MODELLING DETERMINANTS OF FOREST COVER AND CARBON SEQUESTRATION IN CENTRAL KENYA: AN APPLICATION OF SOME STATISTICAL MODELS

VINCENT ONGUSO OEBA

Msc. (Biometry), BEd, (Science)

N85/10038/2008

A Thesis Submitted in fulfillment for the Degree of Doctor of Philosophy in Environmental Science in the School of Environmental Studies of Kenyatta University

October 2011

DECLARATION

Declaration by the Candidate

This thesis is my original work and has not been presented for a degree in any other university or for any other award. No part of this work should be reproduced without prior permission of the author and/ or Kenyatta University.

Signature: ______________________ Date: 18\10\2011

Vincent Onguso Oeba
Department of Environmental Sciences
Kenyatta University

Declaration by Supervisors

I/we confirm that the work reported in this thesis was carried out by the candidate under my/our supervision

Signature: ______________________ Date: 18/10/11

Dr.Samuel C.J. Otor
Department of Environmental Sciences
Kenyatta University

Signature: ______________________ Date: 18\10\2011

Prof. James B. Kung'u
Department of Environmental Sciences
Kenyatta University

DEDICATION

This thesis is dedicated to my late maternal grandmother Yuventina Bochaberi "Nyabokarange" and late paternal grandfather Benard Masita. They encouraged me and shaped my vision of higher education since my childhood.

ACKNOWLEDGEMENTS

My sincere thanks go to Dr. Samuel C.J. Otor and Prof. James B. Kungu for their guidance and supervision during the three-year doctoral study. I am indebted to Dr. Jayne Mugwe who introduced me to my supervisors. My gratitude goes to Dr. Ben Chikamai, Director Kenya Forestry Research Institute (KEFRI), Dr. Benard Kigomo, Deputy Director Research and Development and KEFRI Board of Management for the sponsorship to undertake my doctoral degree programme at Kenyatta University. I sincerely thank Dr. Paul K. Konuche former Director KEFRI for his keenness to ensure that I was on track with my studies. Dr. Muchiri Mbae and Mrs. Rose Osoro are also acknowldeged for their support in coordination of research funds and fees payment, respectively.

I express my special appreciation to Dr. Ebby Chagala Odera for her strong support during my entire period of study and Messers Paul Tuwei and Ely Mwanza, for their continued logistical support. Special thanks go to KEFRI technical support staff; M. Gathura, T. Ondieki, J. Mwaura, G. Omolo, S. Odhiambo, M. Gathara, P. Kibera, S. Kamonde and entire soils staff for their efficient field data collection and laboratory analysis. I appreciate review by Dr.R. Onwong'a and editorial by Mr. C. Kebaya.

My dear wife Lydia Bisieri and children; Cecily Nyaboke, Nelson Mbuni, Petronella Moraa and new born Augustine Masita are thanked them all for their endurance and prayers. I am indebted to my siblings; A. Nyamanga, J. Kemuma, Eng. Sibwoga, Dr. Nyamira, G. Onchieku, J. Nyaema, J. Kimori and my parents; C. Oeba and M. Nyakerario for their prayers and encouragement to pursue higher education. Finally many people contributed to the realization of this thesis. Lack of mention of their names does not in any way mean their deserved contribution is not appreciated but to you all I say thank you and God bless.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

OPERATIONAL DEFINITIONS OF TERMS AND CONCEPTS

Above-ground biomass: This refers to living biomass above the soil including stem, branches, bark, seeds and foliage (Marklund and Schoene, 2006)

Below-ground biomass: This refers to living biomass of live roots (Marklund and Schoene, 2006).

Biomass: This is the organic material both above-ground and below-ground, and both living and dead (Marklund and Schoene, 2006).

Biomass expansion and conversion factor: This is the ratio between above-ground biomass in tones and growing stock in m^3 (Marklund and Schoene, 2006).

Biomass expansion factor: This is the ratio between above-ground biomass and biomass of growing stock (Marklund and Schoene, 2006)

Carbon in above-ground biomass: This is carbon in all living biomass above the soil, including stem, stump, branches, bark, seeds and foliage (Marklund and Schoene, 2006).

Carbon in below-ground biomass: This refers to carbon in all living biomass of live roots (Marklund and Schoene, 2006).

Carbon in litter: This is carbon in all non-living biomass including litter, fumic and humic layers (Marklund and Schoene, 2006)

Carbon sequestration: Refers the process through which agricultural and forestry practices remove carbon dioxide (CO_2) from the atmosphere.

Carbon stock: This is the quantity of carbon in a 'pool', meaning a reserviour or system which has the capacity to accumulate or release carbon (Marklund and Schoene, 2006).

Commonly grown plantation species: This refers to tree species that are mainly planted in government of Kenya gazzetted forests for industrial wood, namely; *Pinus patula, Eucalyptus saligna, Cupressus lusitanica* and *Juniperus procera.*

Forest: This refers to land spanning more than 0.5 ha with trees higher than 5 m and a canopy of more than 10% or trees able to reach these thresholds in situ excluding tree stands in agricultural production systems, for example fruit plantation and agroforestry systems (Marklund and Schoene, 2006).

Greenhouse gas inventory: This is an accounting of the amount of greenhouse gases emitted or removed from the atmosphere over a specific period of time.

Recruitment: This refers to entry of new seedlings and trees into land for increase of forest cover.

Root-shoot ratio: ratio between above-ground and below-ground biomass (Marklund and Schoene, 2006)

Seedling recruit: This has also been defined as a propagule that has been germinated and is able to survive without maternal resources (Ribbens et al., 1994).

Sinks: This is the term used to describe agricultural and forestry land that absorbs CO_2, the most important global warming gas emitted by human activities.

Site index: Term used in forestry to describe the potential for forest trees to grow in particular location or site.

Soil carbon: This refers to organic carbon in mineral and organic soils at specified depth (Marklund and Schoene, 2006)

Validation: This is the quantitative comparison of specific model predictions against independent empirical data.

ABBREVIATIONS AND ACRONYMS

AGB	: Above Ground Biomass
AIC	: Akaike Information Criterion
ANOVA	: Analysis of Variance
ANCOVA	: Analysis of Covariance
ARIMA	: Autoregressive Intergrated Moving Average
AR	: Autoregressive
MA	: Moving Average
ACF	: Autocorrelation Functions
AEZ	: Agro-Ecological Zone
BA	: Basal Area
BAT	: British American Tobbaco
BCEF	: Biomass Conversion and Expansion Factors
CBS	: Central Bureau of Statistics
CDM	: Clean Development Mechanisms
CDV	: Classification of Dependent Variable
CL	: *Cupressus lusitanica*
CO_2e	: Carbon dioxide equivalent
DBH	: Diameter at Breast Height
DRSRS	: Department of Resource Survey and Remote Sensing
ES	: *Eucalyptus saligna*
FAO	: Food Agricultural Organization
FSK	: Forest Society of Kenya
FIREHARM	: Fire Hazard and Risk Model
FullCAM	: Full Carbon Accounting Model
GHG	: GreenHouse Gases
HH	: Household Head
IPCC	: Intergovernment Panel on Climate Change
KEFRI	: Kenya Forestry Research Institute
KFS	: Kenya Forest Service

