SPATIO-TEMPORAL CHANGES IN ABOVE-GROUND SEQUESTERED CARBON AND ITS RELATIONSHIP WITH TREE SPECIES DIVERSITY IN KAKAMEGA AND NORTH NANDI FOREST ECOSYSTEMS

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DECLARATION

This thesis is my original work prepared with none other than the indicated sources and support and has not been presented elsewhere for a degree or any other award.

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CERTIFICATION

The undersigned certify that we have read and hereby recommend for acceptance of Masinde Muliro University of Science and Technology a thesis entitled "**Spatio-Temporal Changes in Above-ground Sequestered Carbon and its Relationship with Tree Species Diversity in Kakamega and North Nandi Forest Ecosystems**".

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DEDICATION

I dedicate this thesis to my beloved mother Mrs. Margret Obonyo who not only provided material support that enhanced my progress but also kept me in prayers for excellence.

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ABSTRACT

Monitoring aboveground carbon (AGC) dynamics and tree diversity functionality relationships is crucial to understanding the role of vegetation in implementing climate change mitigation strategies and promoting sustainable forest management. Despite the continued negative effects of climate change on the biophysical environments, forests that constitute crucial carbon sinks for mitigating climate change continue to reduce in size due to anthropogenic degradation. This study sought to determine the spatial and temporal changes in Aboveground Carbon (AGC) stocks and its relationship to tree species diversity in Kakamega and North Nandi Forests. Specifically, the study (i) determined the spatial changes in AGC stocks (ii) assessed the temporal changes in AGC stocks (iii) evaluated relationships between tree species diversity and AGC stocks. Four study sites were chosen in each of the forest types (least disturbed, plantations and disturbed) for data collection. In each forest type, four 50m x50m quadrat were established within which mature trees were sampled for diameter, height, and wood density, while 192 - 1m x1m plots were laid for herbs and shrubs sampling. In every 50mx50m plot established, all trees were counted, and identified to species level. Tree diameter was measured using the diameter tape at 1.3m above the ground for trees of DBH≥5cm.Tree height was estimated using a Suunto clinometer while wood density obtained from wood density database. Improved Chave allometric equation for the African moist tropical forests ($W=F.\rho D^2H$) was used to estimate tree biomass which was converted to AGC. Landsat satellite images from the United States Geological Survey's Landsat archive for the period 1988 to 2020 were used to obtain temporal biomass from which temporal AGC was determined. SPSS version 25 was used to analyze the data. Kruskal-Wallis and Mann Whitney U tests were performed to assess the variation in carbon and tree diversity between forests and forest status. Correlation was performed to analyze the relationship between tree diversity and AGC. Results showed that Kakamega Forest had the highest mean AGC (157.93 ± 26.91 t ha^{-1}) while North Nandi Forest had (97.83 ± 19.89 t ha^{-1}). Least disturbed forest areas recorded the highest mean AGC (65.96 ± 8.56t ha^{-1}), followed by plantation sites (26.69 ± 1.12 t ha^{-1}), while disturbed forest sites had (3.26 ±0.11t ha^{-1}). This was statistically significant ($X^2(2, N=24) = 17.47$, p= 0.001). Management regime, and variation in tree species diversity were suspected to play key role in carbon variations. Temporally, AGC showed a decadal increasing-decreasing pattern that positively correlated with vegetation cover changes in both Kakamega (r=0.85) and North Nandi (r=0.72) Forests. However, the correlations were not statistically significant ($p>0.05$). Shannon Wiener's diversity index revealed a higher tree species diversity in Kakamega Forest (H´= 1.82 ± 0.95) relative to North Nandi Forest 's (H´= 1.24 ± 0.88). A significant positive correlation between the AGC and tree species diversity (r= 0.62, $p< 0.05$) was recorded. Management regime, and abiotic factors were suspected to play key role in diversity variations. Conclusively, Kakamega and North Nandi forests vary spatially and temporally in their AGC stock. Tree species diversity positively affects carbon stock of these two forests. Mixed indigenous plantations should be adopted in restoration of disturbed forest areas. A holistic management approach involving all players and focused on alternative livelihood options should be prioritized in forest management. Further studies should investigate the below ground carbon stocks to fully understand the role forest compartments play in forest carbon dynamics.

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LIST OF ABBREVIATIONS AND ACRONYMS

AGB- Above Ground Biomass

AGC - Aboveground Carbon

DBH- Diameter at Breast Height

ENVI- Environment for Visualizing Image

FAC- Forest Adjacent Community

GIS - Geographic Information System

IPCC- Intergovernmental Panel on Climate Change

KFS – Kenya Forest Service

KWS – Kenya Wildlife Service

MSS- Multi-Spectral Scanner

NDVI- Normalized Different Vegetation Index

OLI- Operational Landsat Imager

Pg C- Petagrams of Carbon

TgC - Teragrams of carbon

TM- Thematic Mapper

UNSDGs-United Nations Sustainable Development Goals

USGS- United States Geological Survey

CHAPTER ONE

INTRODUCTION

1.1. Background Information

Carbon is not only one of the most abundant elements on earth but also an important element in sustaining life. It is present in both organic and inorganic, gas, liquid, and solid forms. Food, hydrocarbons, fossil fuels, crude oil, and wood, among others constitute the sources of carbon on earth (Hazen *et al.*, 2013). Biologically, it forms part of the compounds that make up living organisms. Despite the many crucial roles that carbon plays in sustaining life, there are forms of carbon that are potentially harmful and toxic in many ecosystems (Schuur *et al.*, 2015). With a relatively longer residence time in the atmosphere, excess carbon dioxide as a greenhouse gas, together with other greenhouse gases form a blanket of gases that only permits entry of radiant energy from the sun into the earth surface but blocks the emission of infrared rays back to the upper part of the atmosphere. This results to an imbalanced heat wave in different part of the earth surface (global warming) leading to climate change (Mohammadi *et al.*, 2013).

Climate change is currently the biggest global concern in the 21st century because of its potential to adversely affect different biophysical environments (Lin & Ouyang, 2014). Some of the adverse effects of climate change include biodiversity loss, reduced agricultural productivity, erratic weather patterns that may lead to droughts, floods, etc. and ultimately food insecurity, outbreaks, and prevalence of emerging diseases, among others. According to Keller (2014), the inability of terrestrial ecosystems such as forests to effectively sequester carbon is one of the major drivers of climate variability.

There is a need for urgent action to avert climate change and its negative effects (Hicks *et al*., 2014).

The United Nation's sustainable development goal number 13 urges all nations to take urgent actions to mitigate climate change and its negative impact. As a committed country to the global missions, Kenya, among other global commitments in this regard signed the COP21, the Paris agreement on climate change which requires nations to take action to reduce the global temperature by 1.5ºC by 20100 (Dalla et al., 2017). To actualize her ambitions to mitigate climate change and its negative impacts, Kenya set the limit of achieving a 30% reduction of domestic greenhouse gas emission by 2030 (Dalla et al., 2017). Nature-based actions such as sustainable management of forest resources enhance the ability for sequestration of excess carbon dioxide by the forests (Murdiyarso *et al*., 2015).

Tropical forests are among the richest ecosystems in the world. They are thus important in the global carbon sink and cycle since they store large amounts of total terrestrial organic carbon through the exchange of carbon dioxide (CO2) with the atmosphere through photosynthesis (Navarrete-Segueda et al., 2018; Keller et al., 2014). However, they are also habitat with the highest rate of degradation attributed to anthropogenic influence (Temgoua et al., 2018; World wildlife fund, 2016; Lucie *et al*., 2018). Primary attention has always been given to forests, which account for 45% of terrestrial carbon stocks and are responsible for 17% of annual radiative forcing through deforestation (Ramachandra and Bharath, 2020; Birdsey et al., 2013; IPCC, 2007, 2010).

Nonetheless, the potential for carbon sequestration in the tropical rainforests is directly linked to tree species diversity Liu *et al*., 2018). The complex connection between tree species diversity and carbon stock has received particular emphasis over the last decades (Gebrewahid and Meressa, 2020; Van Con et al., 2013) as they help to optimize the most environmental benefits of carbon storage and biodiversity conservation in the forest ecosystems. High species richness and abundance contribute to high diversity which can significantly enhance ecosystem resilience and stability thereby promoting ecosystem health, primary production, biomass accumulation and eventually carbon sequestration potential below and aboveground the ground of forests (Di Sacco et al., 2021). A clear understanding of how diversity affects ecosystem function is important as it provides direct strategies for the conservation and restoration of threatened natural ecosystems (Mensah et al., 2016). This presents an urgent need to estimate the level of tree species diversity and the corresponding carbon stocks stored in the existing forests (Mensah et al., 2016).

Dynamics of carbon in different forest sinks, however, depend on the amount of carbon allocation in various carbon pools (Babst *et al*., 2014; Restrepo-Coupe *et al.,* 2017). Globally, world forest ecosystems contain 85-90% of the total vegetation biomass (Guo *et al*., 2013). However, these ecosystems suffer a lot of degradation and disturbances (Agevi *et al.*, 2014). This hampers the forest ecosystem health and impairs their ability to effectively sequester carbon (Garrard and Beaumont, 2014). The major degradation in these forest ecosystems is anthropogenic and includes but not limited to clearance of forests to pave way for large scale agriculture, human settlement, commercial activities, social and recreational purposes, and conversion to pasture lands (Khaine and Woo, 2015). The challenges facing forest ecosystems have been reported in many parts of the world including Brazil, Costa Rica, Indonesia, New Zealand, India, and Congo among others (Lagomasino *et al*., 2019). Kenya is not an exception to these challenges particularly the tropical rain forests of the western part (Kakamega forest ecosystem) which forms the only true tropical rain forest in East Africa (Otieno *et al*., 2014). For instance, a reduction in the overall size of both North Nandi and Kakamega forest has been reported, attributed to anthropogenic activities. According to Bett et al. (2017), North Nandi Forest has lost approximately 1400 ha of land to settlement and agriculture alone since its gazettement in 1936. Additionally, Nyongesah and Li (2021) attributed the 50% loss of the Kakamega forest area since its gazettement in 1933 to largely the encroachments by forest adjacent communities for agriculture, and settlement. The degradation and fragmentation of these study forests continues despite their important roles in providing ecosystem goods and services such as food and climate regulations (Mutoko et al., 2015). The effects of degradation cumulatively contribute to other collateral effects such as severe changes in the climatic patterns, which destroy the forest ecosystems and lead to a reduction of carbon sinks capacity (Garrard and Beaumont, 2014). Other long-term effects include reduced forest cover, increased degradation, and inability of forest ecosystems to effectively offer ecosystem services.

Changes in the forest cover effectively contribute to Spatio-temporal changes in aboveground carbon (AGC) stocks. Spatio-temporal changes in AGC stocks refer to dynamics in the carbon sequestered in the above ground biomass in different geographical areas (Babst *et al*., 2014). Yao *et al. (*2015) affirmed that vegetation reduces atmospheric carbon through photosynthesis and stores excess carbon as biomass. Hicks *et al. (*2014) explained that this phenomenon is of primary importance in determining primary productivity, balancing the atmospheric carbon dioxide and oxygen, and eventually in minimizing the negative effects of climate change which is currently the biggest 21st century global problem of concern. However, the potential for carbon sequestration is anchored on the availability of tree cover, tree abundance and diversity in the terrestrial systems. This study sought to analyze the spatial and temporal changes in AGC stocks and their relationship to tree species diversity in Kakamega and Nandi Forest ecosystems. This will provide understanding of the roles of different vegetation types in carbon sequestration.

1.2. Problem Statement

Drastic dynamics in forest cover due to land use changes occasioned by anthropogenic activities has been witnessed globally (Garbach *et al*., 2014). This in turn has resulted in increased effects of climate change due to reduced forest cover, and changing stand biomass in trees, which in turn reduce terrestrial carbon sink efficiency while promoting global warming.

Kakamega and Nandi Forests experience immense challenges occasioned by rapid population growth that is directly linked to resource extraction (Lagomasino *et al.*, 2018; Vuyiya *et al.,* 2014). Encroachment of Kakamega and North Nandi forests for agriculture, settlements, grazing; timber and wood fuel extractions, illegal charcoal production, and illegal logging are immense (Girma et al., 2015; Nyongesah and Li, 2021). This has been evident through significant reduction in the overall forest cover of these two forests. For instance, Girma et al. (2015) attributed more than 950 ha loss of North Nandi Forest cover between 1967 and 1985 to agriculture and settlement. Nyongesah and Li (2021) reported that close to 50% of the Kakamega forest has been lost to anthropogenic activities since its gazettement in 1933. This possibly drives widespread reduction in vegetation structure, tree species diversity and richness which can impair aboveground carbon sequestration potential thus increasing vulnerability to negative impacts of climate change.

Few studies have been done in Kakamega and North Nandi Forests on carbon storage potential. However, knowledge on the relationship between aboveground carbon (AGC) stocks across these heterogeneous landscapes and how they relate to tree species diversity remains scanty. This is even exacerbated by the fact that accurate measurement of carbon stocks in forest ecosystems is still challenging due to spatial variability of forests, lack of distinction between primary and secondary forests, small inventory areas, and lack of accurate allometric model to use (Chave et al., 2014). Due to degradation, species diversity information is dynamic and requires frequent update. The need for data on carbon variability and species diversity status of Kakamega and North Nandi Forests is real as this can provide useful information for climate change vulnerability assessments, and carbon credit schemes among others.

1.3. Justification

Quantification of the carbon stocks of forests is receiving global attention due the role plants play in carbon sequestration and the mitigation effects they have on climate change. Climate change remains a threat to life on earth in the present as its negative impacts continue to cause detrimental effects on biophysical environments (Peñuelas *et al.*, 2013). Biodiversity loss, emergence and spread of climate-related diseases, loss of agricultural productivity, flooding, phenological changes among others are examples of negative impacts of climate change (Garrard and Beaumont, 2014). Despite the reality of negative impacts of climate change, degradation of the potential carbon sinks (Kakamega and North Nandi Forests) through anthropogenic activities continues to showcase (Bett, 2016; Tsingalia, 2020). This will exacerbate vulnerability to the negative impacts of climate change.

Monitoring spatial changes in aboveground carbon stocks distribution in forest ecosystems and how tree diversity influences it helps to understand the role of vegetation in implementing climate change mitigation strategies in addition to promoting sustainable forest management (Vashum and Jayakumar, 2012). This will go a long way in helping to achieve the sustainable development goal number 13 that requires urgent action to be taken to combat climate change and its negative impacts. It is therefore important to quantify and reduce uncertainty in our estimates of AGC storage to better understand future losses, and to underpin carbon sequestration initiatives aimed at mitigating this loss. Quantification of how tree species diversity co-varies with AGC storage (McNicol *et al*., 2018) to highlight any important trade-offs will help inform mutually beneficial conservation schemes. The findings of this study will be useful to both government agencies in environmental conservation and management, global environmental entities, and scholars in promoting sustainable forest resources utilization and management, and for research improvements.

1.4. Objectives

1.4.1. General Objective

The main objective of this study was to determine the spatial and temporal changes in aboveground Carbon stocks and their relationship to tree species diversity in Kakamega and North Nandi Forest ecosystems.

1.4.2. Specific Objectives

The specific objectives of this study were to:

1. Determine the spatial changes in Aboveground Carbon stocks in Kakamega and North Nandi Forest ecosystems.
2. Determine the temporal changes in Aboveground Carbon stocks in Kakamega and North Nandi Forest ecosystems.
3. Evaluate the relationships between species diversity and Aboveground Carbon stock in Kakamega and North Nandi Forest ecosystems.

1.5. Research Hypothesis

1. H0: There is no significant difference in spatial Aboveground Carbon stocks in Kakamega and North Nandi Forest ecosystems.
2. H0: There is no significant difference in temporal Aboveground Carbon stocks in Kakamega and North Nandi Forest ecosystems.
3. H0: There are no relationships between species diversity and Aboveground Carbon stocks in Kakamega and North Nandi Forest ecosystems.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter describes various literature related to the area of study that have been set forth by other scholars in the past. The chapter specifically focuses on literature on spatial dynamics in carbon stocks, temporal dynamics in carbon stocks, the forest' tree species diversity and AGC stocks in tropical forests, and the knowledge gap. The literature described in this chapter is relevant in identification of the research gap and providing tips for filling them. It also provides insight into the techniques that were employed in estimating the AGC stock in both North Nandi and Kakamega forest ecosystems.

