorbiaceae		1.55	1.40
26	*Solanum mauritanum*	Solanaceae		4.66	4.20
27	*Spathodea campanulata*	Bignoniaceae		0.52	4.90
28	*Trilepisium madagascariense*	Moraceae			2.10
29	*Vangueria apiculata*	Rubiaceae			1.40
30	*Vepris nobilis*	Rutaceae		0.52	1.40
31	*Vernonia auriculifera*	Asteraceae			1.40
32	*Zanthoxylum gilletii*	Rutaceae	0.75	9.84	0.70
33	*Acrocarpus fraxinifolius*	Fabaceae		1.04	
34	*Callistemon spp.*	Myrtaceae		0.52	
35	*Casimiroa spp.*	Rutaceae		1.04	
36	*Chrysophyllum albidium*	Sapotaceae		0.52	

37	*Cordia abyssinica*	Boraginaceae		1.04
38	*Croton macrostachyus*	Euphorbiaceae	0.75	5.70
39	*Cupressus lusitanica*	Cupressaceae		3.11
40	*Eriobotrya japonica*	Myrtaceae		0.52
41	*Eucalyptus grandis*	Myrtaceae	91.73	42.49
42	*Grevillea robusta*	Proteaceae	0.75	9.84
43	*Jacaranda mimosefolia*	Bignoniacaeae		0.52
44	*Kigelia africana*	Bignoniacaeae		0.52
45	*Mangifera indica*	Anacardiaceae		0.52
46	*Olea capensis*	Oleaceae		0.52
47	*Pinus patula*	Pinaceae		1.04
48	*Syzygium guineense*	Myrtaceae		1.04
49	*Trema orientalis*	Cannabaceae		0.52
50	*Vitex keniensis*	Lamiaceae		3.11
51	*Harungana madagascariensis*	Hypericaceae	3.01	

Table 4. 11: Woody species Relative Dominance (RDo %), Relative Density (RD %), Relative Frequency (RF %) and Important Value Index (IVI) in Eucalyptus dominated tree stand.

Woody Species	**RDO (%)**	**RD (%)**	**RF (%)**	**IVI (%)**	**IVI/3**
Eucalyptus grandis	92.47323	94.70588	91.72932	278.9084	92.96948
Harungana madagascariensis	2.693108	1.176471	3.007519	6.877097	2.292366
Croton macrostachyus	0.030959	1.176471	0.75188	1.959309	0.653103
Persea americana	3.794477	0.882353	1.503759	6.18059	2.060197
Grevillea robusta	0.429372	0.294118	0.75188	1.475369	0.49179
Bridelia micrantha	0.141504	1.176471	0.75188	2.069854	0.689951
Markhamia lutea	0.421457	0.294118	0.75188	1.467455	0.489152
Zanthoxylum gilletii	0.43736	0.294118	0.75188	1.483357	0.494452

Table 4. 12: Woody species Relative Dominance (RDo %), Relative Density (RD %), Relative Frequency (RF %) and Important Value Index (IVI) in Mixed tree stand.