KFWG	: Kenya Forest Working Group
KNBS	: Kenya National Bureau of Statistics
KPLC	: Kenya Power and Lighting Company
LM	: Lower Medium
LH	: Lower Highland
LSE	: Least Squares Estimates
LSD	: Least Significant Difference
LTV	: Lifetime Value
MAI	: Mean Annual Increament
m.a.s.l	: Metres above sea level
MENR	: Ministry of Environment and Natural Resources
MDGs	: Millennium Development Goals
NCAS	: National Carbon Accounting System
NEMA	: National Environmental Management Authority
NGOs	: Non-Government Organizations
NFI	: National Forestry Inventory
PACF	: Partial Autocorrelations Functions
PES	: Payment of Environmental Services
PP	: *Pinus patula*
REDD	: Reduced Emissions from Deforestation and forest Degradation
REML	: Restricted Maximum Likelihood Estimate
RGGI	: Regional Greenhouse Initiative
SOC	: Soil Organic Carbon
SOM	: Soil Organic Matter
TBP	: Tree Biotechnology Project
TAFDA	: Teagasc Agricultural and Food Development Authority
TA	: Tropical Alpine zone
UH	: Upper Highland
UM	: Upper Medium

ABSTRACT

Forests play a significant role in the mitigation of climate change and improving livelihoods of people directly and indirectly across the world. Kenya's closed forest canopy is less than 2% as compared to 9% and 21% for the rest of Africa and the world, respectively. The Government of Kenya Forest Act 2005 envisions achieving 10% forest cover through various forestry programmes with farm forestry seen as the main viable option. Statistical models have proved to be useful tools in studying the cause and effect relationship that could lead to insights regarding determinants of tree retention on farm for improvement of forest cover and carbon sinks. However, little has been done in the assessment of tree recruitment, survival, carbon estimation, carbon market and factors associated with tree retention on farm. The objectives of this study therefore were to: determine the recruitment, survival and carbon quantification of commonly grown plantation tree species (*Pinus patula, Eucalyptus saligna, Cupressus lusitanica* and *Juniperus procera*); evaluate income from carbon credits in comparison with sale of wood and analyze determinants of tree retention on farm. The study was carried out in Kiambu and Nyeri Counties covering Lari, Kikuyu, Nyeri South and Nyeri North districts in Central Kenya. Retrospective longitudinal approach for seedling distribution data from Kenya Forestry Service (KFS) and sampled group of nurseries were used to model the trend of seedling recruitment. A list of gazzetted plantation forests was drawn in which stratification and simple random sampling were used in selection of forest stations and species. An inventory data of 2009 from sampled forest stations were used to model the tree mortality of the selected species. Temporal plots were established in the sampled plantations for carbon assessment. Stratification and simple random sampling procedures were used to select farm household in the baseline survey for assessment of tree retention determinants. Seedling distribution data were analyzed using time series (Autoregressive Integrated Moving Average-ARIMA) and linear mixed models. Mortality data were analyzed using survival models. Linear mixed and generalized regression models were used for analysis of carbon estimation and income in comparision with wood sale. Chi-square, Mann Whitney U, Kruskal Wallis H tests, analysis of variance, binary and multinomial logistic regression models were used for analysis of survey data on tree retention determinants. There was a significant decreasing trend on tree rectruitment on farm and gazzetted forests. ARIMA models significantly ($p<0.01$) fitted the data. *Cupressus lusitanica, Pinus patula* and *Eucalyptus saligna* were the dominant tree species planted and had better survival. *Eucalyptus saligna* had highest amount of carbon sequestered below-ground and above-ground (247.9 ± 44.4 MgC ha^{-1}) followed by *Pinus patula* (145.6 ± 44.4 MgC ha^{-1} and *Cupressus lusitanica* (98.4 ± 44.4 MgC ha^{-1}). Income realized from sale of wood as compared to expected carbon credit for above ground biomass was higher. However, with inclusion of soil carbon, expected carbon credits were higher than sale of wood. Study sites, gender of HH, income, land size, age, education, occupation, technical skills, harvesting regulation, extension services and labour, significantly influenced farmer's lifetime value to retain trees on farm. Overall statistical modelling was found useful in identifying suitable determinants of forest cover and carbon sequestration. The study recommends acquisition of more data to maximize the use of time series models on forecasting of seedling recruitment for improvement of forest cover. It also emphasizes the need for developing biomass equations of commonly grown plantation species and trees on farm to improve accurate estimation of carbon sequestration in Central Kenya.

CHAPTER ONE: INTRODUCTION

1.0. Background to the Problem

Forests play a significant role in improving people's livelihoods directly and indirectly across the world. They provide fuelwood, poles, posts, timber, pulp and paper. Importantly, they cycle nutrients, regulate climate change through carbon sequestration, stabilize soil, treat waste, provide habitats, and offer opportunity for recreation. These services are worth more than $4.7 trillion, a total equal to one tenth of the gross world product (Larsen, 2008a). In Kenya, over 100,000 people directly rely on forests and forests industries for employment and income (Kenya Forestry Society [KFS], 2006). The provision of forest benefits is on a continuous decrease due to reduction of area under trees. This has been mainly caused by clearing forestry areas for agriculture and increase of human population resulting to decrease of land area for effective tree planting. Thus, most forests are no longer in their original condition, having changed in composition and quality.

In Kenya, the closed canopy forest cover is considered to be too low (less than 2%) as compared to 9% and 21% for the rest of Africa and the rest of the world, respectively (KFS, 2006). This has been evidenced further by the recent forest cover mapping of Mau forest complex by the Department of Resource Surveys and Remote Sensing (DRSRS) in 2003-2005, which showed that for the gazetted forest blocks, the whole of Molo Forest had been cleared and put under cultivation. In West Molo for instance, the area under natural forest was 82% with the rest being taken by cultivation and shrubs. The most intact of all 22 gazetted forest blocks in Mau complex was Chemogorok, which had lost only 52 ha or 0.35% of its area for cultivation. This was associated with government's control on further encroachment (Mazingira News, 2008).

The loss of forest cover is considered to pose a serious challenge to the country's economy which –heavily dependon agricultural production and whose population relies on forest products and services for many basic requirements. For example, over 90% of the country' domestic energy requirements are met from fuelwood and highest foreign income earner is from Tourism where wildlife takes a chunk of this share. FAO recommends a minimum of 10% forest cover for any country to claim safety on this resource (KFS, 2006).

Kenya through the new Forest Act of 2005, envisions achieving 10% forest cover through various forestry programmes with an emphasis on farm forestry as the main viable option. This is expected to increase the current estimated area (2.4 million ha of which 1.64 m ha are gazetted) under forests. The area of non-gazetted forestland is estimated to be 0.76 million ha fragmented into over 273 forest units, with 43% covering 100 ha or less. The closed canopy indigenous and exotic forest occupies about 1.22 million ha, while plantations cover 0.16 million ha (KFS, 2006). Of the total closed forest cover, 20% are located in Central Kenya, mainly in Mt. Kenya and Aberdares forests.

Central Kenya has a high population growth rate and there is continuous use of agricultural land, causing a lot of pressure on natural and plantation forests as well as partial woodlands for settlement. There is evidence of continuous human encroachment and destruction of existing forests in Aberdares and Mt. Kenya ecosystems. However, with the introduction of mass planting of tree programmes in the country, such as the one billion project tree planting, plant enrichment in natural forest and other rehabilitation methods, provision of various incentives to farmers and other interested investors, are expected to increase the area under tree cover. Similar approaches have been used in other countries like China, where a massive reforestation campaign added an average of 1.8 million hectares each year. This was largely because bans on deforestation near the end of the decade heightened the country's reliance on plantations and imports of forest products from other nations (Larsen, 2008b).