2.2 Spatial Dynamics in Carbon Stocks

Forest ecosystems play crucial life supporting roles (Margono *et al*., 2014). Continuous global rise in human population, industrialization and technological advancement have become drivers of degradation of forest ecosystems, consequently, impairing the ability of global forest ecosystems to effectively perform their roles (Garrard and Beaumont, 2014). These degradations are characterized by global decline in forest coverage, carbon stock and a resultant change of global climate whose effects continue to raise alarm even in the present (Peñuelas *et al*., 2013). Research on major tropical forest ecosystems across the world (tropical America, Asia, and Africa) reveals that forest cover change is directly proportional to spatial changes in carbon stocks (Hansen *et al*., 2019). A review of forest cover trends is therefore very important in the assessment of spatial carbon dynamics in forest ecosystems.

Global forest cover in 2015 was estimated at 31% of the entire land area (3999 Mha) (Keenan *et al*., 2015). Of the 3999Mha, tropical forests accounted for 40%. Europe was leading in forest cover at 25%, followed closely by South America and North America at 21% and 16% respectively (Keenan *et al*., 2015). Keenan *et al. (*2015) showed that high income countries recorded the highest percentage of forest cover compared to their lower income counterparts at cumulative percentage of 25% of the total global forest cover. Between 1990 and 2015 there was a 3% net decrease in the total global forest cover (Keenan *et al*., 2015). A study by Margono *et al. (*2014) on major forest ecosystems in Indonesia revealed that Indonesia surpassed Brazil in annual forest cover loss between the year 2000 and 2012; while between 2010 and 2015, Nigeria, Democratic Republic of Congo and Tanzania recorded the greatest forest cover loss in the continent of Africa (Keenan *et al*., 2015). Battles *et al. (*2018) further reported that forest disturbances from land use changes, wildfires among others continuously reduce the forest cover, and consequently reduce carbon storage potential by 11 TgC (teragrams of carbon) annually in North America.

A continued occurrence of natural disturbances in forest ecosystems poses a projected significant decline on future net carbon stock of the terrestrial forests globally (Battles *et al*., 2018). A study in Ethiopia assessing the carbon variation along different management regime found a high above and below ground carbon stock in the least disturbed areas relative to small carbon stock in highly disturbed areas (Yohannes *et al*., 2017).

Kenya has not been spared in forest cover dynamics and declining carbon stock in forest ecosystems. Were *et al. (*2015) reported forest cover reduction in the eastern Mau Forest due to anthropogenic activities. Mau forest (400km^2) forms one of the largest waters towers in Kenya, and its unsustainable utilization may lead to serious detrimental ecosystems implications (Were *et al*., 2015; Langat *et al*., 2016)). Many other forest ecosystems in Kenya, Kakamega forest included, face the same challenges of degradation as Mau Forest (Vuyiya *et al*., 2014). A research study by (Namasaka, 2021) in Kakamega forest reported a significant decrease in natural forest cover attributed to anthropogenic disturbances such as uncontrolled grazing, bioenergy, charcoal burning and illegal logging. This, according to Namasaka (2021) poses a great threat to tree species diversity in Kakamega Forest (about a half of the native forest cover has been lost). Beier and Gregory (2012) affirm that high level of poverty and rapid population growth around Kakamega forest coupled with high demand for food and economic development drive unsustainable utilization of both Kakamega and North Nandi Forest, further endangering the biotic community in these forests.

Additionally, a study by Agevi *et al. (*2016) on Western Kenya forests affirmed that the perturbations and management regimes have the potential to influence plant growth and survival and eventually inform the tree biomass and carbon stocks. The repercussions of the forest degradations are felt globally especially through climate changes, droughts, reduced agricultural productivity among others (Tarus & Nadir, 2020; Otuoma *et al*., 2016; Nakakaawa *et al*., 2011). Recent studies by Namasaka (2021) and Tsingalia (2020) indicate that Kakamega and North Nandi Forest continue to face degradation even currently, which may exacerbate not only human vulnerability to climate change but also affect other biotic community that depend on these forests.

2.3 Temporal Dynamics in Carbon Stocks

Climate of an area has potential to influence the temporal distribution of carbon in different geographical regions (Fu *et al*., 2015). The implication is that the distribution of carbon varies significantly within different seasons and along geographical gradients. Fu *et al. (*2015) further reported that biological, geological, environmental, and human factors cumulatively contribute to significant temporal changes in Aboveground Carbon stocks (Pan *et al*., 2011).

For instance, a comparative review study of the world's major forests, Pan *et al. (*2011) reported a net decline of 23% in carbon uptake between the years 2000 and 2007 compared to 1990 and 1999 in the tropical forests globally. This was attributed to severe drought in the Amazon Forest, severe deforestation, and land use changes across the tropics, among other factors. This also resulted in a cumulative increase in atmospheric carbon emission from the tropics by 1.5 ± 0.7 Petagrams of Carbon annually (Pan *et al*., 2011).

Globally, the forest cover has been gradually decreasing in tropical Asia, Africa, and Latin America while the reverse is true for the plantations between the year 1980 to 2000 (Houghton, 2005; Payn *et al*., 2015). However, Houghton (2005) reported that in the same period (1980 to 2000), the tropical forest of Asia showed a gradually decreasing decadal carbon stock in tons per hectare; with African tropical forest showing a decadal declining and increasing carbon stocks per hectare whereas Latin America showed an ever increasing per hectare carbon stocks. According to Baccini *et al. (*2017), climate variability has turned tropical forests to more of carbon sources than carbon sinks. The same study by Baccini *et al. (*2017) also reported that Asia contributes to a smaller carbon emission at 16.3 % followed by Africa at 23.8 % while America contributes the greatest at 59.8%. Tropical Africa alone is estimated to contain about 59.8 pentagrams of carbon (Pellikka *et al*., 2018).

A technology-based monitoring study of aboveground carbon stocks conducted by Nyamugama & Kakembo (2015) in South Africa revealed an interchanging declining and increasing pattern of aboveground carbon for the disturbed, transformed, and intact thicket areas over a 38-year period. This pattern of carbon stocks was attributed to overexploitation of forest resources (deforestation and illegal logging, and land use change over time). Zhao *et al. (*2020), in their study assessing the global temporal and spatial carbon variations for future climate between the year 2006 to 2100 established a decreasing and rising carbon scenario. The year 2006 to 2015 of this assessment study was characterized by a pure decline in global aboveground carbon stocks. The increasing and declining carbon stocks between the year 2006 to 2100 was reported to be majorly attributed to management systems in place, forest disturbances, and human activities.

In a monitoring study of the African tropical rainforest assessing the carbon loss hotspots, Csillik *et al. (*2022) also found an interesting pattern of reducing and increasing carbon loss over the years for almost all the sampled countries (23) with rainforests in Africa. This pattern of carbon loss over time was majorly attributed to seasonal changes and forest disturbances. Malhi *et al. (*2013) in their study of the present, past, and future of the African rainforests established that the African tropical forests have an average 395.7 Mg/ha of biomass, which is equivalent to 245.334 Mg of carbon per hectare. In a study assessing how land cover change may influence the carbon dynamics in the Afromontane Forest in Ethiopia between 1985 and 2016), Solomon *et al. (*2018) reported a temporally decreasing and increasing carbon stocks between different land cover types. This trend was majorly attributed to forest structural variations in the sampled forests. At the same time, East Africa forests have experienced a carbon reduction of 5.1% from the year 2000 to 2008 (Pellikka *et al*., 2018).

Kenya forests have undergone severe dynamics in history. Based on Ototo and Vlosky (2018), unsustainable utilization of forest resources was experienced between late 1980s to mid-1990s. This was caused by high demand for forest products such as timber and wood fuel, roundwood for electric poles, agricultural lands, and need for more settlement areas. As a result, a high level of degradation was felt with massive forest cover reduction. This, with a foreseen deficit of roundwood then made the government of Kenya to come up with initiatives such as imposing a barn on logging in 1999 to stop further logging activities, introduction of Shamba system in 2007 to increase regeneration of plantations and improve protection of forest resources by the community among others (Ototo and Vlosky 2018). According to Ototo and Vlosky (2018), when this logging barn was lifted in 2009, another massive degradation of the Kenya forests was prominent in individual forests.

A study done in Taita hills in Kenya and extrapolated from 1987 to 2003 indicated that there was a significant net reduction in AGC stock (Pellikka *et al*., 2018), attributed to land use changes. The Taita Hills forests have, however, proved to be more of carbon sink based on the extrapolated data between 1987 and 2003, while the Kilimanjaro Mountain forests were a significant carbon source (Pellikka *et al*., 2018). Between 1987 to 2003, Kakamega forest showed a carbon stock of 200Mg per hectare (Pellikka *et al*., 2018). Charles *et al*. (2020), in their study that assessed the aboveground biomass carbon sequestration by the carbon pools of southwestern Mau Forests between the year 1985 and 2015 reported an increasing and decreasing pattern of carbon after every 3 years, with a small annual carbon difference. This represented a mean carbon of 4,611.21 Kg/ha. However, variations in carbon stocks between the year 1985 to 2015 were attributed to the several factors including but not limited to both anthropogenic and natural perturbations, and the regeneration effects over time (Charles *et al*., 2020).

Kakamega forest ecosystem faces levels of perturbations that impair its ability to offer essential ecosystem services. According to Osewe et al. (2022) deforestation due to agriculture, overextraction of forest goods such as food, wood fuel, timber, and excisions among others do not only change the biodiversity structure of Kakamega forest but also compromise its ability to sequester carbon, among other essential ecosystem services. A vulnerability and land cover change assessment study in North Nandi Forest by Kuria et al. (2013) for the year 1986 to 2006 reported a significant reduction in natural forest and huge conversion of forest to agricultural land. This was attributed to extreme poverty levels by the North Nandi Forest adjacent communities which attracted overexploitation of forest resources; planned deforestation to satisfy the various development needs; and unsustainable forest management practices such as charcoal burning, overgrazing, illegal logging, and encroachments (Kuria et al., 2013). These activities degrading both Kakamega and North Nandi forests drive not only dynamics in the species diversity but also compromise provision of essential ecosystem goods and services such as climate change mitigation (Kuria et al., 2013; Osewe et al., 2022). Frequent updates of such useful information on diversity and carbon dynamics are lacking in Kakamega and North Nandi forests.

Spatial and temporal analysis of carbon stock in terrestrial ecosystems provides valuable data for the assessment of vulnerability to climate change. Despite its importance, studies done on tropical forests in Kenya (Kakamega and North Nandi forests) which form the true tropical forest in East Africa have not investigated spatial and temporal dynamics in the AGC stock. Lack of spatial and temporal data on the AGC stocks of the Kakamega and North Nandi Forest ecosystems presents a huge climate assessment gap in these two forest ecosystems despite the detrimental impacts of climate change that have remained a global threat to the biophysical environment.

2.4 Species Diversity and Aboveground Carbon Stocks in Forests

The study of plant communities in the forest ecosystem is critical in the analyses of correlation between plant species biodiversity and biomass (Li *et al*., 2018). Different findings have been reported by vast ecologists on the relationship between biodiversity and biomass in forest ecosystems. A cross review study on pine forests in the entire Europe revealed a weak correlation between biomass and biodiversity, while in

Southeast China forests, a similar study revealed a positive correlation between the two (Li *et al.*, 2018; Liu *et al*., 2018). Further studies in agroforestry systems on Java Island of Indonesia revealed lack of correlation between plant species diversity and carbon stocks (Filqisthi and Kaswanto, 2017). Li *et al. (*2018) however affirms that ecosystem functions are enhanced by species richness and this increase productivity, carbon flux and storage. Arasa-Gisbert *et al. (*2018) in their study on how tree species diversity influence carbon stock in the Mexican forest reveled a significant positive relationship between diversity and aboveground carbon stock with species richness as the biggest influencer though other abiotic factors such as climate and edaphic factors could also influence carbon stock of a forest.

Tropical forests are considered the most diverse ecosystems with high potential for carbon storage in the world. According to Day *et al. (*2014), tropical forests provide the largest carbon sinks and can store approximately 40% of the total global carbon of the terrestrial ecosystem. Additionally, tropical forests are also considered as carbon sources. In Africa for instance, tropical forest ecosystems are subjected to high rates of deforestation and degradation due to high dependency on forest resources by forest-adjacent communities, turning these ecosystems into carbon sources. It is estimated that tropical forests emit 12% to 20% of the global greenhouse emission (Day *et al*., 2014).

Forests, especially in the tropics, provide dependable sinks for carbon and are useful in mitigating the negative impacts of climate change. The potential for carbon sequestration in the tropics is directly linked to tree species diversity which in turn enhances carbon storage capacity by improving ecosystem resilience, primary productivity, and tree biomass accumulation (Liu *et al*., 2018).

Based on a study done in subtropical forests of Southeast China, Liu *et al*. (2018) demonstrated that a species rich stand forest ecosystem has higher carbon stocks and flux. Additionally, a peer review study evaluating the forestry systems that optimize carbon sequestration potential of forests established that high species richness and abundance contribute to high diversity and can significantly enhance ecosystem resilience and stability thereby promoting ecosystem health, primary production, biomass accumulation and eventually carbon sequestration potential below and aboveground (Di Sacco *et al*., 2021). In a separate peer review study across tropical forest of the world while investigating the influence of tree species diversity on carbon stock in tropical forest, van der Sande *et al. (*2017) established that carbon stock of a tropical forest positively relates with tree species diversity; and that tree diversity attributes such as species richness must be significantly considered if carbon sequestration potential of a forest is to be improved.

Additionally, Kunwar *et al. (*2021) while assessing relationship between species richness, diversity and aboveground biomass carbon of Nepal reported that tree species diversity and richness are primary predictor variables of aboveground biomass and that they have a significant influence on aboveground carbon. The same study by Kunwar *et al. (*2021) however, revealed that stand structure complexity (DBH) has insignificant and negligible influence on aboveground biomass carbon stock of Nepal forest. Ali *et al. (*2016) in their investigative study of impacts of stand structure and diversity on aboveground carbon in sub-tropical forests of eastern China revealed that stand structure (DBH) has a greater or significant positive influence on aboveground carbon. On contrary, Ali *et al. (*2016) reported that tree species diversity has no impact on the aboveground carbon in sub-tropical forests of eastern China.

Tropical forests in Africa are considered the second most diverse forest ecosystems globally (Day *et al*., 2014). Day *et al. (*2014) explained that Africa tropical forests have a high positive correlation between species richness (66.6%), diversity (59%) to aboveground Carbon respectively. A similar finding was reported in a study on forest ecosystems in Limpopo Province of South Africa (Mensah *et al*., 2016). Additionally, a study in Ghana revealed that species with large diameter at breast height contributed to a bigger percentage of carbon stored in forest ecosystems (Nero *et al*., 2018).

However, other studies have shown that the level of disturbance in the forest ecosystems negatively affect species diversity and carbon stock. This was confirmed by a study done in Taita Hills of Kenya which shows that disturbances altered the forest structure and species composition thereby reducing species diversity, which in turn caused a significant decline in carbon stock (Wekesa *et al*., 2019). Kogo *et al. (*2019) in their study assessing forest cover dynamics, their drivers, and implications in western Kenyan forest ecosystems reported that management regimes determine the level of forest management policy implementations, anthropogenic impacts on the forests, and aboveground biomass carbon accumulation over time. Kogo *et al. (*2019) explained further that areas under regular surveillance by either Kenya Wildlife Service (KWS) and Kenya Forest Service (KFS) are more secure and report low level of anthropogenic disturbances, both high species diversity and aboveground biomass carbon overtime.

Kakamega and North Nandi forests face high levels of degradation due to activities of respective forest's adjacent communities. These activities include unsustainable activities such as illegal logging, deforestation for agriculture, timber production, wood fuel extraction, overgrazing, among others (Girma et al., 2015; Osewe et al., 2022). As human population grow in Kenya, the need for more resources from the forest such as land for agriculture, settlements and other developments, wood fuel, grazing areas, among other are projected to continue in both Kakamega and North Nandi forests (Nyongesah and Li, 2021). These will potentially drive dynamics in tree diversity and carbon stocks in these two forests and need to be continuously updated for climate change vulnerability assessments.

Despite these dynamics in forest ecosystems globally, there is scanty information in North Nandi and Kakamega Forest ecosystems on how tree species diversity may influence the aboveground carbon stocks. Again, there is scanty information in Kenyan tropical forests regarding potential for carbon sequestration in the different forest types (least disturbed, disturbed and plantations) for climate change vulnerability assessments.