Woody species	**RDO (%)**	**RD (%)**	**RF (%)**	**IVI (%)**	**IVI/3**
Acrocarpus fraxinifolius	1.125442	0.4158	1.036269	2.577512	0.859171
Bischofia Javanica	2.858799	1.455301	2.072539	6.386639	2.12888
Callistemon sp	0.0797	0.831601	0.518135	1.429436	0.476479
Croton macrostachyus	5.169485	5.405405	5.699482	16.27437	5.424791
Casimiroa sp	2.817589	0.4158	1.036269	4.269659	1.42322
Chrysophyllum albidium	1.074722	0.2079	0.518135	1.800757	0.600252
Cordia abyssinica	0.388156	1.039501	1.036269	2.463926	0.821309
Cupressus lusitanica	2.780941	1.871102	3.108808	7.760851	2.58695
Eriobotrya japonica	1.526942	0.2079	0.518135	2.252977	0.750992
Eucalyptus grandis	45.15675	41.99584	42.48705	129.6396	43.21321
Ficus sur	0.064022	1.663202	1.036269	2.763493	0.921164
Funtumia africana	0.018013	0.831601	0.518135	1.367749	0.455916
Grevillea robusta	10.71762	5.821206	9.84456	26.38338	8.79446
Jacaranda mimosefolia	0.053548	0.831601	0.518135	1.403283	0.467761
Kigelia africana	0.053548	0.831601	0.518135	1.403283	0.467761
Maesopsis eminii	8.72571	0.4158	1.036269	10.17778	3.392593
Mangifera indica	0.709484	0.2079	0.518135	1.435519	0.478506
Markhamia lutea	0.447058	4.365904	3.108808	7.921771	2.64059
Olea capensis	0.018013	0.831601	0.518135	1.367749	0.455916
Pinus patula	0.14672	1.663202	1.036269	2.846192	0.948731
Psidium guajava	0.039947	2.494802	1.554404	4.089153	1.363051
Sapium ellipticum	0.071647	2.494802	1.554404	4.120853	1.373618
Solanum mauritanum	0.269387	7.484407	4.663212	12.41701	4.139002
Spathodea campanulata	2.248485	0.2079	0.518135	2.97452	0.991507
Syzygium guineense	1.421989	0.4158	1.036269	2.874058	0.958019
Trema orientalis	0.064793	0.831601	0.518135	1.414528	0.471509
Vepris nobilis	0.062458	0.831601	0.518135	1.412193	0.470731
Vitex keniensis	0.575444	4.365904	3.108808	8.050157	2.683386
Zanthoxylum gilletii	11.3136	9.56341	9.84456	30.72157	10.24052

Table 4. 13: Woody species Relative Dominance (RDo %), Relative Density (RD %), Relative Frequency (RF %) and Important Value Index (IVI) in Indigenous tree stand.

Woody species	**RDo (%)**	**RD (%)**	**RF (%)**	**IVI (%)**	**IVI/3**
Alangium chinese	0.288421	0.278552	0.699301	1.266273	0.422091
Albizia grandibracteata	0.341564	0.278552	0.699301	1.319417	0.439806
Albizia gummifera	0.754735	0.278552	0.699301	1.732587	0.577529
Antiaris toxicaria	22.30675	3.064067	7.692308	33.06313	11.02104
Bischofia Javanica	27.15203	8.356546	16.78322	52.29179	17.4306
Blinghia unijugata	0.086317	1.114206	0.699301	1.899824	0.633275
Bridelia micrantha	1.459281	0.557103	1.398601	3.414985	1.138328
Celtis gomphophylla	0.00483	1.114206	0.699301	1.818337	0.606112
Clausena anisata	0.086317	1.114206	0.699301	1.899824	0.633275
Croton megalocarpus	0.419658	0.557103	1.398601	2.375362	0.791787
Dracaena fragrans	0.039171	3.62117	2.797203	6.457544	2.152515
Ficus exasperata	1.19067	1.949861	2.797203	5.937734	1.979245
Ficus sur	23.64641	9.192201	10.48951	43.32812	14.44271
Funtumia africana	0.282084	16.99164	11.18881	28.46254	9.487513
Heinsena dorvilleidae	0.158931	2.506964	2.097902	4.763797	1.587932
Lantana camara	0.058572	2.228412	1.398601	3.685586	1.228529
Maesopsis eminii	0.118572	0.278552	0.699301	1.096424	0.365475
Manikara butungi	0.288421	0.278552	0.699301	1.266273	0.422091
Margaritaria discoidea	0.048902	1.114206	0.699301	1.862409	0.620803
Markhamia lutea	0.027505	3.342618	2.097902	5.468025	1.822675
Oncoba spinosa	0.031297	1.114206	0.699301	1.844804	0.614935
Persea Americana	1.322306	0.278552	0.699301	2.300158	0.766719
Polyscias fulva	1.772991	2.785515	2.797203	7.355709	2.451903
Psidium guajava	0.298042	18.9415	11.88811	31.12766	10.37589
Sapium ellipticum	0.276216	1.392758	1.398601	3.067575	1.022525
Solanum mauritanum	0.265727	6.685237	4.195804	11.14677	3.715589
Spathodea campanulata	7.839813	1.949861	4.895105	14.68478	4.894926
Trilepisium madagascariense	8.064812	1.671309	2.097902	11.83402	3.944674
Vangueria apiculata	0.060129	2.228412	1.398601	3.687143	1.229048
Vepris nobilis	0.011068	2.228412	1.398601	3.638081	1.212694
Vernonia auriculifera	0.033632	2.228412	1.398601	3.660646	1.220215
Zanthoxylum gilletii	1.264821	0.278552	0.699301	2.242673	0.747558