Consequently, the culture of tree cutting shows that nearly half of the forests are at risk across the worldhence posing a serious challenge of global warming. For example, over the past 100 years (20th Century), Mt. Kenya lost 92% of its ice mass while Mt. Kilimanjaro lost 82% which comprises an important source of river streams and springs (NEMA, 2007). The global mean sea level is reported to have risen by 20-30 cm. There are changes in the ecosystem and loss of biodiversity, spread of infectious diseases such as malaria since increase of temperature favours the breeding of disease carrying insects, animals and microbes in the places they did not exist before (NEMA, 2007).

Prolonged droughts have been occurring in the country in the recent past and are becoming more frequent and severe with time. For instance, *La Nina* of 1999-2001 was an extreme drought condition which occurred again from January- March 2006 (NEMA, 2007). Flooding has become a common phenomenon and a menace in many parts of the country such as Budalangi floods (along River Nzoia) in Western Kenya arising from Cherangani Hills; Kano plains (along Nyando River) in Nyanza Province arising from Nandi hills while Tana River floods arise due to poor land use practices in Mt. Kenya and Aberdares catchment areas (NEMA, 2007). These effects of climate change have caused severe socio-economic impacts including loss of human life and livestock, damage to infrastructure, poor crop yield, famine due to food shortage, wildlife migrations, human migrations and displacements, which are affecting livelihoods and posting negative economic performance.

The situation is worsened by the fact that about 80% of the Kenyan population is rural based and depends on rain-fed subsistence agriculture (KFS, 2006).

A number of attempts to reduce sources of Greenhouse gases, (GHG) emissions that are causing global warming have been made. Among them are: introduction of Clean Development Mechanisms (CDM) projects, like KenGen's ongoing geothermal and hydropower projects which assist KenGen to lower the use of thermal power generation plants, thereby replacing expensive heavy fuel; diesel and gas fired generation leading to reduction of CO_2 emissions to the atmosphere by generating energy without GHG emissions. Other projects include promotion of bio-fuels use of clean energy like hydro generated electricity, energy saving stoves, among others. However, the most significant one in mitigation of climate change, which can be attained through proper management, is reforestation leading to increase in the forest cover and natural carbon sinks. The CDM of the Kyoto protocol, emerging voluntary carbon markets and the proposed programme of Reduced Emissions from Deforestation and forest Degradation (REDD) forms critical incentives in reducing global warming (NEMA, 2007).

Tree planting is very crucial in controlling climatic changes as young growing trees in particular remove more carbon dioxide from the atmosphere than they will release, hence more carbon storage in the plants and soils. However, little has been done in the assessment of tree recruitment, survival, carbon estimation, carbon market and factors associated with tree retention on farm. Therefore, this study addresses modelling the recruitment and survival of commonly grown plantation and other species; estimation of carbon sequestered by commonly grown plantation species; evaluation of the economic returns of tree farming in comparison with carbon market as incentives of promoting forestry. This study also sought to model the determinants of the lifetime value of the farmer willing to retain trees on farm for longer period in improving the forest cover and carbon sinks in Central Kenya.

1.1. Statement of the Problem and Justification

Kenya has been losing forests at a rate of approximately 19,000 ha annually for the last 20 years (Central Bureau of Statistics [CBS], 2004). Between 1990 and 2000, it lost 12,600 ha of forest resulting in 0.34% rate of forest decrease. At independence, gazetted forests covered 1.8 million ha, representing 3.5% of the total land area of the country. This has dwindled considerably due to pressure from agricultural expansion and settlement. Large areas of the remaining natural forests have been degraded through over exploitation and poor harvesting techniques. The area under industrial plantations, which has been a major source of poles, posts, timber, pulp and paper production has decreased from 164,000 ha to 80,000 ha (CBS, 2004).

An analysis of the supply and demand of wood products shows that the country is not currently able to meet its wood requirements. According to Kenya Forest Master Plan (Ministry of Environment & Natura Resources [MENR], 1994), the annual sustainable wood supply was approximated to be 22 million m^3 in 1995 while the demand stood at 25 million m^3. By the year 2020, annual wood demand will be about 45 million m^3 while the supply would only be 38 million m^3, occasioning an annual deficit of 7.0 million m^3. This deficit, which is already manifesting itself, will lead to further deforestation and environmental degradation; hence increase of GHG emissions which in turn have devastating effects on climate and the economy.

In Central Kenya, incidences of deforestations on gazetted plantations and natural forests as well as human encroachment on these forests are on the increase. A number of reforestation and rehabilitation projects on degraded sites have been initiated on government land, trust land and private lands by the government, Non-governmental Organizations (NGOs), organized groups, corporations, farmers and other stakeholders, but little is known on the current status of forest cover within this region. Subsequent to these, research trials on performance of major tree plantation species under different silvicultural management have been established over along period of time by relevant research institutions and other stakeholders, but limited effort has been laid on effective cohort follow-up from seedlings survival, growth and maturity in determining the rate of forest cover and predicting the forest stock.

Moreover, the introduction of carbon market in developing nations and some pilot projects around Mt. Kenya region requires accurate data and methodologies on carbon sequestration. This would help in estimating the amount of carbon that various tree species can sequester at different ages of growth and location.This will reliably provide farmers with competitive incentives for reforestation in comparison with other income accrued from tree products. Carbon sequestration models have been developed and applied in other countries such as Australia, Canada, Switzerland, and, among other industrialized countries. However, no such attempts have been made in Kenya and other African countries, yet the carbon market is taking central role in controlling deforestation and changes on land use.

On the other hand, the culture of tree planting has been rekindled in Central Kenya by various environmental conservation and nursery groups through supply of high quality seeds and fast growing seedlings by Kenya Forestry Research Institute (KEFRI), Tree

Biotechnology Project (TBP), and other organizations. The enactment of Forest Act No. 7 of 2005 envisions that Kenya would attain its forest cover to the minimum recommendation of 10%. Therefore, this study provides; methodologies on how to undertake regular analysis of information trends, modelling and forecasting to develop knowledge for accurate planning and informed decision making on tree growing investment; estimates of carbon quantification from commonly grown plantations species across ages anad sites; estimates economic valuation of carbon and wood sale of commonly grown plantation species in Central Kenya anddeterminants of the lifetime value of the farmer willing to retain the trees on farm for improvement of forest cover in Kenya.

1.2. Research Questions

The study endeavoured to answer the following questions:

i. What is the trend of seedling recruitment and tree survival of commonly grown plantation species and how does it contribute to forest cover in Central Kenya?

ii. What is the amount of carbon sequestered by commonly grown plantations species in gazzetted forests and how does it vary among species across sites and ages?

iii. What are the estimates of income to be realized from carbon sequestered by commonly grown plantation species and how does it vary with sale of wood?

iv. What are the determinants that can influence the lifetime value of the farmer willing to retain trees on farm for long period of time and how do they lead to improvement of forest cover?

1.3. Research Hypotheses

i. Successful recruitment and survival of the commonly grown plantation tree species under different environmental locations have a significantly positive effect in contributing to forest cover.
ii. Quantity of carbon sequestered by commonly grown plantation tree species varies significantly varies across age and sites.
iii. The amount expected to be realized from sell of carbon credits from commonly grown plantation species will be significantly higher than that of sale of wood.
iv. Household, farm and tree management determinants will significantly influence the lifetime value of the farmer willing to retain trees on farm.