2.5 Wood Specific Gravity, Diameter at Breast Height, and Tree Height as Complementing Variables in Tree Biomass Estimation

Several studies have shown the importance of wood specific density, diameter at breast height and tree height in augmenting each other in biomass estimation. For instance, Chave (2006) reported that Wood specific gravity supplements DBH in determination of tree biomass- carbon stock. Wood specific gravity is the ratio of the total oven-dry mass of a tree to its green volume (Chave, 2006). Current ecologists have widely included wood density in the estimation of AGC because it has been established that together with tree height and DBH, the accuracy of the estimate is improved (Chave *et al*., 2005; Ketterings *et al*., 2001). Chave *et al. (*2005) further explains that DBH of a tree is a common predictive variable and cannot miss while the other two which are also crucial in AGB estimation in improving precision (tree height and wood specific gravity) may miss out depending on the forest type one is working on. According to Ketterings *et al. (*2001) inclusion of the tree height (H) in tree biomass estimation results in a slight improvement in precision. Tree height inclusion is also suited when one is comparing biomass of different sites (Ketterings *et al*., 2001).

2.6 Forest Understory Biomass

Understory of a forest refers to a vertically stratified layer of a forest sandwiched between the forest floor and the canopy layer and contains mainly shrubs and herbs (Ren *et al*., 2014). The penetration of light is very little into this layer and therefore species found in this layer are shade tolerant. In a study done in different forest ecosystems in South China, Chen *et al. (*2015) reported that understory contribute to about 20% of the total carbon stock in tree plantations of China. The tree trunks and canopy layer contain comparative large quantity of carbon relative to understory layer while old forest store large amount of carbon compared to the young forest (McGarvey *et al*., 2015). However, a study done in Northwestern Montana in USA indicates that the contribution of understory layer in carbon storage is significant and cannot be left out while determining the Aboveground Carbon content of a forest (Schaedel *et al.*, 2017). Zhao *et al. (*2014) affirm in a study done in Liaoheyuan (China) that forest floor and understory layers have small sequestration of carbon compared to canopy layer however all the layers must be considered when determining Aboveground Carbon content.

2.7 Biomass Estimation in Forest Ecosystem

Two methods were available for tree ABG estimation, the destructive and non-destructive methods. According to Vashum and Jayakumar (2012), even though destructive method is very direct and produces the most accurate result for tree AGB, it has several limitations which hinder its wide adoption globally. It is destructive of the environment, hence its name; it is also expensive, tedious, time consuming and cannot be used in disturbed and large geographical areas. (Vashum and Jayakumar, 2012). The use of allometric equations has provided a better alternative (non-destructive method) which has been widely adopted in the estimation of above ground biomass since it is non-destructive to the ecosystem in nature (Vashum and Jayakumar, 2012). It is best suited for areas with protected or rare species and high thickets because it does not require felling off vegetation (Kuyah *et al*., 2012a; Vashum and Jayakumar, 2012).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter describes methods and materials used to make the research study a success. Specifically, it describes the study location, the research design and sampling procedures and finally outlines how the sampled data was analyzed and presented.

3.2 Study Area

This study was carried out in North Nandi and Kakamega forests in western Kenya (Figure 1).

3.2.1 North Nandi Forest

The North Nandi Forest is in Nandi County and is considered one of the fragments of the once continuous easternmost Guinea-Congolian forests, Kakamega Tropical Rainforest, which formally constituted Kakamega, South and North Nandi Forests (Wachiye *et al*., 2013). though reported to have an area of 11 850hectares at gazettement in 1936 (Bett et al., 2017) extending in the two districts of Nandi County (Nandi north and central districts), about 960 hectares were lost to agriculture and settlement between 1967 and 1985 (Girma et al., 2015). The current area of this forest is 10 500 ha (Bett et al., 2017; Melly *et al*., 2020). This forest is bordered to the north-east by Uasin Gishu county; North-west by Kakamega County; and to the southeast by Nandi- south (Melly *et al*., 2020). It lies in the following global positions; (between longitude 34˚ 51' 0" E and 35˚ 10' 0" E; between the latitude 0˚ 12' 30" N and 0˚ 28’ 20” N; and at an altitude range of between 1700 and 2500 m above the sea level (Melly *et al*., 2020).

The forest and its surrounding experience bimodal rain patterns with long rain falling between March and June while short rain falls between September and October, which cumulatively results to an average rainfall of between 1200 and 2000 mm per year (Wachiye *et al*., 2013). The forest is drained by the following rivers: Clare, Kipkaren, Yala, Nonie, and Kingwal. North Nandi. The soil type is generally clay-loam and sandy while a larger area has humic nitisols which is supportive for farming. This type of soil drives agriculture by the forest adjacent communities who are largely small-scale mixed farmers growing crops such as maize, tea, among others, keeping animals such as cattle, goats, donkey, among others. The agriculture around this forest, coupled with settlement results in forest encroachment which not only diminishes the size of the forest, but also gradually degrades its biotic complexity (Girma et al., 2015). North Nandi Forest adjacent community also draw goods such as wood fuel, food; and high level of grazing which jeopardize the ecosystem health of this important forest (Wabusya *et al*., 2020). Forest is slightly higher in altitude and less diverse than Kakamega Forest area (Otieno *et al*., 2014).

3.2.2 Kakamega Forest

Kakamega Forest on the other hand is situated in Kakamega County in Western Kenya. The forest lies between longitude 34º 40’ E and 34º 57’ 30’’ E; latitude 0º 15’’ S; and at altitude range between 1250 and 2000 M above the sea level (Vuyiya *et al*., 2014). The area around this forest experiences a warm and wet climate with two rainy seasons. Short rain is experienced between July and October while long rain falls between March and June, which cumulatively results in annual rainfall between 1500 and 2000 mm (Fashing *et al*., 2012).

Government of Kenya (2019) confirms that Kakamega County where the Kakamega Forest is situated had a population of 1,861,332 people with population density of 618 persons per km^2 based on the Kenyan population census of 2019. The dense population around this forest together with high level of poverty drives the forest adjacent community to over-depend on this forest for several goods and services (Wabusya *et al*., 2020). Adjacent communities to Kakamega Forest are small-scale mixed farmers growing similar crops to those listed in North Nandi Forest (Mbuvi *et al*., 2015). They draw goods such as firewood, thatching grass, foodstuff; and graze their cattle, among other benefits. Forest encroachment for settlement, infrastructural developments among others extend the importance of this forest to the forest adjacent community. The over-dependence in this forest by the forest adjacent community subject it to continued disturbances and degradations which not only reduce its size via fragmentation but also threatens its biotic component (Wabusya *et al*., 2020).

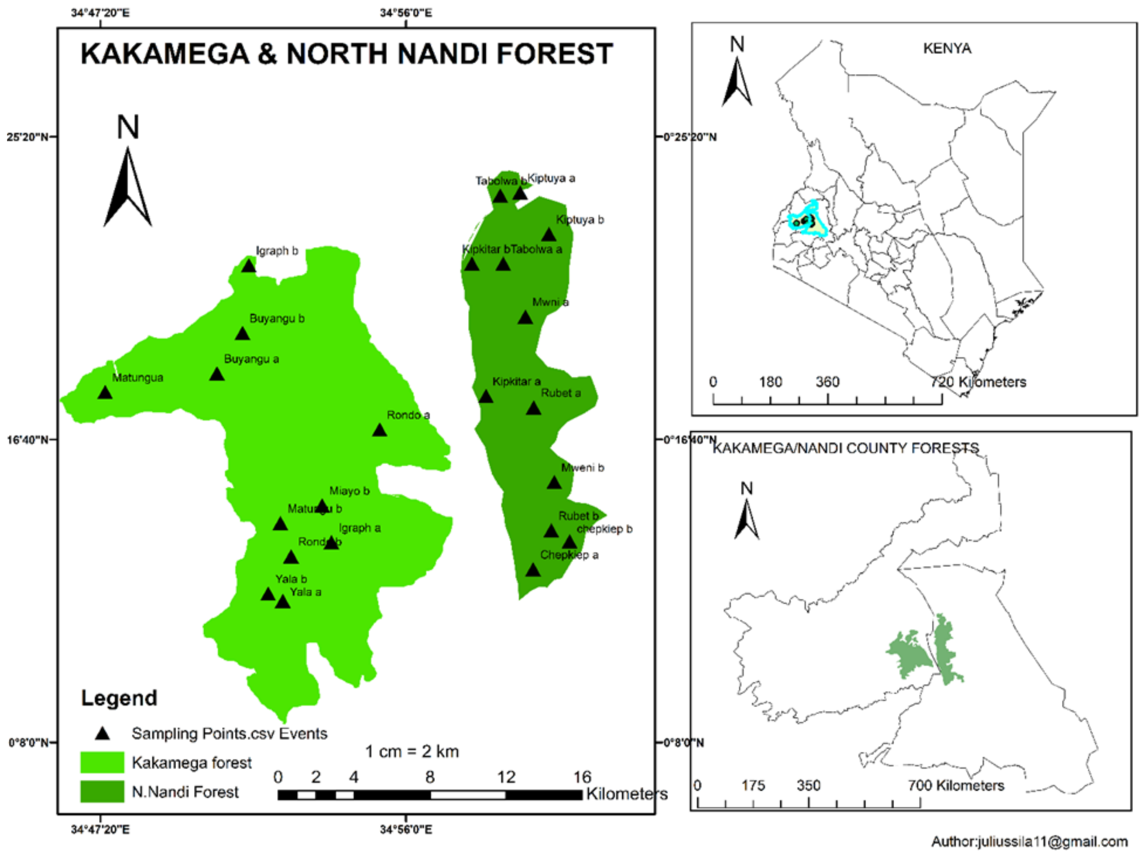

Figure 1: Study area, Kakamega and North Nandi Forests

3.3 Sampling Design

This study adopted stratified and simple random sampling designs. In this case, maps of forest demarcation of each study forest's management plan as augmented by forest cover maps drawn from Kenya Forest Service was used to demarcate the forest ecosystems into 3 distinct forest status/types (the least disturbed, plantations/transformed, and disturbed forest areas) from which vegetation biomass data was drawn. Least disturbed areas were areas of natural or mature old secondary forest whose management styles do not allow unauthorized access by the public (canopy cover not less than 70%). Due to reduced disturbances, the least disturbed areas should have high vegetation cover, more tree species of large trunks and aged species of trees. The reverse is true for the disturbed sites which constituted areas of natural forests that faced or were still facing perturbations (majorly anthropogenic such as over-browsing or natural such as floods) that do not allow full development of such areas to be dominated by woody trees (canopy cover not exceeding 30%). Plantations were forest areas which were either disturbed by natural or anthropogenic actions and have so far been restored to forest areas (majorly tree plantations of any type).

A nested approach was used to sample the 3 Forest types in every Forest ecosystem (Figure 2). At least a one-kilometer interval was maintained between one sampling plot to another to avoid sample overlap. To reduce the sampling biasness associated with the forest edge effect, researchers also maintained not less than one kilometer distance from the forest edge before any sampling could begin in the forest. In each of the 3 established forest type (least disturbed, plantations and disturbed sites), four (4) quadrats measuring 50m by 50m were randomly placed for sampling, resulting to 12 quadrats per forest ecosystems, and a grand total of 24 quadrats sampled for the two forest ecosystems.

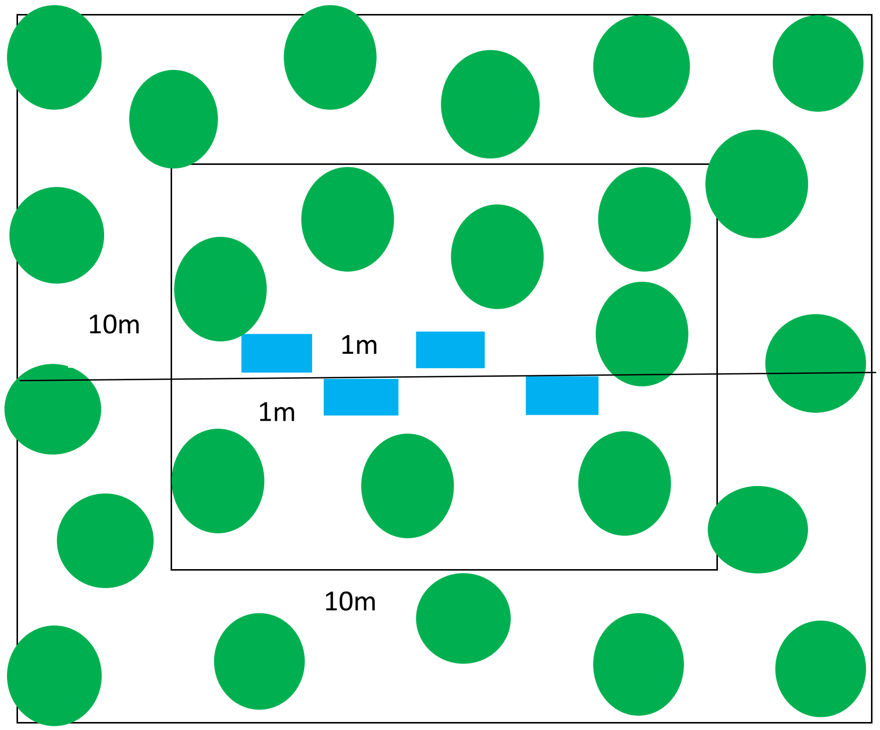

Figure 2: Condensed display of adopted nested approach (source: produced by the researcher).

Trees ≥ 5 cm diameter at 1.3 m inside the plot

Understorey herbs and shrubs sampling plot

Simple random sampling design was used to establish the sampling quadrats in each forest status for data collection. At the midpoint of each square plot of 50 m x 50m quadrat (25th m mark), a straight line was established perpendicularly. On either side of the established line, trees of DBH≥ 5cm were identified and their DBH measured. However, in exceptional cases where irregularities such as tree bends and other abnormal tree growths occurred at the breast height, the length of an area affected by the irregularity was measured using a tape measure and an equivalent distance to it was established upwards, just after the measured point of irregularity, where the DBH measurement was then taken as described by Hairiah *et al*., 2001). For every tree whose

DBH was measured, their tree heights and wood density were obtained measured. Two nested quadrats of 10m x 10m were randomly selected within the larger 50m x50m quadrats, where four (4) 1m x 1m plots were again randomly established for destructive herbs and shrubs sampling (Figure 3) resulting to 96 per forest ecosystem and 192 for the two forests combined. Each 1m x 1mquadrat was divided into four quarters of which the opposite quarters measuring 0.5m x 0.5m were destructively sampled for smaller trees of DBH < 5cm, herbs, and shrubs.

3.4 Data Collection

3.4.1 Determination of Spatial Changes in Aboveground Biomass

Woody trees in each of the study forests were supple nun-destructively. In this case, the tree diameters (DBH) were measured using the diameter tape at 1.3m above the ground for all trees of DBH≥5cm within the 50m x50m quadrats. Tree height was estimated using a Suunto clinometer while wood density was obtained from wood density database, http://db.worldagroforestry.org/wd. The obtained estimates for DBH, tree height and wood density were equated in an improved Chave equation for the African moist tropical forests ($W=F.\rho D^2H$) to estimate the tree biomass. Trees with a DBH <5 cm were considered, and their biomass estimated as part of understory because they constitute a very small fraction of AGB in the forests as reported by Chave *et al*. (2014). In the allometric equation $\boldsymbol{W=F.\rho D^2H}$;

W - Tree biomass

F- Multiplicative coefficient

D- The predictor variable (DBH)

H- Tree height

ρ -wood specific gravity

This equation ($W=F.\rho D^2H$) was preferred because it is the general allometric equation for tropical rain forest that takes into consideration, the diversity in the forest ecosystems (Chave *et al*., 2014).

3.4.1.1 Sampling Understory for Biomass

For each of the 4 smaller plots of 0.5m x 0.5m (Figure 3), herbs and shrubs, with smaller trees of diameter < 5cm were harvested using knife at the center and at the four corners of the quadrats. The weight of the understory harvested vegetation was taken at the point of harvesting when fresh using an electronic weighing machine. They were then transported in tight collection containers and oven dried in the laboratory at a constant temperature of 80ºC for 72 hours and their dry mass was determined using an electronic weighing machine. The resulted dry mass was used to calculate the biomass of the understory layers using the following formula as described by Hairiah *et al. (*2001);

$$\text{Total dry weight (kg/ m2)} = \frac{\text{TFW(kg)} * \text{SSDW (g)}}{\text{SSFW (g)} * \text{SA (m2)}}$$

whereby.