APPENDIX IV

PHOTOGRAPHS DURING THE RESEARCH

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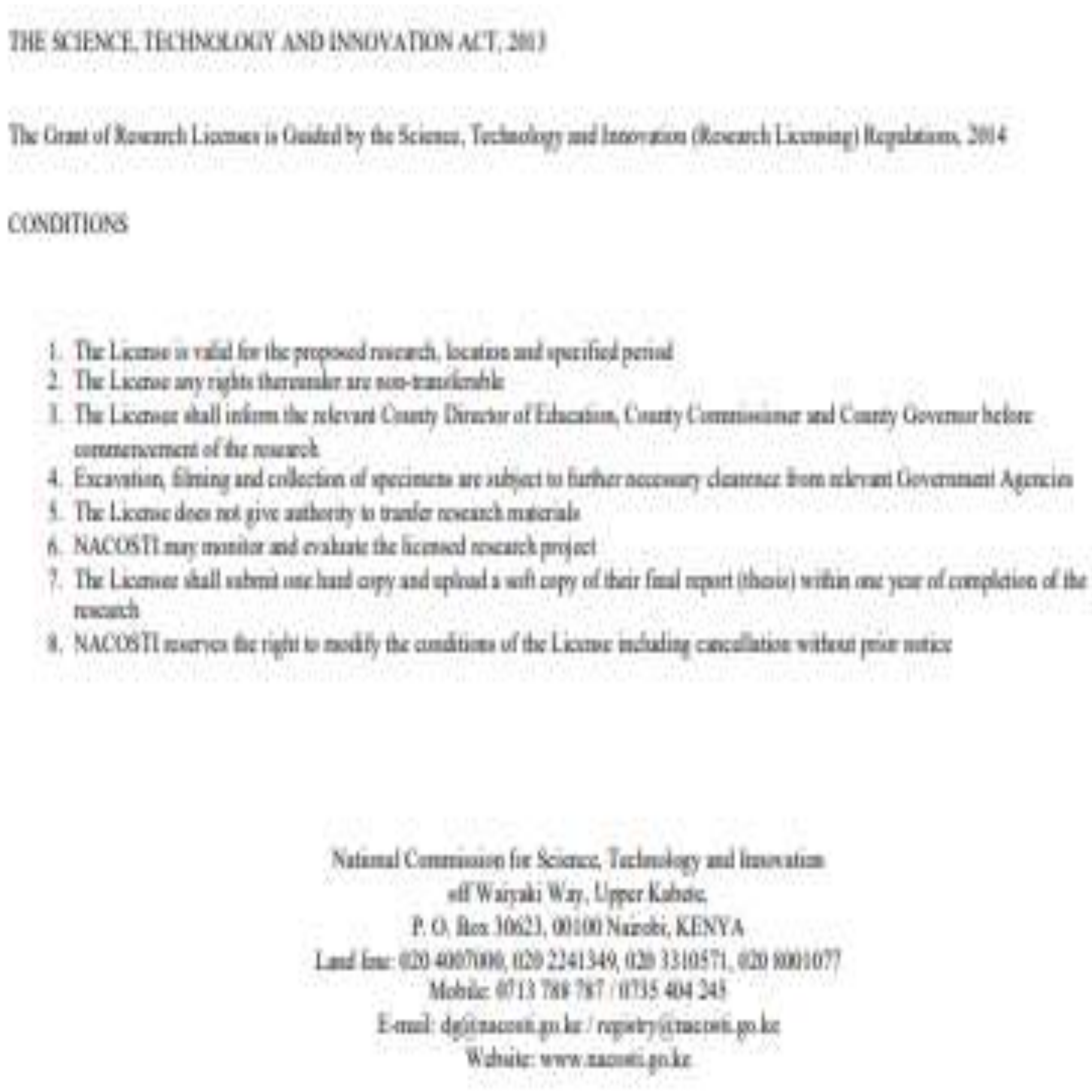

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