1.4. Research Objectives

The overall objective of this study was to model the determinants of forest cover and carbon sequestration in Central Kenya. Specifically the study sought to:

i. Determine the recruitment and survival trend of commonly grown plantation tree species in contributing to forest cover under different environmental sites.
ii. Quantify and analyze carbon sequestered by commonly grown plantation tree species at different ages of growth and environmental sites.
iii. Evaluate expected income of carbon quantified from commonly grown plantation tree species in comparison with sale of wood.
iv. Identify and model determinants of lifetime value of the farmer willing to retain trees on farm in improving forest cover and carbon sinks.

1.5. Significance of the study and anticipated Output

The enactment of Forestry Act No. 7 of 2005 focuses on the promotion of community participation in efficient management forests, forest rehabilitation and reforestation including the private sector in the development of woodlots and agro-forestry. Therefore, this study would significantly contribute in shading light on the appropriate application tools and models that would sufficiently inform various stakeholders in forestry on the possible scenarios that would improve forest cover. For instance, the recruitment, survival, growth and maturity data of the commonly grown plantation tree species would provide a sound basis for developing probabilistic scenarios that would guide the forest sector.

The introduction of carbon markets in Sub-Saharan Africa, so far, lacks well developed methodologies for specific regions hence the need for it to be addressed. This study, therefore, contributes significantly to the current and pressing needs of quantifying the amount of carbon from commonly grown plantation tree species across ages and environmental sites. The comparison of income realized from sale wood would provide competition on prices of carbon sale. This study evaluated the likely carbon prices that tree growers would consider in case they forgo sale of wood. In the long term, this would contribute significantly to the Millennium Development Goals (MDGs) of halving the proportion of people living in extreme poverty by 2015, ensuring environmental sustainability through increase in the area under forest cover and land protected to maintain biological diversity.

Forestry programme takes different forms with an aim of improving tree cover and health environment. Understanding that among the key players and beneficiaries are farmers; there is need of assessing the extent to which farmers are likely to carry out sustainable forest management. Therefore, this study identified and analyzed determinants associated with farmers' likelihood of retaining trees on farm for longer period in improving forest cover and carbon sinks.

1.6. Conceptual Framework

Tree establishment on farm or in any forestry system is as a result of natural regeneration, enrichment, establishment of field trials and general tree planting. However, this depends on the availability of seedlings, area to be planted, among other factors. The transition of seedlings to saplings to trees in a forest system follows a recruitment process that is generally stochastic and can be modeled in a stochastic time series sense. During the growth period, trees require carbon dioxide for photosynthesis and releases oxygen to the atmosphere hence carbon sequestration. This entails assessment of carbon on the living biomass, soil organic and wood products.

Quantified carbon has a potential in carbon markets as opposed to sale of wood. The income likely to be realized from either sale of carbon or wood would act as an incentive in promoting forest cover and consequently mitigating climate change. However, unsustainable wood sale would enhance more removal of trees resulting to low forest cover and environmental degradation. Consequently, the participation of farmers in tree planting and retention has a direct positive effect on forest cover. Conversely, the tendency of farmers unwilling to retain trees on farm for long periods of time negatively affects forest cover and hence low carbon sinks. The interconnectedness of these concepts has certain attributes which can be used in statistical modelling, hence the basis of this current study as illustrated in the figure below.

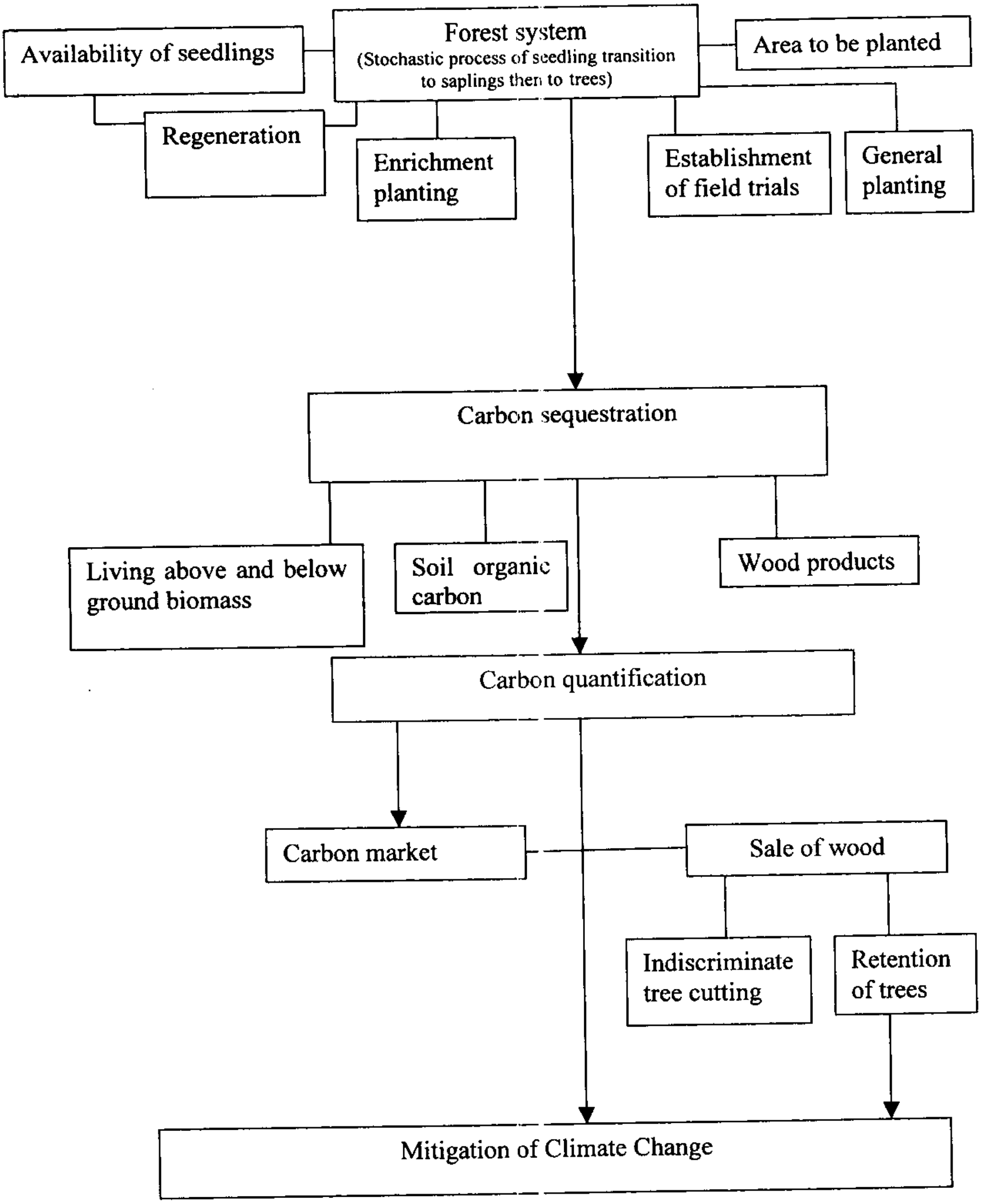

Figure 1.1: Conceptual framework for forest cover and mitigation of climate change
Source: Author's own conceptualization from literature

1.7. Limitations and Scope

The limitations of this study were; ban on tree harvesting in gazzetted forests, which could have helped in developing biomass equations; financial resources to purchase tree from farm and payment of labour for clearfelling and uprooting stumps for developing biomass equations; rocky nature of some study sites hampered soil sampling at the targeted one metre depth; local biomass conversion and expansion factors (BCEF) for commonly grown plantation tree species are not readily available neccesistating the use of default figures. The scope of this study was limited to Government gazzetted industrial forest plantations trees and trees on farm covering Aberdares and slopes of Mt. Kenya. Model development focused on recruitment of seedling into the forest system, survival, growth, maturity and tree retention. The estimation of carbon sequestration was restricted to plantation forests for above-ground and below-ground biomass.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

This chapter presents review of studies on forest cover and carbon sequestration globally, regionally and locally. A review on statistical modelsfor the determinants of forest cover and carbon sequestration and their relevance to this study was found vital in building the foundation of this study. In particular, models for tree recruitment, forest growth dynamics, survival and mortality, biomass estimation and carbon sequestration in forestry systems, economic analyses of carbon market and tree retention determinants were presented. A summary of literature review provided at the end of this chapter identifies the knowledge gap that the study addresses.