TFW- total fresh weight

SSDW- Sub Sample Dry Weight

SSFW- Sub Sample Fresh Weight

SA- Sample Area

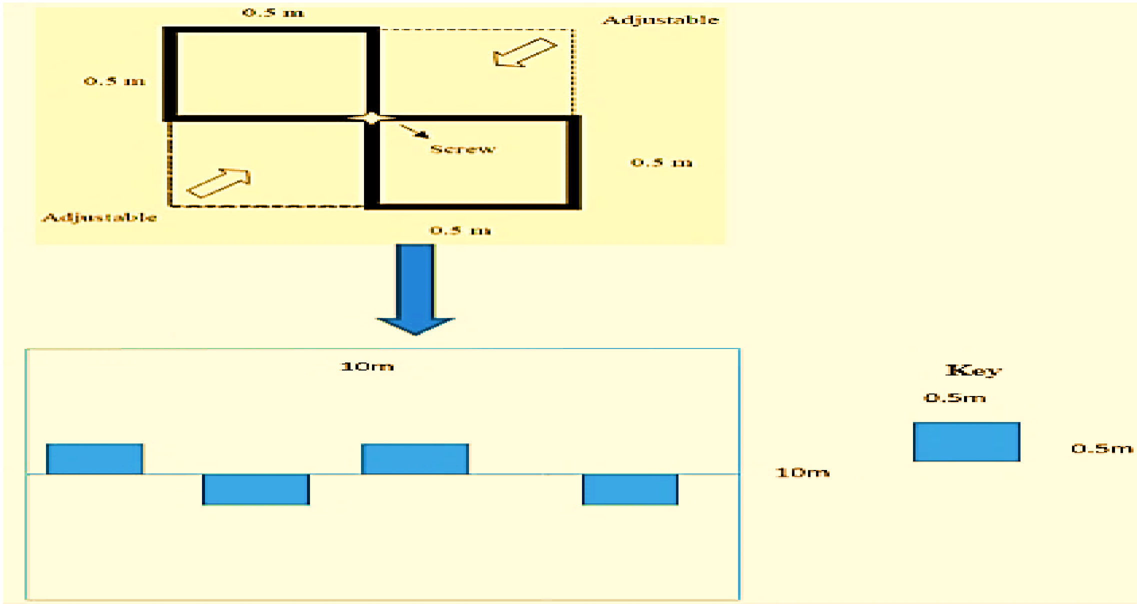

Figure 3: Sampling design for understory (source: Hairiah ***et al*.,** 2001)

3.4.2 Assessment of Temporal Changes in Aboveground Carbon Stocks

Data on temporal changes in AGB was obtained from satellite Landsat images. GIS version 10.8 was used to obtain remote sensed data from the United States Geological Survey's Landsat archive (http://earthexplorer.usg.gov. This provided remotely sensed images from Operational Land Imager (OLI), Thematic Mapper (TM) and Multi-Spectral Scanner (MSS) taken during both dry and rainy seasons for the last 32 years at an interval of 10 years (1988, 2000, 2010 and 2020. Data obtained was taken at a 16-day temporal resolution and 30mx30m spatial resolution. This data was pre-processed to eliminate image distortion and imperfections. The software for assessing image distortion, Environment for Visualizing Image (ENVI) was used to check and correct the distortion due to environmental conditions in images in the data pre-processing activities. After image correction of Landsat images for the years 1988, 2000, 2010, and 2020; the Arc GIS software version 10.8 was used to classify each image based on the land cover type to help assess the land cover change over time. The same version of Arc GIS software was used to obtain the Normalized Different Vegetation Index (NDVI) values for each image. The NDVI values were fitted in an NDVI- Biomass model (biomass (t ha^{-1}) = 20.19 + 156.1*NDVI) described by Macave *et al. (*2022) to estimate the Forest ecosystem biomass.

3.4.3 Determination of Changes in Species Diversity

Species diversity was assessed by first determining the abundance and richness of the trees in sampling plot of 50m x 50m. All tree species within the quadrat (50m x 50m) were counted. All plant species sampled were identified to species level in the two study forests using a book on woody plants of Kakamega Forest (Dalitz et al., 2011). Tree abundance was established by direct physical count of the number of individuals of each species per quadrat, while richness was determined by direct physical count of the variance of tree species that were found in each quadrat. The Shannon Wiener diversity index was used to determine the species diversity as shown in the formula below.

$$\text{Shannon Index (H)} = - \sum_{i=1}^{s} p_i \ln p_i$$

where p is the proportion (n/N) of individuals of a particular species (n) divided by the total number of individuals (N), ln is the natural log, ∑ is the sum of the calculations, and s is the number of species. Shannon diversity index considers species richness (total number of different species), tree abundance (total number of trees) and the relative species abundance or evenness (count of trees for each species). The Shannon Wiener diversity index was chosen for this analysis over other indices because it accounts for evenness which shows class frequency relationships that are observed. It is also appropriate when undertaking studies on carbon estimation. The index is simple to use, and more reliable as reported by Palaghianu (2016).

3.5 Estimation of the Aboveground Carbon

To estimate the spatial and temporal aboveground carbon stocks, the total biomass was first calculated. The sum of biomass of trees and that obtained from the forest understory provided the total spatial biomass, while biomass obtained from Landsat image processing provided estimates for temporal biomass. The product of the biomass obtained spatially and temporally, and the carbon conversion factor for tropical Africa moist Forests (0.62) provided the estimates for both the spatial and temporal AGC respectively for the two forests. The total spatial aboveground carbon was then extrapolated to per hectare.

3.6 Data Analysis

Data obtained was entered into an excel worksheet for data management. However, data analysis was done using the Statistical Package for Social Sciences (SPSS) version 25. The data obtained was subjected to normality test (Shapiro-Wilk goodness-of-fit test) since the two sites were considered heterogeneous, and when found to be not normally distributed, then the variation in the carbon stock in the two forest ecosystems and 3 forest types were ascertained by performing Kruskal-Wallis and Mann Whitney U tests where applicable.

Comparison of the temporal trends over the last 32 years were done by first calculating the differences in carbon stock per hectare per decade for at least 30 years alongside the mean carbon and mean carbon difference over that same period. The carbon obtained was converted into tons per hectare and trends analyzed using graphs. Correlation analysis was performed to assess the relationship between the AGC and the land cover change over time.

Pearson's correlation test was performed to check the relationship between AGC and species diversity, AGC and DBH, tree species richness, and tree species abundance. Results of this study were presented in, graphs, tables, and figures where applicable.

CHAPTER FOUR

RESULTS

4.1 Introduction

This chapter presents the main findings of this study as per the research's specific objectives. It describes the main findings of the spatial and temporal carbon stock of both North Nandi and Kakamega forest ecosystems' least disturbed, plantations and disturbed areas. The chapter also describes the relationship between the tree species diversity and the AGC; alongside relationship between the AGB and the tree species richness, abundance, and DBH.

4.2 Spatial Changes in Aboveground Carbon Stocks

Kakamega Forest had the highest amount of mean AGC (157.93 ± 26.91 t ha^{-1}) while North Nandi Forest had (97.83 ± 19.89 t ha^{-1}). This difference was, however, not statistically significant (U(N=24) =70, p= 0.932) as revealed by Mann-Whitney U test.

Least disturbed forest areas recorded the highest mean AGC (65.96 ± 8.56t ha^{-1}), followed by plantation sites (26.69 ± 1.12 t ha^{-1}), while disturbed forest sites had (3.26 ± 0.11t ha^{-1}) (Figure 4). This difference was statistically significant ($X^2(2, N=24) = 17.47$, p= 0.001).

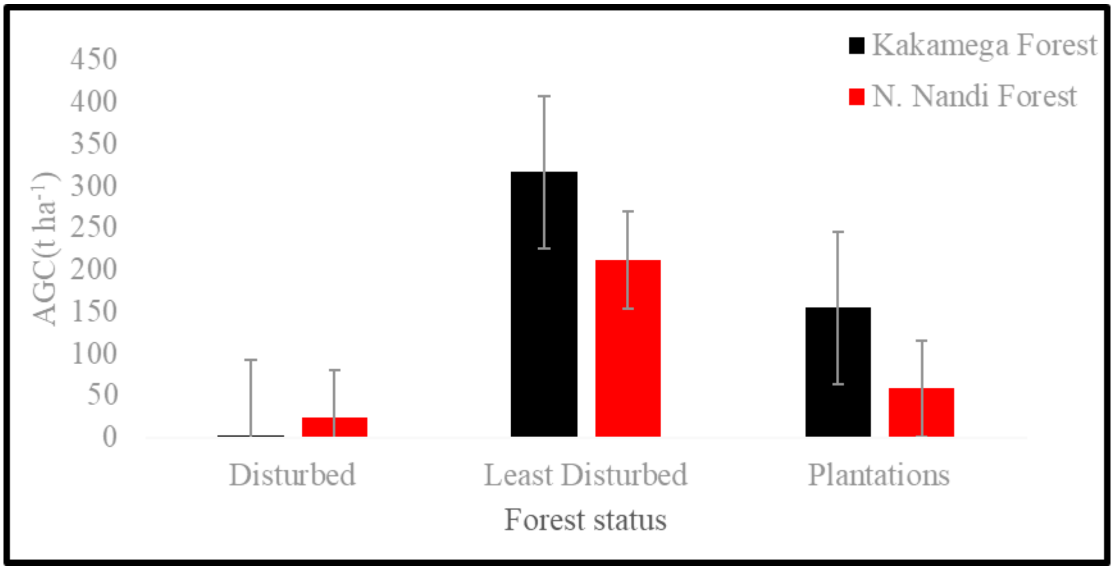

Figure 4: Average quantity of carbon stock in tons per hectares in disturbed, least disturbed and plantation areas of North Nandi and Kakamega forest ecosystems

Least disturbed were more stocked in terms of carbon, followed by plantation and lastly disturbed sites and this difference was statistically significant ($X^2(2, N=24) = 17.47$, $p = 0.001$). Kruskal-Wallis test revealed statistically significant spatial variation in aboveground carbon stock ($X^2(5, N=24) = 18.79$, $p = 0.002$) among different forest status in Kakamega and North Nandi Forest ecosystems (Table 1).

Table 1: Comparison of Spatial changes in Aboveground Carbon stock for various forest types in Kakamega and North Nandi Forest Ecosystems.

Forest type	N	Mean Rank	X2	p
North Nandi Least Disturbed	4	20.75		
Kakamega Least Disturbed	4	18.5		
Kakamega Transformed	4	15.5	18.79	0.002
North Nandi Disturbed	4	5.75		
Kakamega Disturbed	4	4		
North Nandi Transformed	4	10.5		

Test Values≡ $X^2 (5, N=24) = 18.79$, $p = 0.002$

Based on forest status, in Kakamega Forest ecosystem, AGC was highest in least disturbed sites (316.31 ± 15.64 t ha^{-1}), followed by plantations (154.96 ± 4.99 t ha^{-1}), and lastly disturbed sites (2.53 ± 0.77 t ha^{-1}). The carbon variation among the forest status of Kakamega Forest ecosystem was significant at $X^2(2, N=12) = 7.73$, $P = 0.021$ as revealed by Kruskal-Wallis's test (Table 2). In North Nandi Forest ecosystem, AGC was highest in least disturbed sites (211.40 ± 40.82 t ha^{-1}), followed by plantations (58.57 ± 16.06 t ha^{-1}), and lastly disturbed sites (23.54 ± 9.85 t ha^{-1}) (Figure 4). Mean AGC among the forest status of North Nandi Forest ecosystem was significantly different at $X^2(2, N= 12) = 8.38$, p=0.015 under Kruskal-Wallis's test (Table 2).

Table 2: Carbon variation per Forest type based on Forest Ecosystem

Forest ecosystem	**Forest type**	**N**	**Mean Rank**	**X^2**	**p**
Kakamega	Least Disturbed	4	9.25	7.73	0.021
	Transformed	4	7.75		
	Disturbed	4	2.5		
North Nandi	Least Disturbed	4	10.5	8.38	0.015
	Transformed	4	5.75		
	Disturbed	4	3.25		

Test values: Kakamega= $X^2(2, N=12) = 7.73$, p =0.021; North Nandi= $X^2(2, N= 12) = 8.38$, p=0.015

Statistically significant carbon stocks variation was recorded between Kakamega least disturbed and disturbed sites ($p<0.05$); and between North Nandi least disturbed and Kakamega disturbed sites ($p<0.5$) upon Kruskal-Wallis's test.

4.3 Temporal Changes in Aboveground Carbon Stock in Kakamega and North Nandi Forest Ecosystems

Four different land cover types were observed for both North Nandi (natural fores, secondary forest, grasslands, and shrub-vegetation) and Kakamega (natural forest, secondary forest, shrub-vegetation, and bare lands /waterbodies) Forests. This study observed a drastic drop in size of grassland between 1988 (30.47 km^2) and 2000 (6.56 km^2) which continued to drop in 2020 (table 3) in North Nandi Forest; and, in natural forest between 2010 (48.9 km^2) and 2020 (21.33 km^2). Additionally, the Natural Forest of Kakamega forest also dropped drastically between 2010 (114.1 km^2) and 2020 (27.98 km^2) when shrub vegetation also increased from 1.6 km^2 to 116.6 km^2.

The results of this study revealed a temporally changing pattern of land cover types over a period of 10 years for both the North Nandi and Kakamega Forest ecosystems (Table 3). North Nandi Forest was dominated by secondary forest covering 48.23km^2 (40%) in the year 1988, followed by natural forest at 34.42 km^2 (28%) while the least was shrub vegetation covering 7.98km^2 (7%). In the year 2000, natural forest increased by 29% from 1988 to dominate the land cover types, covering 48.51 km^2(57%). It was followed by secondary forest that covered 30.4 km^2 (35%), which also reduced by 5% from the year 1988. Shrub lands were not visible in the year 2000, from the 7% recorded in 1988. In the year 2010, the natural forest of North Nandi maintained the dominance of the land cover types, covering 48.9 (52%) though representing a reduction by 5% from the record of the year 2000. Secondary forest increased by 1% from the 2000's record to become the second dominant covering 33.72km^2 (36%) in the year 2010; while shrub lands increased by 9%, covering 8.25km^2. In 2020, secondary forest dominated the land cover types, covering 45.19km^2 (48%) which represented a 12% increase from 2010. Shrub lands increased by 16% from the recorded 9% in 2010 to become the second most dominant land cover type in 2020, covering 23.73km^2 (25%). Natural forest drastically reduced by 29% from the record of 2010 to become the third most dominant covering only 21.33km^2 (23%) while grassland was the least dominant at 3.34km^2 (4%) (Table 3).

Table 3: Area coverage of different land cover types for North Nandi Forest ecosystem between 1988-2020.

	1988		**2000**		**2010**		**2020**	
Land cover type	**Area (km^2)**	**%**	**Area (Km^2)**	**%**	**Area (Km^2)**	**%**	**Area (Km^2)**	**%**
Natural forest	34.42	28	48.51	57	48.9	52	21.33	23
Secondary forest	48.13	40	30.4	35	33.72	36	45.19	48
Grassland	30.47	25	6.56	8	2.71	3	3.34	4
Shrub vegetation	7.98	7	0	0	8.25	9	23.73	25

Four major land uses were also observed between 1988-2020 in Kakamega Forest. These are natural forests, secondary forest which comprise moderate forest, shrub vegetation and waterbodies/bare land. In 1988, secondary forest was the dominant land use at 50.4% (116.36km^2). This was followed by natural forest at 41.7% (96.24km^2). In 2000, natural forest was the major land use at 49.2% (114.11km^2) followed by secondary forest at 27% (107km^2).

Water bodies/bare land was the least at 10.3% (23.69km^2) (Table 4). In 2010, natural forest was still the major land use. In 2020, shrub vegetation which comprises the guava vegetation became the major land use at 50.5% (116.62km^2) of the total land area.

Natural forest exhibited an increase from 96.2km^2 in 1998 to 114.11km^2 in 2010. This further declined to 27.98km^2 in 2020 (Table 4).

Table 4: Area coverage of different land cover types for Kakamega forest ecosystem between 1988-2020.

	1988		**2000**		**2010**		**2020**	
Land cover type	**Area (km^2)**	**%**	**Area (Km^2)**	**%**	**Area (Km^2)**	**%**	**Area (Km^2)**	**%**
Natural forest	96.24	41.7	113.7	49.2	114.1	49.5	27.98	12.1
Secondary forest	116.4	50.4	62.43	27	107	46.4	73.49	31.8
Shrub vegetation	15.06	6.5	31.18	13.5	1.68	0.7	116.6	50.5
Waterbodies/bareland	3.28	1.4	23.69	10.3	7.58	3.3	12.87	5.6

The pattern of area cover change for the two forest ecosystems was also reflected in the NDVI values over the period between 1988-2000 for the two forest ecosystems (Kakamega and North Nandi) (Figure 5 and Figure 6) respectively.

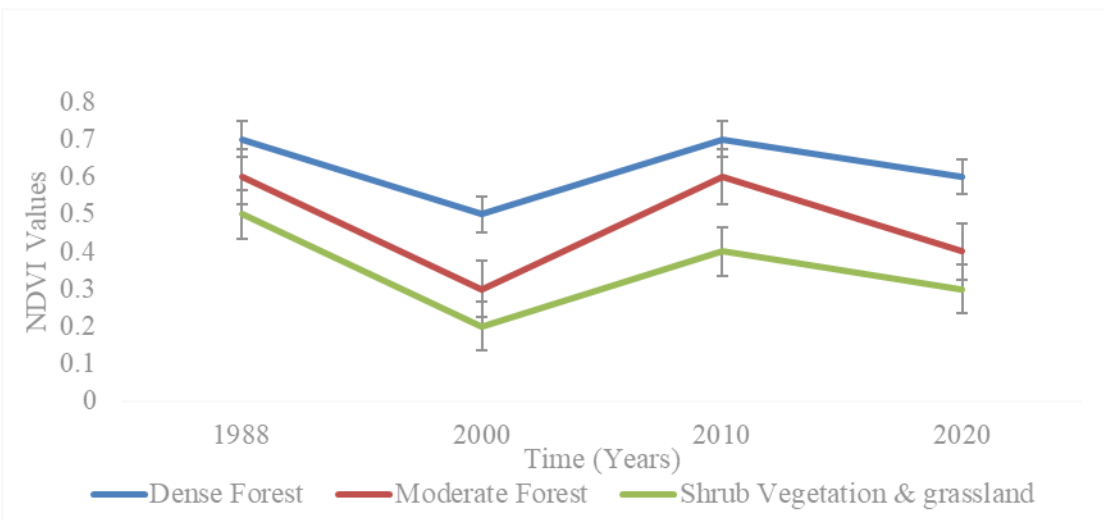

Figure 5: Phenological graph on vegetation index between 1988-2020 for North Nandi Forest ecosystem.

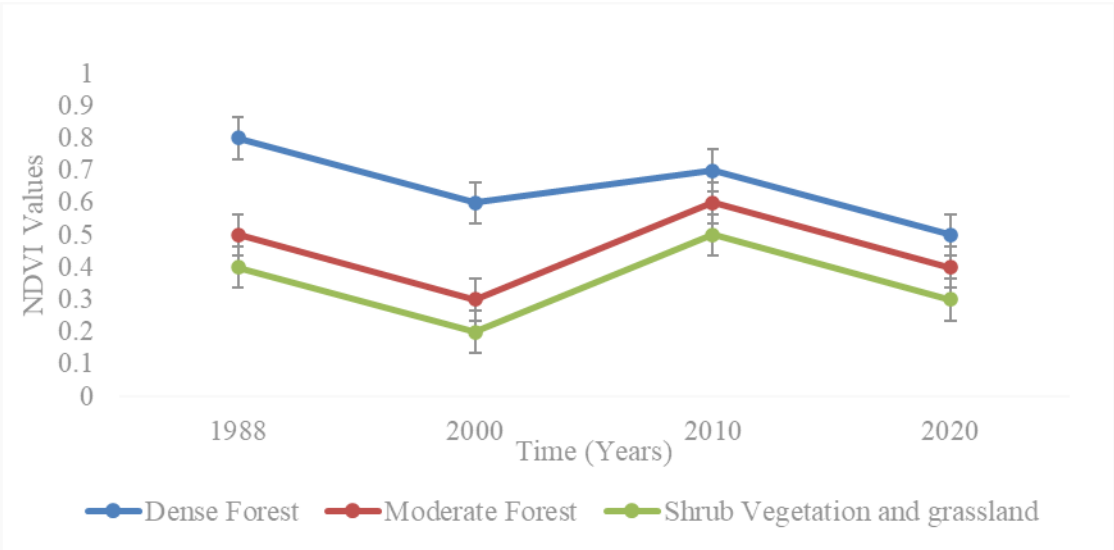

Figure 6: Phenological graph on vegetation index between 1988-2020 for Kakamega Forest ecosystem.

These vegetation cover changes over time for both the forest ecosystems corresponded to the yearly cumulative AGC stocks for these two study sites (Table 5). This study revealed a temporally changing pattern of AGC stock for both the Kakamega and North Nandi Forest ecosystem over time. For both the forest ecosystems, the carbon stock in tons per hectare has shown a rising and falling pattern or trend over a period of a decade (Figure 7), with a mean carbon of 177.89 t ha^{-1} in Kakamega forest and 199.37 t ha^{-1} in North Nandi Forest. The carbon range was 144.01-202.08 t ha^{-1} for Kakamega Forest ecosystem, and 124.66-243.64 t ha^{-1} for North Nandi Forest ecosystem. North Nandi Forest reported the highest amount of carbon stock per hectare, 243.64 t ha^{-1} in the year 1988 compared to 124.66 t ha^{-1} recorded in the same forest in the year 2000: a difference of 118.98 t ha^{-1}. In the year 2010 however, North Nandi Forest showed an increase in AGC stocks (233.96 t ha^{-1}), a difference of 109.3 t ha^{-1} from the year 2000.

In the year 2020, North Nandi Forest ecosystem recorded a decline in AGC (195.24 t ha^{-1}) relative to the 233.96 t ha^{-1} recorded in the year 2010; a difference of 38.72 t $ha^{-1.}$ Kakamega Forest ecosystem recorded an AGC stocks of 202.08 t ha^{-1}, relative to 144.01 t ha^{-1} recorded in the year 2000; a difference of 58.07t ha^{-1}. The year 2010 was characterized by an increase in carbon stock per hectare for Kakamega Forest ecosystem (211.76 t $ha^{-1)}$ relative to 144.01 t ha^{-1} recorded in 2010, a carbon difference of 67.75 t ha^{-1}. The year 2020 revealed a decline carbon stock (153.69 t $ha^{-1)}$ relative to the year 2010's record (211.76 t $ha^{-1),}$ a difference of 58.07t ha^{-1} (Table 5).

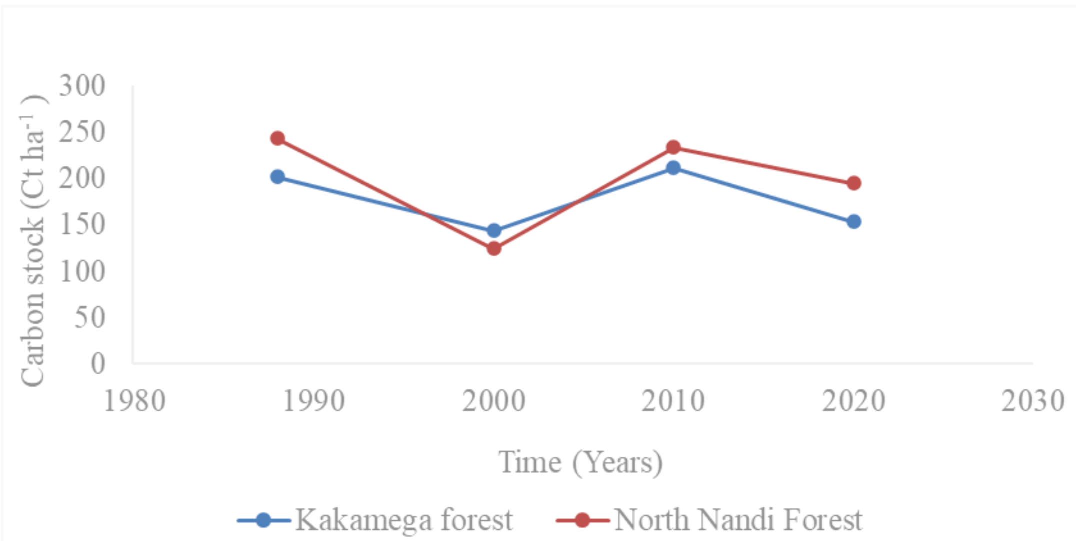

Figure 7: Temporal carbon stock trend over the years for North Nandi and Kakamega Forest ecosystems.

Table 5: Vegetation cover changes and their corresponding AGC stocks for Kakamega and North Nandi Forest ecosystems between 1988-2020.

Time (Years)	Kakamega Forest vegetation Area coverage (km sq.) and AGC		North Nandi Forest vegetation Area coverage (km sq.) and AGC	
	Area (km sq.)	AGC ($Ct\ h^{-1}$)	Area (km sq.)	AGC ($Ct\ h^{-1}$)
1988	227.68	202.08	121.02	243.64
2000	207.28	144.01	85.47	124.66
2010	222.79	211.76	93.57	233.96
2020	218.09	153.69	93.58	195.24

In both the Kakamega and North Nandi Forest ecosystems, the correlation analysis revealed strong positive relationship between the AGC, and the land cover changes over time at r = 0.852, and r= 0.722respectively. However, these relationships were not statistically significant at $p>0.05$ (Table 6).

Table 6: Correlation between temporal AGC and vegetation cover change over time for Kakamega and North Nandi Forest ecosystems.

Forest Ecosystem	**Correlation Test Values**		
	r^2	p	N
North Nandi & Kakamega Combined	0.167	0.693	8
Kakamega	0.852	0.148	4
North Nandi	0.722	0.278	4

4.4 How Changes in Species Diversity Affect AGC in Kakamega and North Nandi Forest Ecosystems

The findings of this section are organized into analysis of the tree species diversity, components (abundance and richness), and DBH followed by the relationship between diversity and the AGC.

4.4.1 Relationship Between Tree Species Abundance and AGC

This study sampled (N=1511) trees from 100 different tree species of which 45 (45%) were only found in Kakamega, 28 (28%) found only in North Nandi while 27 (27%) of the species were common to both the forest ecosystems. From all the sampled trees, the most dominant species was *Cupressus lusitanica* with 407 individuals (representing 26.9%) followed by *Eucalyptus saligna* with 87 individuals (representing 5.7%), then *Macaranga kilimandscharica* with 60 individuals (representing 4.0%); *Funtumia africana* with 58 individuals (representing 3.8%), while the fifth dominant species was *Polycias fulva* with 51 individuals (representing 3.4%). At the least dominant were several species not limited to *Vitex keniensis*, and *Xymalos monospora* with one individual each (representing 0.07% each).

Cumulatively, sampled areas revealed the highest tree abundance in North Nandi Forest ecosystem (840=55.6%) relative to 671(44.4%) recorded in Kakamega Forest ecosystem. In North Nandi Forest ecosystem, the highest tree abundance was recorded in plantations where 427 individuals were sampled (50.8%), followed by least disturbed areas with 348 individuals (41.5%), while disturbed sites had 65 individuals (7.7%). In Kakamega forest however, the abundance was highest in the least disturbed sites with

328 individuals (48.9%), followed by plantations with 301 individuals (44.9%), and lastly disturbed areas with 42 individuals (6.3%).

The correlation analysis revealed statistically significant strong positive relationships (r = .679, p<0.05) (Table 7) between AGC and tree species abundance in the two forest ecosystems combined. However, Kakamega forest ecosystem had a strong positive correlation between AGC and tree species abundance (r = .912, p< 0.05) whereas North Nandi Forest ecosystem showed a moderate positive correlation (r =.378, p <0.05); (Table 7).

Table 7: General correlation between AGC and Tree species abundance for North Nandi and Kakamega forest ecosystems.

Forest Ecosystem	**Correlation Test Values**		
	r^2	p	N
North Nandi & Kakamega Combined	0.679	0.01	24
Kakamega	0.912	0.01	12
North Nandi	0.378	0.05	12

Based on Forest ecosystem, Kakamega least disturbed areas showed a strong positive relationship between AGC and tree species abundance, r =0.962, p< 0.05, followed by Kakamega plantations r =0.873, p < *0*.05, while Kakamega disturbed areas showed a weak negative relationship (r = -0.089, p< 0.05). In North Nandi Forest ecosystem, least disturbed Forest areas revealed a statistically significant strong positive correlation (r =0 .800, p< 0.05) between AGC and tree abundance; followed by plantations (r = 0.687 at p< 0.05) while a weak negative correlation (r = -0.092, p = 0.05) was recorded in disturbed site. (Table 8).

Table 8: Summary of correlation results based on ecosystem category and Forest types for different variables of both North Nandi and Kakamega Forest Ecosystems.

Variable	**Least disturbed K**	**Plantations K**	**Disturbed K**	**Least disturbed N**	**Plantations N**	**Disturbed N**
AGC and tree spp. Biodiversity	r = .965 p=0.05	r = .200 p= 0.05	r = .603 p= 0.05	r = .800 p= 0.05	r = -.772 p= 0.05	r = .051 p= 0.05
AGC & tree Sp. Richness	r = .935 p=0.01	r = .400 p= 0.05	r = .344 p= 0.05	r = .800 p= 0.05	r = -.738 p= 0.05	r = -.200 p= 0.05
AGC & tree Sp. abundance	r = .962 p= 0.01	r = .873 p= 0.05	r = -.089 p= 0.05	r = .800 p= 0.05	r = 0.687 p= 0.05	r = -.092 p= 0.05
AGC & tree Sp. DBH	r =.999 p= 0.01	r= .800 p= 0.05	r= .021 p= 0.05	r= .083 p= 0. 05	r =.400 p= 0.05	r= 1.00 p= 0.01

4.4.2 Relationship Between Tree Species Richness and AGC

Kakamega Forest ecosystem species richness was (n=72) while North Nandi Forest ecosystem had richness of (n=55) tree species. Regarding Kakamega Forest ecosystem, least disturbed sites were richer (51 different species) with *Funtumia africana* as the most dominant species having 51 individuals (7.6%); followed by plantations (49 species) with *Cupressus lusitanica* having 83 individuals (12.4%) as the dominant species; while disturbed sites had the least richness (12 species), with *Sesbania sesban* as the dominant species having 13 individuals (1.9%). In North Nandi Forest ecosystem, least disturbed sites were richer (43 different species), with *Syzygium guineense* as the most dominant species having 56 individuals (6.7%); followed by disturbed sites (18 species), with *Acacia nilotica* as the dominant species having 14 individuals (2.1%); while plantation areas had the least richness (9 different species), with *Cupresus lusitanica* having 324 individuals (38.6%) as the dominant species.

This study recorded a strong positive correlation between species richness and AGC (r =0.85, $p < 0.05$) (Table 9) for the two forest ecosystems combined. Statistically significant strong positive correlation was also observed separately for North Nandi Forest (r =0.806, $p<0.05$) and Kakamega forest ecosystems (r =0.79, $p<0.05$) (Table 9).

Table 9: General correlation between AGC and Tree Species Richness for North Nandi and Kakamega forest ecosystems combined.

Forest Ecosystem	**Correlation Test Values**		
	r^2	p	N
North Nandi & Kakamega Combined	0.846	0.01	24
Kakamega	0.784	0.01	12
North Nandi	0.806	0.01	12

Based on the forest ecosystem, Kakamega Forest ecosystem recorded a statistically significant strong positive relationship between AGC and tree species richness in least disturbed areas (r =0.935, p<0.05), followed by a moderate positive relationship in both plantations and disturbed sites at r =0.400, p=<0.05; and r =0.344, $p < 0.05$ respectively. In North Nandi Forest ecosystem, least disturbed sites had a significant strong positive relationship between AGC and species richness (r =0.800, $p < 0.05$); followed by North

Nandi plantations at r =-.738, $p<0.05$; while North Nandi disturbed sites revealed a weak negative correlation between species richness and AGC at r = -0.200, $p < 0.05$ on a Spearman's correlation test (Table 8).

4.4.3 Relationship Between DBH and AGC

The diameter at Breast Height (DBH) for the entire study area ranged between was 5-130cm with a mean DBH of 27.28cm out of all the (N=1511) trees sampled. In Kakamega forest ecosystem, least disturbed areas had a 5-130cm DBH range with an average DBH of 38.45 cm. Plantations site in Kakamega Forest had a DBH range of 5-110cm with mean DBH of 34.33cm; while their disturbed site counterparts had a DBH range of 6-48cm with a mean DBH of 11.2cm. The highest number of trees (161) were found in the DBH range of 5-14 cm while the least (1 tree each) were found in the DBH range of 115-125cm and 125-134cm respectively in Kakamega Forest ecosystem (Figure 4-5). In North Nandi Forest ecosystem, least disturbed sites had a DBH range of 5-120.5cm with a mean DBH of 33.48cm; followed by plantation areas with a DBH range of 5-100cm with a mean DBH of 19.31cm; while disturbed sites had a DBH range of 5-108cm with a mean DBH of 26.9cm. In this distribution, the highest number (295) of trees in North Nandi Forest ecosystem were recorded in the DBH range of 15-24cm while the least number (1) was found in the DBH range of 125-134cm (Figure 8).