2.2. Forest Cover and Drivers of Deforestation

Since 1960, global industrial wood production rose by 50% to 1.5 billion cubic metres, four fifths of which was from primary and secondary-growth forests. About the same quantity, 1.8 billion cubic meters, is burned directly as wood fuel each year in developing countries. Of the 200 areas of high biological diversity worldwide, illegal logging threatens 65% of 200, which has devastated public forests around the globe, reducing incentives for locals to invest in sustainable forestry and accumulating losses of revenue to governments of about $15 billion annually (Larsen, 2008a).

Forest cover has subsequently continued to decline across the world with tropical and subtropical regions of Africa leading in forest destruction. Uncontrolled timber harvesting, conversion of forests to farm and pasture lands, increased needs of human population, road construction, fire outbreaks and other related mortality factors have been identified as the main drivers of deforestation (Mahapatra and Kant, 2005).

Studies such as Dolisca et al., 2007; Pahari et al., 2000 have shown that in developing countries, the economic value of forests, population density, infrastructure, education (educated farmers are less likely to clear forests), income per capita, length of residency, migration, energy prices and land tenure (farm households who occupied land illegally or insecure land title deeds are more likely to clear forests for agricultural expansion), among others, have been found to influence deforestation. Analyses carried out to establish the relationship between population and deforestation, has found that the correlation between the logarithm of the population density and the total accumulated forest loss is the most significant, with the correlation factor ranging from 0.71 to 0.91 for various regions of the world (Pahari and Murai, 1999).

Deforestation was predicted to likely continue at a very significant rate, especially in the developing countries but most severe in Africa, where it was predicted that more than 30% of the forests in 1990 would be lost by 2025, which corresponds to an annual deforestation rate of 1.06% (Pahari and Murai, 1999). In Nigeria the rate of deforestation was reported to be alarming as only 10% of the tropical rainforest area was remaining as of 20th century. The estimated average annual deforestation was 285 x 10^3 ha yr^{-1} between 1976 and 1980, increasing to an estimated 400 x 10^3 ha yr^{-1} by 1990 (Onyekwelu, 2007).

In East Africa, the Food Agricultural Organization (FAO, 2003) estimated that 10% of forest cover was lost between 1990 and 2000 due to human encroachment, government settlement, population pressure among others, with highest rate recorded in Uganda. Similar scenarios were observed in Cameroon where about 200,000 ha of the forest were lost annually due to high rates of exploitation as compared to 1.4 m ha yr^{-1} in Brazilian Amazon rain forest. Some of these anthropogenic activities have resulted to loss of habitats for important flora and fauna, increased local flooding which sometimes results in loss of human life and property, reduced water quantity and quality of rivers and streams, and destructive climate change (Evelyn, 2009).

Forest plantations cover more than 187 million hectares, less than 5% of total forested area, but account for 20% of current world wood production. As natural forests are exhausted or come under protection, a growing share of future wood demand will be satisfied from tree on farms. Well-planned and managed plantations can efficiently satisfy timber demand. Unfortunately, the world has seen many plantations raised at the expense of old growth or other extremely diverse natural forests. In some cases, governments grant forest concessions to logging companies contingent on their planting of replacement trees, but after the companies clearcut, they leave the land bare and move to new areas. In Indonesia, for example, 9 million hectares were allocated for development as industrial timber plantations, but only 2 million hectares were replanted (Larsen, 2008a). It has been argued that a significant increase of plantation forests has expanded forest cover in North America, Europe and China while diminishing in the tropics. Whilst this helps to offset the loss of natural forests, it has a negative impact on overall decline in global biodiversity as single species plantations replace their biologically richer natural counterparts.

2.2.1 Forest Cover in Kenya

Kenya, among the East African countries, shares the problems of small, fragmented areas of forest under extreme pressure of encroachment and exploitation. It has a total forest cover of 37.6 million ha out of which 2.1 million ha are woodlands, 24.8 million ha are bushlands and 10.7 million ha are wooded grasslands. Out of the total forest cover, only 1.7

million ha are gazetted and managed by Kenya Forestry Service (KFS). A total of 9.4 million ha of variety of trees coverage exist in farmlands, settlement areas and urban centres. Overall, indigenous gazetted forests cover1.2 million ha as compared to gazetted plantations 160,000 ha (1995), 165,000 ha (1998) and 120, 000 ha in 2002 as compared to unknown acreage of dry land/woodlands, farmland forests and other landscapes (Mathu, 2007).

Forest patches make up less than 3% of the land area in the East Africa region and they are often heavily degraded. It has been suggested that the forest cover in East Africa was much more extensive some millennia ago. Some decrease of the area of natural forest was due to excisions from forest reserves. A recent study by International Union of Nature Conservation about trends in forest cover in Kenya concluded that in spite of intentions stipulating that forest excisions [from government forest reserves] should cease, degazettement continues, and the forests that are excised are often significant in terms of biodiversity or in size, and important criterion in the maintenance of biodiversity. The study further concluded that since 1986, Kenya has lost about 15,000 hectares of natural forest due to excisions (http://www.easternarc.org/pub).

Department of Resource, Survey and Remote Sensing (DRSRS) and Kenya Forestry Working Group (KFWG) on degradation of Mau complex, among other few water towers (Mt. Kenya, Aberdare Range, Cherangani Hills and Mt. Elgon), found that forest cover has continued to decline at alarming rate. A total of 9,813 ha were cleared of which 94.7% were indigenous as compared to 7,084.24 ha in 2000-2003 where most of it were of plantations (DRSRS and KFWG, 2006). Of the 14 sites identified, eight were new implying that destruction was spreading. Forests in other four water towers showed no sign of deforestation between 2003 and 2005 where Mt. Kenya specifically showed signs of improvement even though there are reports that deforestation is ongoing in some parts. As the government gears her efforts in conserving its "five water towers" and improving the forest cover, the success of the rehabilitation programme will entirely depend on changes of human habits and customs which take time and sometime resistence to government efforts. Evelyn (2009) reported that in such cases, compromises are necessary in order to obtain a near optimal solution and sometimes the government would be forced to implement rehabilitation strategies through policies and legislation.

Enhancement of farm forestry offers a viable option for only attaining the goal of 10% forest cover. The new Kenyan Forest Act No. 7 of 2005, provides incentives for extension services, promotion of community based projects, and support of management of natural forest on farmlands, improved marketing and access to quality seedlings, among others, in meeting the goal of forest cover (Kenya Forestry Society, 2006). The country currently produces 41 million seedlings against the target of 80 million seedlings per year of which 80% come from the private sector. Most of the nurseries have exotic seedlings mainly Eucalyptus species/clones, *Grevillea robusta,* pines, cypress, among others. Indigenous species are always limited in supply, knowledge of growth and yield as well as silvicultural management, initial difficult of establishing them in plantations, coupled with their slow growth rate compared with exotic plantation tree species, affects the enhancement of forest cover in the country.

Potential stakeholders taken as out growers have been found increasing significantly the area under trees. These include: Pan African Paper Mills, Kenya Power and Lighting Company, Nyayo Tea Zones, British American Tobbaco, Master Mind Kenya Limited, One Billion Tree Project, among others. For instance, Pan African Paper Mills, which prefers growing *Pinus patula*, *Cupressa lusitanica* and *Eucalyptus* species, establishes 1500 ha in the clear felled exotic plantations on government land every year. This mainly involves replacement of clearfelled plantations. The Company is reported to be in the process of contracting farmers from 11 districts of Western Province where at least 500 farmers expressed interest of joining the scheme. The same has been observed in a number of companies (Kenya Forestry Society, 2006). This was all geared towards increasing tree cover in the country as well as meeting various demands and generating revenue to the nation and individuals.

2.3. Models of Tree Recruitment and Forest Growth Dynamics

The estimation of forest cover takes different angles with forest growth modelling depending on the tree species and site conditions. However, there are difficulties on handling temporal variations of growth conditions since forests typically grow over decades to centuries hence practically no forest can be assumed to have developed under constant environmental conditions. Unknown factors and process chains may cause decade lasting growth depressions, enhancements or trends. Therefore, in the case that long term growth conditions fluctuate notably over time, it might be helpful to analyse forest growth behaviour by using model simulations generated by assuming unchanging environmental impacts as baseline scenarios (Mette et al., 2009).

To examine the speed of tree regeneration, for instance, spatially explicit simulation model, which incorporates the interaction between the changing herb layer and growth, has been used. It incorporates vegetation and simulates spatial changes in the herb layer using cellular automaton combined with Markov transition matrix (Rammig et al., 2006). The results of this model through sensitivity analysis revealed that seed availability, seedling survival and presence of advance regeneration were key processes of successful reforestation. However, their study indicates that the model could be improved regarding to crown projection for trees taller than two metres and competition between larger trees. Overall, the authors' model shows that recruitment of new trees depending on vegetation types and advances regeneration were two key processes for successful reforestation and concludes that their model can potentially be used to examine the associated processes in a detailed manner, and it may eventually be used to predict future stand developments.

FORSKA_MOD model for forest succession describes the state of each stand (gap) by the population of trees belonging to it, species, diameter at breast height (DBH), leaf area, bole height and age. Based on these characteristics, the area of cross-section of tree's stems (basal area), stand biomass, productivity, mortality, density of every species on plot area are calculated in the model. Its applications on empirical data shows that gap-model FORSKA is better in describing biological aspects of development of forest phytocenosis (Nedorezov et al., 2001). It is reported that gap models have been classified as a special category of tree level modelling since they define and keep track of individual trees competing and growing in a restricted area (Porte and Bartelink, 2002). These models are more flexible than stand level even though they heavily rely on descriptive relationship. For instance, mechanistic models have been developed for simulation for forest growth based on species requirement and growing conditions. They draw heavily on tree allometry and combine functional relationships with tree based simulation approach. However, their major draw back has been the requirement of large amount of detailed eco-physiological data, thus lendering these models largely descriptive in nature for many causal relationships (Porte and

Bartelink, 2002; Zhang et al., 2009; Leskinen et al., 2009; Rammig and Fahse, 2009; Sprugel et al., 2009; Wamelink et al., 2009a and Yemshanov and Perera, 2002).

Porte and Bartelink (2002) review the classification of forest growth models as presented by different authors where the basis of this classification is on single tree distance dependent model, single tree distance independent model and whole stand distance independent model. Other authors have expanded their tree growth modelling from this classification and resulted to forest and tree models for even- edged and uneven-edged mono and mixed in distance dependent and distance independent classification. Other notable development s on this classification is on stand and individual based models for growth and yield in distance dependent and independent as well as gap models.

Overall, Porte and Bartelink (2002) found that these classifications were based on size of the organizational level, heterogeneity of the object, distance dependency, spatial explicitness, size of the regeneration units, use of class sizes and deterministic or stochastic. They, therefore, came up with a new classification based on smallest unit identified such as branch, and tree stand, spatial dependence and whether or not forest heterogeneity has been taken into account. These resulted to a new classification based on stand and tree models where stand models contained distance dependent and independent with later constituting average tree distribution models. For the tree models, the distance independent consisted on non-gap and gap models. In applying their classifications they argued that forest dynamics were mostly modelled using distribution, gap and distance dependent tree models. The latter appeared to be less suitable because of difficulties in modelling three-dimension stand structure over large periods and areas. Gap models could be applied to larger areas and time periods than distribution models, especially when they included detailed descriptions of the ecological functioning of the ecosystem.

Empirical models appear more accurate in their predictions than mechanistic models, but they highly depend on the data used for parameterisation, which makes them unsuitable for extrapolation to other systems or conditions. Although mechanistic models can be misused, adding mechanistic approaches to empirical observations is necessary to model growth and dynamics of complex forest systems. For instance, in distance independent tree models for non-gap class models, recruitment is generally modelled at the stand level where the number of recruits per species is represented as a function of stand variables like basal area, density, species proportion and site characterization whereas in gap models it's modelled as stochastic process triggered by light availability and other environmental conditions. The regeneration routine determines the species that will reproduce in a gap, the number of new individuals (saplings rather than seedlings as seedling establishment are difficult to simulate because light modeling approach used in gap models underestimates light levels at the forest floor) that will appear and their initial dimensions (Porte and Bartelink, 2002).

Similar approaches of forest recruitment and growth have been applied in agricultural systems. For instance, Stilma et al. (2009) uses mechanistic, logistic and light interception model in describing population growth dynamics of associated plants in crop canopy under the influence of shading. They were motivated in using simple mechanistic model following the fact that annual plants in a growing crop experience a rapidly changing light environment due to the development of crop leaf cover and canopy closure. As a result of increasing shading by the crop, the initial flush of germination and recruitment is followed by a phase of decline numbers. They therefore hypothesized that the effect of the crop on plants could be captured by the amount of light penetrating through the canopy; hence a function for light penetration over time was derived with asset of alternative population dynamic models describing the changes in the number of annual plants as the balance between a germination and a death process, both influenced by the amount of available light. Their findings showed that logistic functions provided good descriptions of light interception through time in different treatments. This corroborates well with Halofsky and Ripple (2008) who found out that as *Conifer* increased its encroachment, *Aspen* recruitment declined. In contrast, the number of *Aspen* originating within exclosures began to increase after the fences were constructed.

2.4. Models for Tree Survival and Mortality

Trees die when they cannot acquire or mobilize sufficient resources to heal injuries or otherwise sustain life (Waring, 1987). The interaction of factors influencing individual tree survival remains one of the least understood elements of forest growth and yield estimation. Of the thousands seedlings produced by typical mature tree a few survive to full maturity. A number of individual tree-survival models have been developed for various forest types and geographic regions. Many of these models predict survival as a function of tree size, and a combination of tree-and other stand-level variables such as tree vigor, site quality, basal area per acre, crown ratio and others.

Teck and Hilt (1990), on their study in Northeastern United States on individual tree probability of survival model using logistic regression approach, shows that survival rates predicted decrease with increasing competition of Basal area (BAL) for a given DBH and site Index. These modelers were motivated by the fact that models that predict the probability of survival of individual trees were an essential component of forest-growth prediction. Therefore, linking survival models with individual-tree DBH, height and growth allowed them to predict forest stand development over time. In their modelling they further found out that survival rates increased with increasing DBH for a given value of BAL, reach a maximum, and then begin to decrease as DBH continues to increase; the DBH at which survival peaks was species specific and it was dependent among various interactions. They also found that survival rates decreased with increasing site index (SI) for a given DBH and BAL. Equally, survival rates for a given DBH and SI approached a minimum as inter-tree competition (BAL) increased. With these findings, they, however, caution that users should be careful when applying this model for young stands unless data was available. Further, they caution that in case of high mortality, the model may tend to overpredict survival.