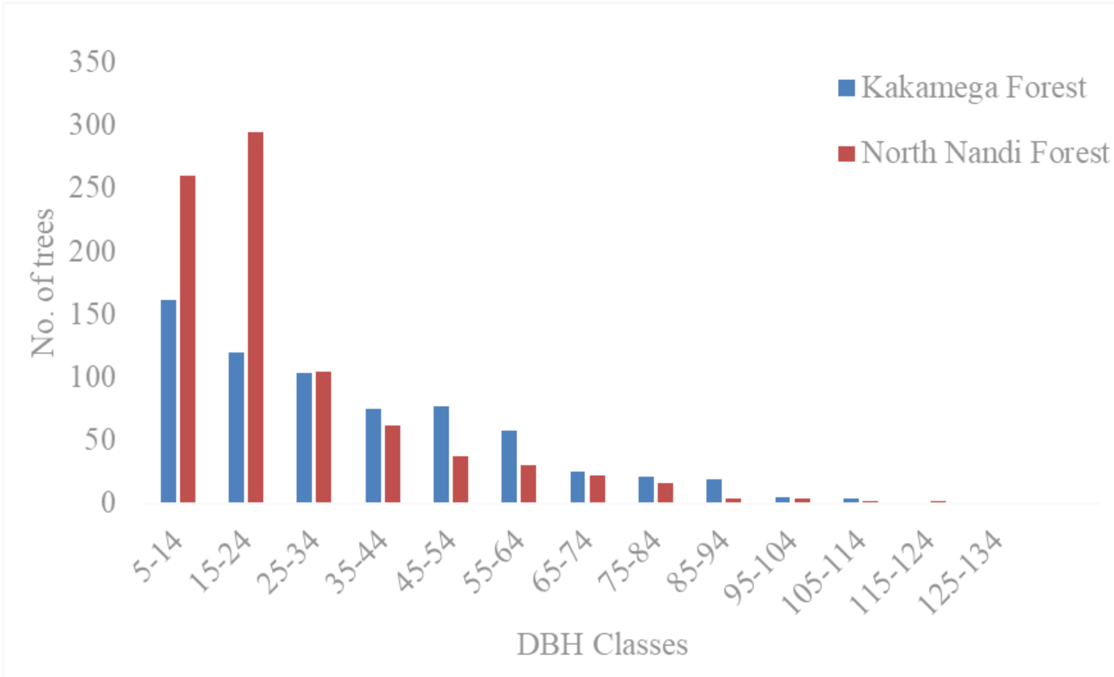

Figure 8: DBH distribution in North Nandi and Kakamega Forest ecosystems.

A Spearman's correlation test between AGC and DBH for the entire study area revealed a significantly significant strong positive correlation (*r*=0.92 a p<0.05) (Table 10). The strong positive correlation between DBH and AGC was also recorded in both Kakamega Forest (*r*=0.909, p< 0.05) and North Nandi Forest ecosystem (*r* =0.83; p<0.05) (Table 10).

Table 10: General correlation between AGC and DBH for North Nandi and Kakamega forest ecosystems.

Forest Ecosystem	**Correlation Test Values**		
	r^2	p	N
North Nandi & Kakamega Combined	0.915	0.01	24
Kakamega	0.909	0.01	12
North Nandi	0.828	0.01	12

This study revealed a significant strong positive correlation between AGC and DBH in Kakamega least disturbed sites (r =0.999 at p< 0.05) and plantation (r=0.8 and p<0.05); while disturbed sites recorded a weak positive correlation at r=0.021, p<0.05. In North Nandi disturbed sites, a perfect positive correlation (r=1.00 at p<0.05) was recorded between AGC and DBH. North Nandi plantations however revealed a moderate positive correlation between AGC and DBH (r =.400, p< 0.05); while a weak positive correlation between AGC and DBH was recorded in North Nandi least disturbed areas at r=0.083, p<0.05 on a Pearson's Correlation test (Table 8).

The tree's height ranged between 2-48 meters (m). Cumulatively, the highest abundance of trees (778) recorded the height between 11-20m, while the least (33 trees) were recorded in a height range between 31-45m (Figure 9). Kakamega forest recorded the highest tree height of 48m while the least was of 2m. North Nandi Forest on the other hand recorded the highest tree height of 30m while the least was recorded in a tree of 2m in height.

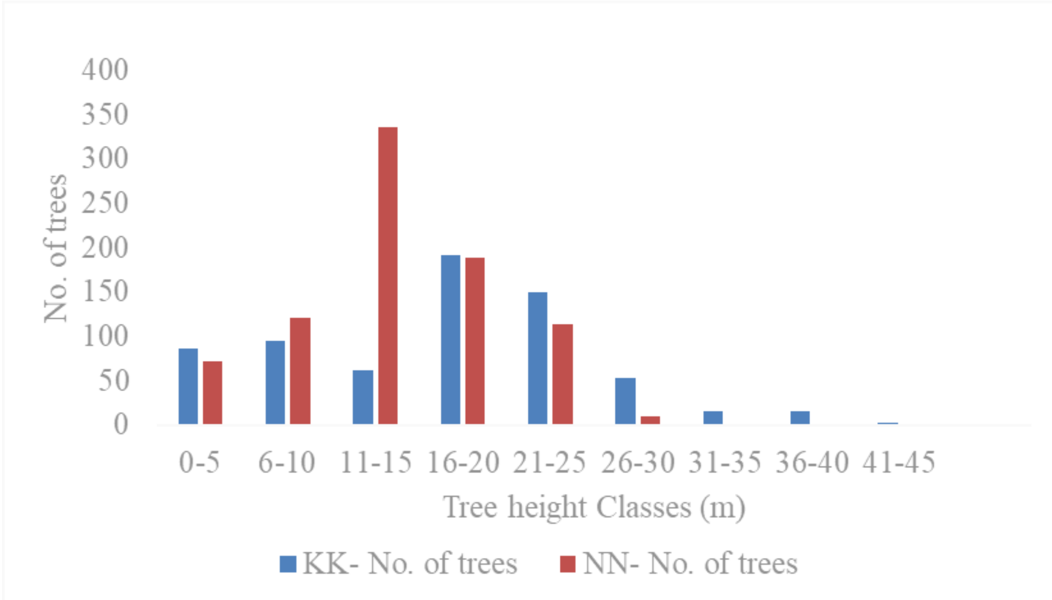

Figure 9: Tree Height distribution for Kakamega and North Nandi Forest ecosystems.

4.4.4 Species Diversity and its Relation to AGC

The Shannon Wiener's diversity index revealed a higher tree species diversity in Kakamega Forest (H′= 1.82 ± 0.95) relative to North Nandi Forest ecosystem's (H′= 1.24 ± 0.88). Generally, when the two forests were combined and variation assessed based on forest status, least disturbed site were the highest diverse (H′= 2.35± 0.85), followed by disturbed sites (H′= 1.17± 0.87), while the least diverse generally was transformed sites (H′= 1.07± 0.65) (figure 10).

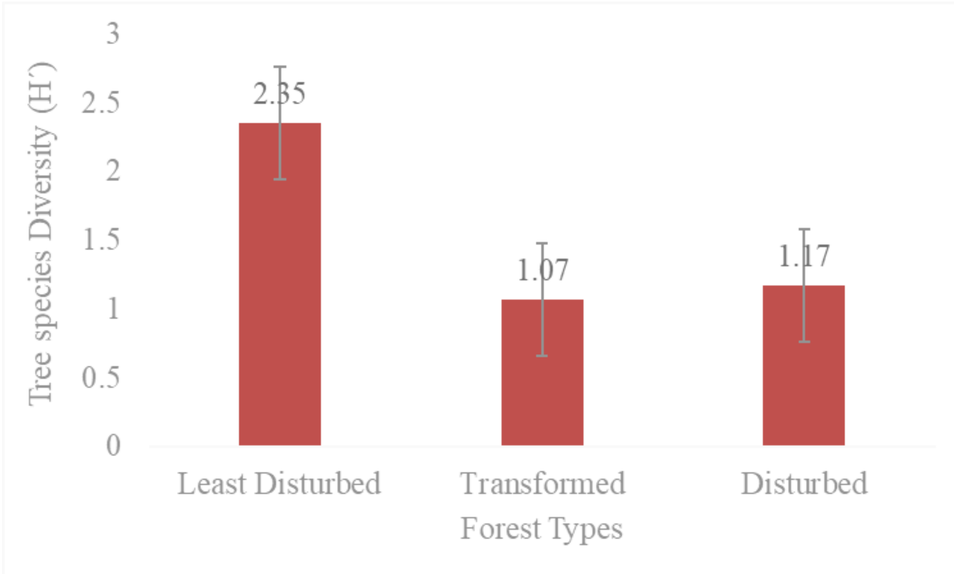

Figure 10: Tree species diversity in Least Disturbed, Plantations, and Disturbed sites

Based on forest ecosystems, in Kakamega Forest, least disturbed areas recorded the highest tree diversity (H´= 2.65 ± 0.45) followed by plantation areas (H´= 1.84 ± 0.91), and lastly disturbed areas (H´= 0.98 ± 0.66). In North Nandi Forest ecosystem however, least disturbed sites had the highest diversity (H´= 2.06 ± 0.45), followed by disturbed sites (H´= 1.36 ± 0.75), while plantation areas had the least diversity at H´= 0.32 ± 0.20 (Figure 11).

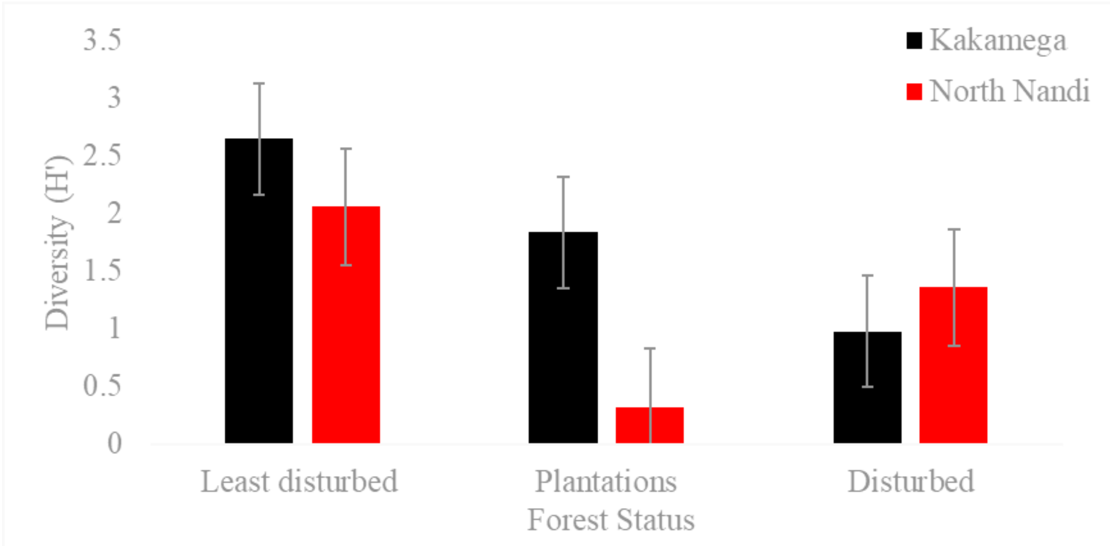

Figure 11: Tree species diversity variation per Forest type based on Forest Ecosystem per hectare.

The diversity of these forest ecosystems thus revealed a general statistically significant positive correlation with AGC (r= .616, $p< 0.05$) (Table 11). Both Kakamega and North Nandi Forest ecosystems independently revealed statistically significant positive correlation between AGC and tree species diversity at r= .665, $p< 0.05$; and r = .604, $p < 0.05$ respectively (Table 11).

Table 11: Relationship between tree species diversity and AGC stocks in North Nandi and Kakamega forest Ecosystems.

Forest Ecosystem	**Correlation Test Values**		
	r^2	p	N
North Nandi & Kakamega Combined	0.616	0.01	24
Kakamega	0.665	0.05	12
North Nandi	0.604	0.05	12

Based on the forest ecosystems, this research revealed a statistically significant strong positive correlation between AGC and tree species diversity in Kakamega least disturbed areas at r=0.965, $p<0.05$; followed by Kakamega disturbed sites with a strong correlation coefficient of $r = 0.603$, $p < 0.05$; while Kakamega plantations recorded a weak positive correlation between AGC and tree species diversity at r =0.200, $p< 0.05$. In North Nandi Forest ecosystem, the least disturbed areas revealed a statistically significant strong positive correlation (r =0.800, $p < 0.05$) between AGC and tree species diversity; followed by North Nandi disturbed sites with a weaker positive relationship at r =0.051, $p<0.05$; and lastly a strong negative relationship between AGC and tree species diversity at $r = -0.772$ $p<0.05$ in North Nandi Forest plantations (Table 8).

CHAPTER FIVE

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Introduction

This chapter discusses the main findings of this study based on the three specific objectives; giving detailed possible explanation to both spatial and temporal variation in carbon stock in both the Kakamega and North Nandi Forest ecosystems, alongside how species diversity relates to AGC. The chapter also presents conclusions and recommendations derived from the findings.

5.2 Discussion

5.2.1 Spatial Changes in Aboveground Carbon Stock in Kakamega and North Nandi Forest Ecosystems

A higher Aboveground Carbon stock was reported in Kakamega forest ecosystem compared to North Nandi Forest ecosystem. Kakamega forest's carbon stocks finding (particularly in least disturbed sites) is slightly above 200 t ha^{-1} reported in the same forest status in the same forest between the years 1987-2003 by Glenday in 2006 (Pellikka *et al.,* 2018). This increase in carbon stock per hectare from Pellikka *et al.* *(*2018) as revealed by our current study could be attributed to several factors. Such factors could include the enhanced government policy and commitment to achieving the 10% forest cover by the government of Kenya, that has seen a significant embracement of forestry system in the private lands (on farm-agroforestry) and urban forestry systems. This provided the much-needed forest resources in the homesteads hence reduced the pressure on public forest by the forest adjacent community thus allowing adequate regeneration and development of vegetation which is responsible for overall increased biomass- carbon accumulation. It could also be attributed to massive awareness campaigns by non-government organizations (NGOs) on the importance of planting more trees; that has significantly reduced the pressure on the Kenyan gazette forests by the local communities living adjacent to these forest ecosystems.

The replicated trend of carbon stock in both Kakamega and North Nandi forests in which least disturbed were highly stocked followed by plantations, and then disturbed sites could be attributed to several reasons. Firstly, this finding explains the impact of forest disturbance/ management regime on carbon sequestration potential of forest. In this study, the least disturbed areas were areas of thick forest whose management styles do not allow access by humans. In Kenya, forests are managed by the Kenya Wildlife Service (KWS), the Kenya Forest Service (KFS) and County Governments. Generally, these two forests are managed similarly except that North Nandi Forest is lacking the KWS which is critical in forest protection, while Kakamega forest is managed by all the three entities synergistically in coordination. Kenya Wildlife Service does not permit any form of human exploitation in forest under its management. It's clear that management regimes influence forest health, biomass accumulation and biomass carbon stocks. Due to reduced disturbances, the least disturbed area has high vegetation cover, more tree species of large trunks and aged species capable of sequestering huge amount of carbon relative to disturbed areas with low tree species abundance, little aboveground vegetation, and consequently low carbon. This finding agrees with Battles *et al. (*2018) finding in North America that forest disturbances from land use changes, wildfires among others continuously reduce the forest cover, and consequently reduce carbon storage potential by 11 TgC (teragrams of carbon) annually in North America. This study also agrees with a study in Ethiopia by Yohannes *et al. (*2017) assessing the carbon variation along different management regime which found a high above and below ground carbon stock in the least disturbed areas relative to small carbon stock in highly disturbed areas. Additionally, the finding of the carbon trends in least disturbed, plantations, and disturbed forest status are also in line with Agevi *et al. (*2016) assessing management regime on biomass variation at Masinde Muliro University of Science and Technology (MMUST) which found that the perturbations and management regimes have the potential to influence plant growth and survival and eventually inform the tree biomass and carbon stocks.

Secondly, the sequential high trends of carbon in least disturbed areas, followed by plantations and lastly disturbed sites in both Kakamega and North Nandi Forest ecosystem could be attributed to differences in tree species diversity, richness, and abundance. The species richness, abundance, and diversity were least in disturbed sites, medium in plantations and highest in least disturbed areas; and so was their aboveground carbon stocks. High species richness and abundance contribute to high diversity (as shown in least disturbed areas contrary to disturbed areas) and could significantly enhance ecosystem resilience and stability thereby promoting ecosystem health, primary production, biomass accumulation and eventually carbon sequestration potential of vegetation. This finding conforms to the findings by Di Sacco *et al. (*2021) in their cross-review study evaluation the forestry systems that optimize carbon sequestration potential which reported that a high tree species diversity enhances both ecosystem health and stability thus promoting both forest biomass and carbon below and aboveground.

Kakamega plantations, which were the second most diverse in terms of species after the least disturbed areas of both the forest ecosystems also reflected a high value in mean carbon stock compared to the poorly diverse North Nandi plantations, and disturbed sites of both the two forest ecosystems. Kakamega forest plantations mostly had a mixed indigenous tree, which could have influenced its diversity and thus the high carbon stock.

Additionally, there was a strong significant spatial variation of carbon between least disturbed areas and plantations, even though they are both under similar management regime, with almost similar conditions and experiences. This could be specifically attributed to tree species diversity. The high species abundance in the plantations could however not translate into as high tree species diversity as was recorded in the least disturbed areas. For instance, the dominant tree species of Kakamega plantations contribute to less than 50% of the total tree abundance of all the plantations in Kakamega forest; relative to the poorly diverse and less carbon stocked plantations of North Nandi Forest where the dominant species accounts for at least 80% of the total tree abundance of the sampled plantations. Despite the 80% dominance by one species of the overall abundance in North Nandi plantations, about 50% of the plantations consisted of young plantations of less than 10 years of age compared to old mixed indigenous plantations of Kakamega plantations. This finding agrees with Liu *et al.* *(*2018) finding that old forests sequester huge amounts of carbon compared to young forest. This finding is in agreement with the findings by Liu *et al*., (2018) in Gutianshan National Nature Reserve of South East China; and review study by Di Sacco *et al*., (2021) which reported that one of the mechanisms for optimizing carbon sequestration potential of forests and agroforestry systems is by planting a mixed species which not only influence carbon indirectly via promoting ecosystem resilience, but also by promoting mutualistic relationships that enhance vegetation health and primary productivity.

5.2.2 Temporal Changes in Aboveground Carbon Stock in Kakamega and North Nandi Forest Ecosystems

This study revealed a temporal decreasing-increasing pattern of carbon for both Kakamega and North Nandi Forest ecosystems. These finding are within the global carbon range in the tropical dry forests of 50-350 t ha-1 reported by Solomon *et al. (*2018); and 395.7 Mg/ha of biomass, which is equivalent to 245.334 Mg/ha for the tropical Africa forests reported by Malhi *et al. (*2013). The decreasing-increasing pattern of temporal carbon found in this study could be attributed to forest cover changes over time (appendix 3), both anthropogenic (illegal logging, overgrazing, charcoal burning, encroachments for agricultural) and natural perturbations (pest and diseases, harsh weather), and management regimes (unsustainable utilizations, etc).

According to Ototo and Vlosky (2018), a large extent of unsustainable logging for roundwood for electric poles and timber occasioned by deficiency for such forest products drove Kakamega and North Nandi Forest to huge degradation and reduced forest cover between late 1980s and 1990s. upon realizing continued high demand for the forest products despite the huge degradation that had gone on for long, the government of Kenya imposed a logging barn in all Kenyan forest including the Kakamega and North Nandi forests Ototo and Vlosky 2018). This barn, together with other sustainable foret management mechanisms such as the introduction of Shamba system in 2007, not improved the plantation establishments but also enable regain of significant forest cover. However, Ototo and Vlosky (2018) and Namasaka (2021) explained that when the burn was lifted in 2009, major degradation was witnessed leading to another loss of a half of natural forest area in Kakamega forest between 2010 and 2020. The findings in this section agree with several studies globally, regionally, and locally. For instance, the findings in this section agree with a technology-based monitoring study of aboveground carbon stocks by Nyamugama & Kakembo (2015) in South Africa, which revealed an interchanging declining-increasing pattern of aboveground carbon for the disturbed, transformed, and intact thicket areas over a 38-year period. This pattern of carbon stocks over a 38-year period was attributed to overexploitation of forest resources (deforestation and illegal logging, and land use change over time).

Additionally, findings in this section conform to the findings by Houghton (2005) and Payn *et al. (*2015) that reported a gradually decreasing decadal carbon stock in Asia; when African tropical forest showed a decadal declining-increasing carbon stocks trends whereas Latin America showed an ever increasing per hectare carbon stocks in a global spatial and temporal carbon assessment between 1980 and 2000. Furthermore, the findings in this section are in line with findings by Zhao *et al. (*2020) in their assessment study of the global temporal and spatial carbon variations for future climate between the year 2006 to 2100, which also found a decreasing-increasing temporal patterns attributed to the management systems in place, the forest disturbances, and human activities. Additionally, the findings in this section agree to those by Solomon *et al*. (2018) assessing how land cover changes influenced the carbon dynamics in the Afromontane Forest in Ethiopia between 1985 and 2016) and Charles *et al*. (2020) assessing the aboveground biomass carbon sequestration by the carbon pools of southwestern Mau Forests in Kenya between the year 1985 and 2015; which both reported a temporally decreasing-increasing pattern of carbon stocks between different land cover types. This was attributed to forest's structural variations, anthropogenic and natural perturbations, and the regeneration effects over time.

5.2.3 Tree Species Diversity and Aboveground Carbon Relationships in Kakamega and North Nandi Forest Ecosystems

There was a positive correlation between AGC and tree species diversity in 5/6 of the total sites sampled. High tree species diversity enhances ecosystem functions and productivity, which in turn contributes to high forest carbon. This finding agrees with Liu *et al. (*2018) finding in Southeast China, and Day *et al. (*2014) finding in tropical African forest which reported that tree species diversity was positively correlated with Aboveground Carbon. These findings are however in disagreement with the findings by Filqisthi and Kaswanto (2017) in agroforestry system of Java, Indonesia that found no correlation between tree species diversity and Aboveground Carbon. The findings in this research also agrees with the finding by Ali et al (2016) which found a positive correlation between species diversity and aboveground carbon in the sub-tropical forest of Eastern China.

The least disturbed areas in North Nandi and Kakamega Forest Ecosystems showed a strong positive correlation between the AGC and the tree species diversity. These areas had mixed indigenous old growth tree species that are protected by either KWS or KFS. This may explain their high tree species diversity and carbon stock as plant species survival and productivity were highly enhanced through enhanced forest protection by KWS and KFS. This finding agrees with the finding by Kogo *et al. (*2019) assessing forest cover dynamics, their drivers, and implications in western Kenyan forest ecosystems, which reported that management regime under the Kenya Forest Service and Kenya Wildlife Service enhance the forest protection against deforestation and other anthropogenic disturbances hence high species diversity and richness thus enhanced biomass carbon accumulation over time.

All the forest types revealed a positive correlation between tree species richness and the above ground biomass except for the disturbed areas of North Nandi Forest. This finding could be attributed to the level of disturbances such as forest illegal logging and charcoal burning, abiotic factors, and management regime such as unsustainable utilization of forest resources as supported by a study in Mexican forest by Arasa-Gisbert *et al. (*2018) assessing influence of tree species diversity on carbon stock. The disturbed sites that showed negative correlation between tree species richness and biomass were low in tree species abundance, uneven in distribution of trees, and were highly exposed to both abiotic stress and observable anthropogenic disturbances. These areas were less protected and were prone to livestock grazing, among others. Arasa-Gisbert *et al. (*2018) explained that anthropogenic perturbations impair not only forest ecosystem health but also stand growth and development which eventually reduce both species richness and diversity thus low aboveground biomass carbon accumulation over time.

This study revealed a strong positive correlation between tree species abundance and the AGB, and consequently Aboveground Carbon stock. Generally, a higher individual tree number of results to a high cumulative biomass level of that ecosystem due to combined effect in the primary productivity. This finding supports the finding in Southern China forest by Li *et al. (*2018) and another study by Liu *et al. (*2018) that revealed a strong positive correlation between tree abundance, primary productivity, and biomass, which translate into the Aboveground Carbon stock. In all the sampled plots of this study, DBH and AGB showed a positive correlation. Trees of bigger DBH correspondingly have huge biomass which translate into large quantities of stored carbon with time. This finding agrees with many findings including Nero *et al. (*2018) finding that trees of huge DBH are very low in abundance but rather high in both tree biomass and carbon stock. Age could be a significant mediator in the relationship between tree biomass and DBH. Generally, trees of huge DBH were those of old ages, mature secondary forests, found majorly in the least disturbed or protected areas as opposed to areas of young plantations. These trees of huge DBH could have potentially taken part in longtime primary productivity that have resulted to large biomass accumulation that consequently have stored enormous amount of biomass carbon, and hence the strong DBH- Biomass carbon relationship. The finding in this research agrees with Ali *et al. (*2016)'s finding in sub-tropical forests of Eastern China which reported a strong positive relationship between strand structure (DBH) and aboveground biomass. This finding, however, contradicts Kunwar *et al. (*2021) finding which reported that DBH has very negligible and insignificant influence on aboveground biomass carbon in tropical forests.

5.3 Conclusions

Kakamega and North Nandi forests vary spatially in Aboveground Carbon stocks, with Kakamega forest having more carbon stocks than the North Nandi Forest ecosystem. Least disturbed forest areas have high carbon storage potential, followed by plantations and lastly disturbed forest sites. The forest management regime and variation in diversity among the forest status/types were suspected to be the main cause of these dynamics in both the forests.

Kakamega and North Nandi forests exhibited temporal changes in aboveground carbon stocks which correlated with forest cover changes within the study period. Management regime (unsustainable utilization of forest resources plus government intervention to regain the forest’s ecological and economic integrity after major degradation) were suspected to be the main cause of temporal variations.

Tree species diversity positively impacts carbon stocks as shown in both Kakamega and North Nandi Forest ecosystems. Kakamega forest ecosystem was more diverse compared to North Nandi and this largely explains the high amount of Aboveground Carbon stocks. Management regime that alters vegetation regeneration and development over time were suspected to be the main players in this change.

5.4 Recommendations

i. Forest management should focus on enhancing species diversity and mixed indigenous plantations as opposed to pure stand plantations while at the same time protecting the existing least disturbed forest areas and or restoring disturbed forest ecosystems to the least disturbed or thicket nature/type. This promotes carbon sequestration and storage potential of forests.

ii. A well-coordinated collaborative and holistic approach of management that involves locals and all other players and provides alternative livelihood options should be prioritized in forest management to reduce forest degradation.

iii. Forest protection options such as fencing of forest areas should be explored to reduce forest degradation while promoting tree species diversity.

Recommendations for Further Studies

iv. Further studies should be done to investigate the below ground carbon stocks to fully understand the role these forest compartments play in forest carbon dynamics and influencing climate change.

v. Further studies should also be done to investigate the carbon potential of individual tree species in the forest at different size-classes.

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APPENDICES

Appendix 1: NACOSTI Research Approval Permit

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION

Ref No: 631572

Date of Issue: 16/December/2020

RESEARCH LICENSE

This is to Certify that Mr.. AMOSE OUKO OBONYO of Masinde Muliro University of Science and Technology, has been licensed to conduct research in Kakamega, Nandi on the topic: SPATIO TEMPORAL CHANGES IN ABOVE GROUND CARBON AND TREE DIVERSITY IN KAKAMEGA AND NORTH NANDI FOREST ECOSYSTEMS. for the period ending : 16/December/2021.

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Appendix 2: MMUST Graduate School Permit

MASINDE MULIRO UNIVERSITY OF SCIENCE AND TECHNOLOGY
(MMUST)

Tel: 0702597360/61
: 0733120020/22
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P.O Box 190
50100 Kakamega
KENYA

Directorate of Postgraduate Studies

Ref: MMU/COR: 509079

9th September, 2020

Amose Ouko Obonyo
SEV/G/01-52531/2018
P.O. Box 190-50100
KAKAMEGA

Dear Mr. Obonyo,

RE: APPROVAL OF PROPOSAL

I am pleased to inform you that the Directorate of Postgraduate Studies has considered and approved your Masters proposal entitled: ***"Spatio Temporal Changes in above Ground Carbon and Tree Diversity in Kakamega and North Nandi Forest Ecosystems"*** and appointed the following as supervisors:

1. Dr Humphrey Agevi - MMUST
2. Prof. Harrison Mugatsia Tsingalia - JOUST

You are required to submit through your supervisor(s) progress reports every three months to the Director of Postgraduate Studies. Such reports should be copied to the following: Chairman, School of Natural Sciences and Technology Graduate Studies Committee and Chairman, Department of Biological Sciences. Kindly adhere to research ethics consideration in conducting research.

It is the policy and regulations of the University that you observe a deadline of two years from the date of registration to complete your Master's thesis. Do not hesitate to consult this office in case of any problem encountered in the course of your work.

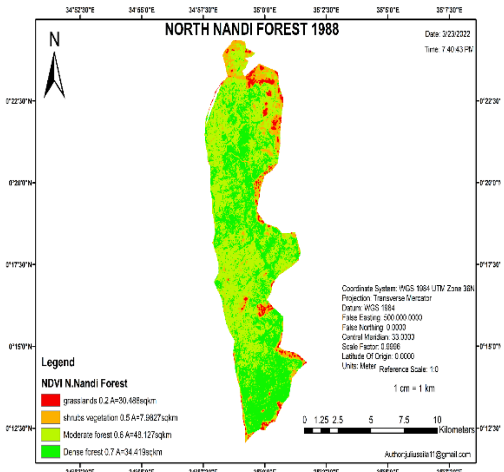
We wish you the best in your research and hope the study will make original contribution to knowledge.