Lynch et al. (1999) uses a logistic regression model in predicting the survival models for shortleaf pine trees growing in uneven-aged stands in Southwestern Arkansas. They used ratio of quadratic mean stand DBH to individual tree DBH to predict the probability of individual tree survival in which they found that BAL was significantly related to individual tree survival. Karlsson and Norell (2005) also used logistic regression model in modelling survival probability of individual tree in Norway spruce stands under different thinning regimes. The explanatory variables in their study were DBH, quadratic mean DBH, thinning intensity, thinning quotient, basal area, number of stems per hectare, stand age, number of thinnings and site index. Their findings show that the diameter distribution and site characteristics providesufficient information in obtaining reasonable predictions about which individual trees would remain after thinning programme.

Woodall et al. (2005), uses survival and hazard functions in quantifying the probability distribution of tree mortality in a large scale forest inventory in Minnesota where individual tree size and growth increaments were used as the explanatory variables. Their findings concurred with Teck and Hilt (1990) and Lynch et al. (1999), who used logistic regression model in estimating the survival rate of trees. The evaluation of logistic regression model was done using the chi-square test described by Hamilton & Edwards (1976); Hosmer & Lemeshow (1989); Hosmer & Lemeshow (1980) and Neter & Kurter (1989). Similarly, Keane et al. (2001) estimates tree mortality using gap models and their application to climate change. In their study, they have identified three needs that are required to improve mortality simulations in gap models which include: process based empirical analyses needed to create more climate sensitive stochastic mortality functions, fundamental research required to quantify biophysical relationships between mortality and plant dynamics as well as extensive field data to quantify, parameterize and validate existing and future gap model mortality functions. They, however, recommend- the development of stochastic mortality functions that would be process based, like fire ignition probabilities could be simulated from climate based variables and research to be expanded to enhance understanding of the relationship between ecophysiological processes and plant mortality.

Stochastic models have been used in analyzing longitudinal data on aging and mortality (Anatoli et al., 2007). In gap-models, the probability of a tree's mortality increases if increment of DBH becomes below the critical value of 2.5 cm. Only 1-2% of such trees will survive during the 10 years. Trees with normal rate of growth have lower probability of mortality, the natural mortality of plants. At that, the value of probability is set so that only 1-2% of trees will achieve a maximal age (Nedorezov et al., 2001). However, it is desirable to model the annual survival rate function that can be defined between 0 and 1 (Buchman et al., 1983) since the probability lies within this range (Hamilton & David, 1986). The sigmoid shape of the logistic function lends itself to modelling survival besides other mathematical functions that have been used to model survival (Hett, 1971; Rennolls & Peace, 1986).

Keane et al. (2010) use- Fire Hazard and Risk Model (FIREHARM) to compute common measures of fire behaviour, fire danger, and fire effects over space in natural forest. In this model, tree mortality is calculated as the ratio of pre-burn live trees to post burn dead trees within burned sample plot in the three wildfire burn areas. In this case, tree mortality is simulated accurately when occurrence of canopy fire is predicted correctly. However, FIREHARM tends to underpredict tree mortality in areas that experiencelow intensity fires, particularly when all trees are predicted to survive. They also found out that while there was no significant correlation between model output and field observations of tree mortality, the statistics on 1% agreement indicated that some cases in the model were correctly predicted.

Other related models that have been successfully applied in other research sectors include a transition model for estimating academic survival of primary school pupil movement from one class to the next through cohort analysis (Odhiambo and Khoghali, 1986); a stochastic model for estimating academic survival in an education system (Odhiambo and Owino, 1985); stochastic model for analysis of longitudinal data on aging and mortality (Anotoli et al., 2007). In the latter model, they indicated that an organism's optimal (normal) physiological state changes with age, affecting the risk values of disease and death. The resistance to stress, as well as, adaptive capacity declines with age. In the past states of continuous time, Markov models for ecological communities (Spencer, 2008) showed how the time-reversal of Markov chain can be used to estimate the distribution of time series since the last occurrence of some state of interest at appoint, given the current state of the point. These models especially for growth and survival are gaining prominence in forestry research like in any other field of research as provided in the subsequent sections of this review.

2.5. Growth Performance of Commonly Grown Plantation Species

Wide studies have been carried out on growth performance, survival, disease resistance and biomass accumulation of Eucalypts across the world. Models have been developed to predict the growth and biomass increase of various eucalyptus species across sites for sustainable use. Much of the recent research has so far concentrated on genetic improvement and increase of productivity (Oeba, et al., 2009; Epila-Otara & Ndhokero, 2009; Msangi et al., 2009; Kirongo & Muchiri, 2009; Mutitu et al; 2007; Nyeko et al., 2007; Ginwal, 2009; Pukkala et al., 2009; Wamalwa et al., 2007). In particular, Ginwal (2009) found that the relationship of growth traits of provenances and family of *Eucalyptus tereticornis* with geographical location of the provenance particularly latitude, longitude and altitude was evident between latitude and height, latitude and growth at breast height, longitude and number of branches. This was associated with temperature variations, rainfall and changes in soils away from the equator. The study further shows a considerable amount of genetic variability indicating a good scope of genetic improvement in the material by selecting suitable seed trees of most promising provenances.

Recent reviews shows that the mean annual increament (MAI) of eucalypt stands used as a control in all the mixed species experiments found in the literature ranged from 3 to 17 $m^3ha^{-1}yr^{-1}$ (Laclau et al., 2008). Similarly, Brazil is reported to have highest productivity (75 m^3 $ha^{-1}yr^{-1}$) of eucalyptus species. In Kenya, the initial productivity of most widely grown species, *E. grandis* was between 20 and 30 $m^3ha^{-1}yr^{-1}$ but through breeding this has doubled to 70 $m^3ha^{-1}yr^{-1}$ (Wamalwa et al., 2007). Thus improving the understanding of inter-specific early competition is essential for predicting combinations of species and sites that would lead to increased stand productivity like the use of eucalypt seedlings that had been improved genetically (mean height of 18 m at age of 3 years, Wamalwa et al., 2007).

Studies on *C. lusitanica* shows that it's a fast growing tree species, it produces high quality timber and torelates a wide range of resulting environmental conditions. It performs best in areas with mild climates, and rainfall of between 1000 and 3000 mm yr^{-1}. However, it is susceptible to salt laden winds, and intolerant of exposure to light and also exhibits a preference for nutrient rich, deep, well aerelated soils with neutral pH. This has led to its wide planting both as an ornamental tree and for timber productionin many warm temperate and subtropical regions throughout the world. Productivity model developed for young densely stocked of *C. lusitanica* plots found volume mean annual increament was most strongly related to mean annual air temperature (Watt et al., 2009).

Similarly, Miyamoto et al. (2010) found out that among the three coexisting conifer species (white spruce [*Picea glauca*], lodgepole pine [*Pinus contorta* var. *latifolia*] and subalpine fir [*Abies lasiocarpa*]) studied show different patterns in growth responses to growing season temperatures across the sample sites in British Columbia and Yukon. Their findings suggest that white spruce growth was broadly influenced by summer temperatures with unique growth responses between warmer and cooler sites, where on cooler sites, higher growing season temperatures may increase spruce growth whereas on warmer sites, spruce growth may be affected negatively. The response of pine to increased growing season temperatures appeared to be more interconnected to moisture availability making pine growth response to warmer temperatures negative on drier sites and positive on the wetter sites. Hence such species-specific trends would likely translate to high spatial variability in future changes in interactions among coexisting tree species in a changing climate.