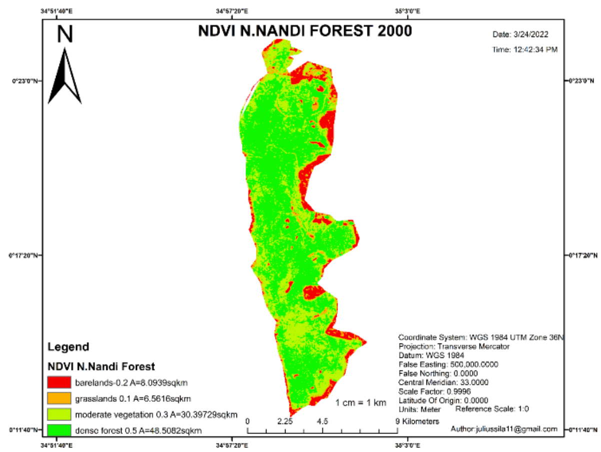
Yours Sincerely,

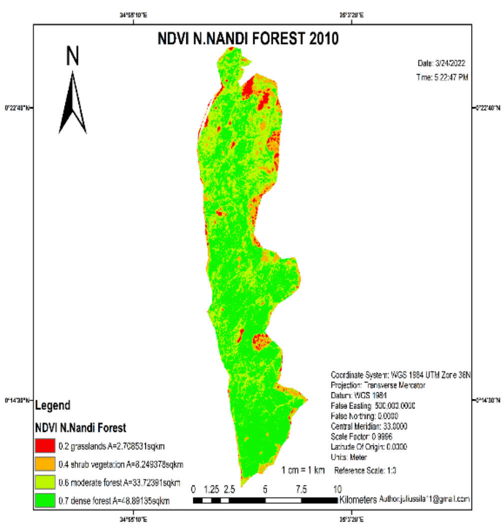
DEAN
SCHOOL OF GRADUATE STUDIES
MASINDE MULIRO UNIVERSITY
OF SCIENCE & TECHNOLOGY

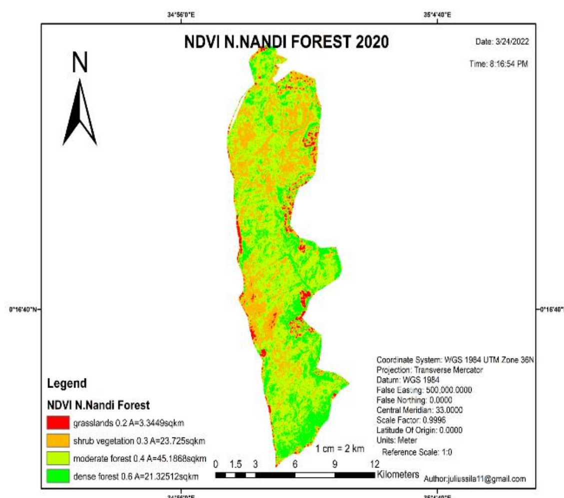
Prof. John Obiri ..... Sign ....
DIRECTOR, DIRECTORATE OF POSTGRADUATE STUDIES

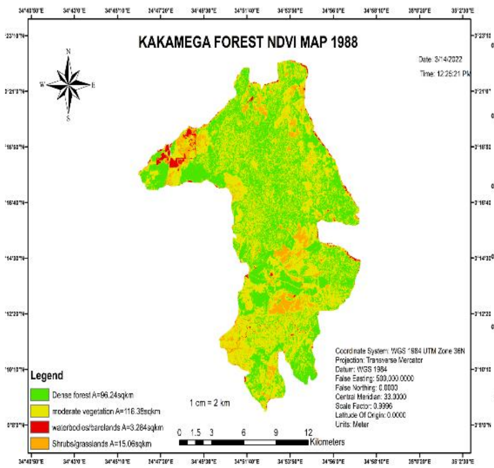
Appendix 3: NDVI Maps for North Nandi and Kakamega Forest Ecosystems Between 1988-2020

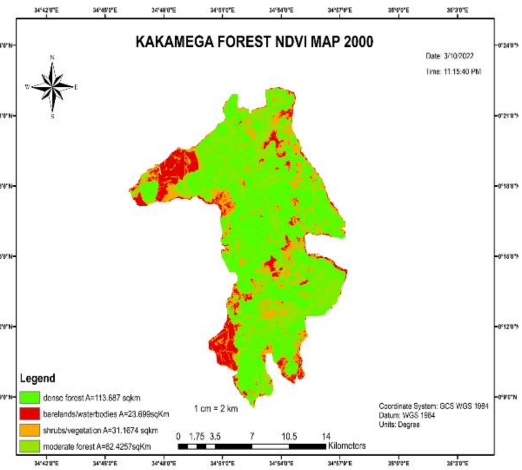


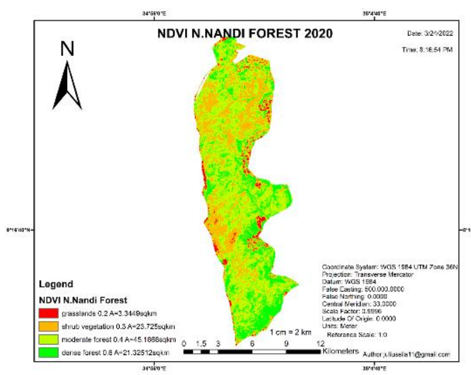


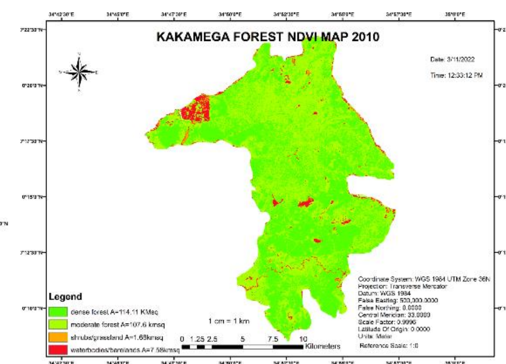


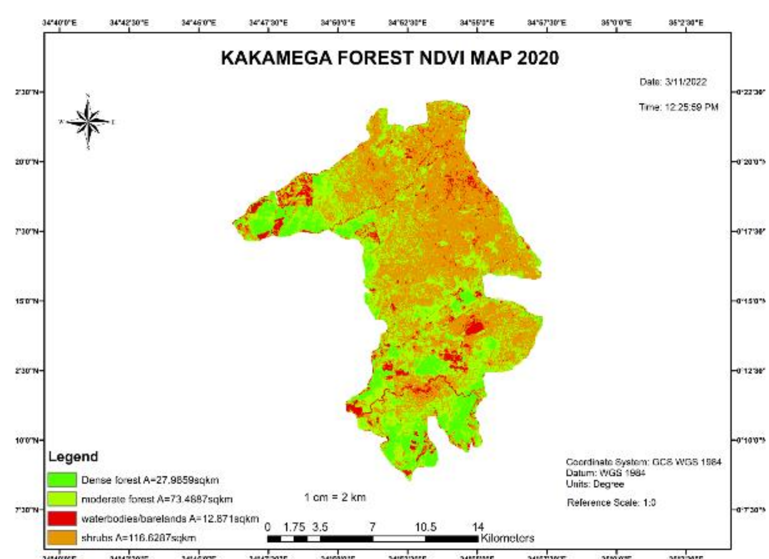



KAKAMEGA FOREST NDVI MAP 1988
Date: 3/14/2022
Time: 12:25:21 PM
N
S
W
E
Legend
Dense forest A=96.24sqkm
moderate vegetation A=116.38sqkm
waterbodies/barelands A=3.284sqkm
Shrubs/grasslands A=15.06sqkm
1 cm = 2 km
0 1.5 3 6 9 12
Kilometers
Coordinate System: WGS 1984 UTM Zone 36N
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 33.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter


KAKAMEGA FOREST NDVI MAP 2000
Date: 3/10/2022
Time: 11:15:40 PM
Legend
dense forest A=113.687 sqkm
barelands/waterbodies A=23.699sqKm
shrubs/vegetation A=31.1674 sqkm
moderate forest A=62.4257sqKm
1 cm = 2 km
0 1.75 3.5 7 10.5 14
Kilometers
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree


NDVI N.NANDI FOREST 2020
Date: 3/21/2022
Time: 8:16:54 PM
N
Legend
NDVI N.Nandi Forest
grasslands 0.2 A=3.3449sqkm
shrub vegetation 0.3 A=23.725sqkm
moderate forest 0.4 A=45.1868sqkm
dense forest 0.6 A=21.32512sqkm
1 cm = 2 km
0 1.5 3 6 9 12
Kilometers
Coordinate System: WGS 1984 UTM Zone 36N
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 33.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter
Referance Scale: 1:0
Author:juliusella11@gmail.com


KAKAMEGA FOREST NDVI MAP 2010
Date: 3/11/2022
Time: 12:33:12 PM
Legend
dense forest A=114.11 KMsq
moderate forest A=107.6 kmsq
shrubs/grassland A=1.68kmsq
waterbodies/barelands A=7.58kmsq
1 cm = 1 km
0 1.25 2.5 5 7.5 10
Kilometers
Coordinate System: WGS 1984 UTM Zone 36N
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000.0000
False Northing: 0.0000
Central Meridian: 33.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter
Reference Scale: 1:0


KAKAMEGA FOREST NDVI MAP 2020
Date: 3/11/2022
Time: 12:25:59 PM
Legend
Dense forest A=27.9859sqkm
moderate forest A=73.4887sqkm
waterbodies/barelands A=12.871sqkm
shrubs A=116.6287sqkm
1 cm = 2 km
0 1.75 3.5 7 10.5 14
Kilometers
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
Reference Scale: 1:0

Appendix 4: Study Area's Tree Species and their Abundance

Species name	**Species abundance**
Acacia abyssinica	*2*
Acacia nilotica	*14*
Acrocarpus fraxinifolius	*20*
Alangium chinense	*4*
Albizia gummifera	*11*
Allophylus abyssinicus	*11*
Aningeria altissima	*4*
Antiaris toxicaria	*21*
Bequaertiodendron oblanceolatum	*2*
Bersama abyssinica	*3*
Bischofia javanica	*34*
Blighia unijugata	*16*
Bridelia micrantha	*10*
Casearia batiscombei	*31*
Cassipourea euryoides	*5*
Cassipourea ruwensorensis	*2*
Celtis africana	*23*
Celtis brownii	*16*
Celtis gomphophylla	*1*
Celtis mildbraedii	*2*
Chaetachme aristata	*4*
Chrysophyllum albidum	*3*
Combretum collinum	*1*
Cordia africana	*5*
Craibia brevicaudata	*7*
Croton macrostachyus	*17*
Croton megalocarpus	*27*
Croton sylvaticus	*3*
Cupressus lusitanica	*407*
Diospyros abyssinica	*8*
Drypetes gerrardinoides	*1*
Drypetes littoralis	*1*
Ehretia cymosa	*24*
Ekebergia capensis	*11*
Eucalyptus saligna	*87*
Fagaropsis angolensis	*3*
Ficus exasperata	*10*

Ficus lutea	*3*
Ficus mucuso	*1*
Ficus sansibarica	*7*
Ficus sur	*18*
Ficus thonningii	*1*
Flacourtia indica	*6*
Funtumia africana	*58*
Grevillea robusta	*2*
Harungana madagascariensis	*8*
Heinsenia diervilleoides	*23*
Jacaranda mimosifolia	*1*
Juniperus procera	*2*
Macaranga bachmannii	*2*
Macaranga kilimandscharica	*60*
Maesa lanceolata	*1*
Maesopsis eminii	*13*
Makhamia lutea	*5*
Manilkara butugi	*12*
Margaritaria discoidea	*3*
Milicia excelsa	*1*
Monodora myristica	*2*
Morus alba	*3*
Morus mesozygia	*8*
Neoboutonia macrocalyx	*1*
Nuxia congesta	*5*
Ochna holstii	*1*
Olea capensis	*10*
Olea europaea	*1*
Oxyanthus speciosus	*14*
Piliostigma thonningii	*3*
Pinus patula	*43*
Podocarpus latifolius	*1*
Polycias fulva	*51*
Premna angolensis	*5*
Prunus africana	*29*
Psidium guajava	*14*
Rawsonia lucida	*2*
Rhus natalensis	*1*
Rinorea brachypetala	*7*
Ritchiea albersii	*4*
Rothmannia urcelliformis	*1*

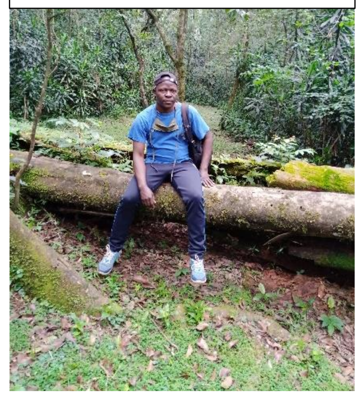
	Sapium ellipticum	*7*
	Schefflera abyssinica	*1*
	Sesbania sesban	*13*
	Spathodea campanulata	*3*
	Strombosia scheffleri	*34*
	Strychnos usambarensis	*25*
	Synsepalum afzelii	*1*
	Syzygium guineense	*63*
	Tabernaemontana pachysiphon	*2*
	Teclea nobilis	*1*
	Toona ciliata	*4*
	Trichilia emetica	*5*
	Trilepisium madagascariense	*42*
	Trimeria grandifolia	*8*
	Turraea nilotica	*2*
	Uvariopsis congensis	*4*
	Vangueria esculenta	*3*
	Vangueria Infausta	*2*
	Vepris nobilis	*3*
	Vitex keniensis	*1*
	Xymalos monospora	*1*
	Zanthoxylum giletii	*2*
TOTAL	**100**	**1511**

Appendix 5: Sampled Gallery During Sampling

At N. Nandi Forest; research team consulting on next move

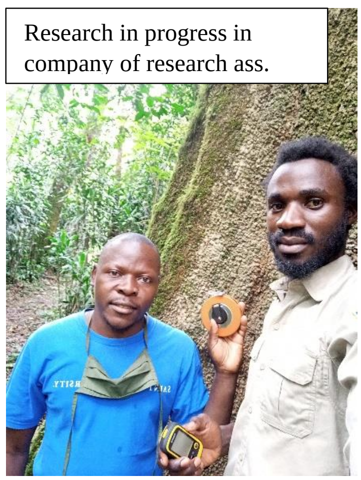
At N. Nandi Forest; research team consulting on next move

After tireless sampling, a rest is necessary at Kakamega Forest



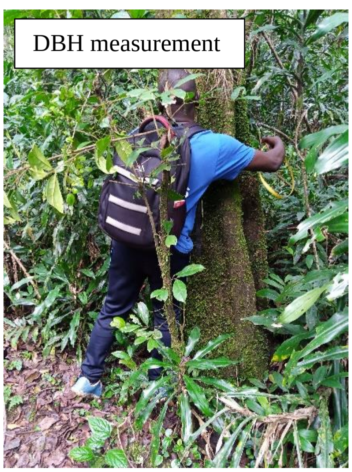
Research in progress

Research in progress in company of research ass.

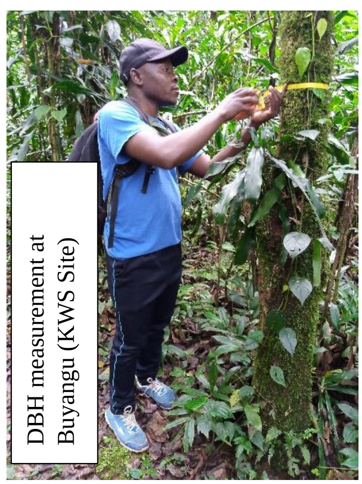


Research in progress

DBH measurement



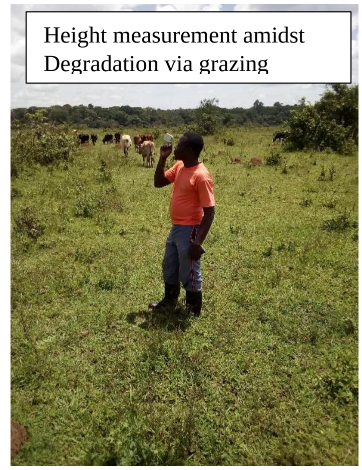
DBH measurement at Buyangu (KWS Site)



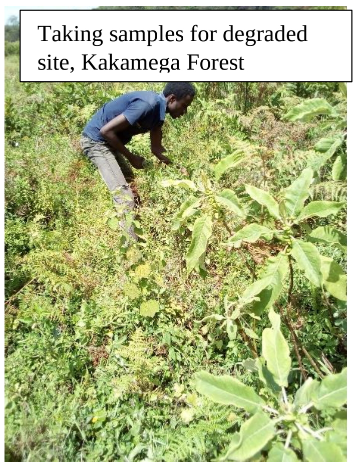
Entry into sampling site

Height measurement at Kakamega disturbed site

Degradation through grazing



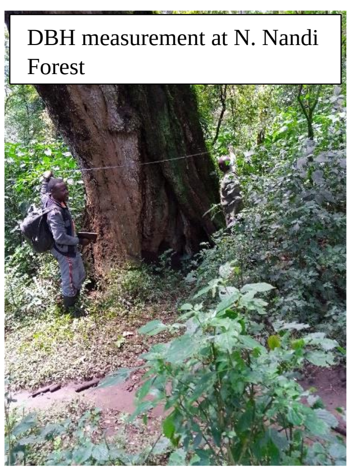
Height measurement amidst Degradation via grazing



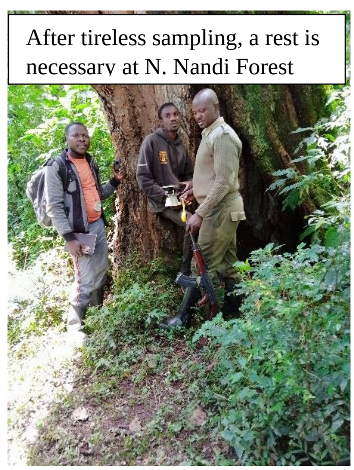
Taking samples for degraded site, Kakamega Forest

DBH measurement at N. Nandi Forest

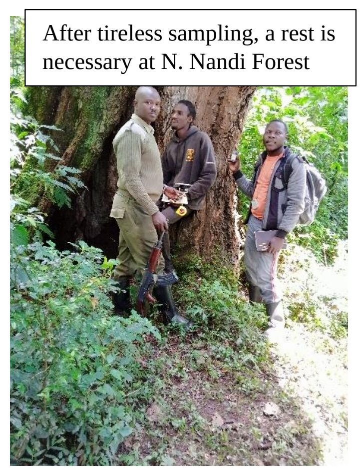
DBH measurement at N. Nandi Forest



DBH measurement at N. Nandi Forest



After tireless sampling, a rest is necessary at N. Nandi Forest



After tireless sampling, a rest is necessary at N. Nandi Forest