2.6. Above-ground and Below-ground Biomass Estimation and Carbon Sequestration in Forest Systems

Forests play a critical role in sequestering carbon or release carbondioxide into the atmosphere and therefore key to climate change mitigation through increasing amount of carbon in the forest systems. In this way carbon sequestration may become one of the major services that forests would provide. Under the Kyoto Protocol, which was adopted in 1997 and enforced on 16th February 2005, signatory countries were allowed to credit forest carbon sinks against greenhouse gas (GHG) emissions in order to fulfill their emissions reduction commitments (Sasaki and Kim, 2009; Pohjola and Valsta, 2007).

Minimal studies have been conducted that incorporates changes in land area and carbon stocks in all forest types. In this light, Sasaki and Kim (2009) conducted a study to estimate biomass carbon sinks using land and Richard's growth model in Japanese forests under then current management trends between 1966-2012 with a special emphasis on the first commitment period of Kyoto Protocol between 2008 and 2012. They found out that in natural forests, the carbon stock (above ground and root carbon) increased from 48.7 MgC ha^{-1} in 1966 to 76.0 MgC ha^{-1} in 2012 representing annual increase of approximately 0.6 MgC ha^{-1} as compared to carbon stock in plantation forests which increased about five fold within the same period from 24.3 MgC ha^{-1} in 1966 to 101.6 MgC ha^{-1} in 2012 representing average increase of 1.7 MgC ha^{-1} over the whole period and about 1.2 MgC ha^{-1} between 2008 and 2012. Similar studies on carbon stocks in Japanese forests have been studied (Fukuda et al., 2003; Fang et al., 2005) where Fang et al. (2005) found that above-ground carbon stocks in plantations and natural forests increased from 26.1 to 46.5 MgC ha^{-1} and 32.5 to 40.7, respectively between the periods 1957-1961 and 1991-1995.

However, this was in contrast with Miller et al. (2004) who found 84 MgC ha^{-1} and 78 MgC ha^{-1} of above-ground biomass for large trees during 1984 and 2000 surveys in Tapajos National forest, Brazil, respectively. This indicated that there was no accumulation of carbon in large trees during the specified period and concluded that there was no biometric evidence of rapid carbon accumulation by the forest and believed the net accumulation from 1984 to 2000 was close to zero. These findings were further inconsistent with Glenday (2008a) who found that levee forest plots had highest mean total carbon density (234 ± 27 MgC ha^{-1}) than carbon densities in clay evergreen forests (164 ± 13 MgC ha^{-1}) and transitional forests/woodland areas (156 ± 15 MgC ha^{-1}) in Tana River. These differences were primarily the result of significantly higher stem densities of large (DBH ≥ 50 cm) and very large (DBH ≥ 70 cm) trees, which explained 30% of the total variation in plots tree carbon across all forest types. In addition, Glenday (2006) found area weighted mean carbon density for indigenous forest was 330 ± 65 Mg C/ha greater than hardwood plantations (280 ± 77 MgC ha^{-1}) and significantly greater than that of softwood plantations (250 ± 78 Mg C/ha). These differences were attributed to the age where hardwood plantations were 70% younger with low carbon while indigenous forest was 89% older. This was further evidenced with young hardwood plantations that had greater mean density (240

± 71 MgC ha^{-1}) than young indigenous forest (170 ± 78 MgC ha^{-1}), although these were not significantly different.

Glenday (2008b) argues that to slow carbon stock loss from forest areas undergoing transition to woodland cover, ongoing clearance and tree felling observed could rapidly decrease carbon storage, unless sustainable harvesting and management were employed to balance wood removal with regeneration rates accompanied by tree planting activities to address fuel and wood needs of local communities. These findings were similar to those of Williams et al. (2008) who found stem carbon stock in woodlands to be 23% higher (19.0 ± 8.0 MgC ha^{-1}) compared to the oldest (> 20years) abandoned machambas (15.0 ± 3.9 MgC ha^{-1}) which significantly correlated with time. This implied that carbon stocks had significantly decreased when the woodland was cleared for agriculture and steadily gained over time when the land was abandoned for natural regeneration.

However, in soils, there was no clear trend of carbon stocks in the top 0.3 m along the abandoned machambas, which could be explained by disturbance of soils associated with cultivation that led to rapid decline in soil organic carbon content as a consequence of enhanced microbial respiration. Overall, other studies from Malawian Miombo woodland had observed carbon reductions of 40% after conversion to agriculture. Notably, the same development has been documented for European Union forests where carbon sequestration between 1990 and 2005 took place in relatively mature forest stands (8% by 2005) which existed already in 1990 as compared to most recent expansion of forest area that had a marginal effect on the carbon budget (Rautiainen, 2010).

Bamboo species constitute a larger proportion of forestry especially in China (3% of total forest area) and have been known to reach maximum biomass within very short periods. They compare favourably well with many different types of forests in its ability to store large amounts of carbon. For instance, studies carried out by Chen et al. (2009a) in China following national forestry inventory (NFI) showed annual increment of 4.73 m MgC yr^{-1} to 2.40 m MgC yr^{-1} between 1st and 2nd NFI; , 5.20 m MgC yr^{-1} to 10.39 m MgC yr^{-1} between 2nd and 3rd NFI; , 5.84 m MgC yr^{-1} to 4.35 m MgC yr^{-1} between 3rd and 4th NFI; , 6.08 m MgC yr^{-1} to 13.71 m MgC yr^{-1} between 4th and 5th NFI and 16.56 m MgC yr^{-1} to 20.14 m MgC yr^{-1} between 5th and 6th NFI.. Overall, their calculations show that carbon stocks in bamboo stands increased in the last five decades and contributed 10% of carbon stocks in living biomass of forests in China. These findings concurred with other studies on changing stock of biomass carbon in a boreal forest over 93 years where they found out that on average, the expanding biomass stock sequestered 18 t C/year/km^2 (Kauppi et al., 2010).

Weishampel et al. (2009) quantified the major C pools and above-ground net primary production of a complex forest and peatland mosaic in northern Minnesota, USA. They sectioned cores into 0-10, 10-20, 20-40 cm depth increments. Their findings showed that total C pool did not vary significantly among upland areas dominated by aspen (160 ± 13 MgC ha^{-1}), mixed hardwoods (153 ± 19 MgC ha^{-1}) and conifers (197 ± 23 MgC ha^{-1}) and soils including forest floor accounted for another 35-40%, with remaining carbon stored as detrital wood. Compared to upland areas, total C stored in peatlands was much greater 1286 ± 125 MgC ha^{-1}. Of this total C90-99% was found in peat soils between 1 to 5 m in depth.

Navar (2009) who observed from forest inventory coupled with generalized biomass prediction equations for conifers and broadleaf tress predicted a mean of 130 Mg ha^{-1} in trees biomass for all 637 sampled plots inventoried in temperate forests of south central Durango. Of this, 62, 29 and 9% belonged to boles, branches and foliage and coarse roots, respectively. Tree biomass of conifers explained 62% as compared to broadleaf trees (38%) of the total biomass in temperate forest. This gave a mean carbon stock of 65 MgC ha^{-1}in standing trees, including coarse roots. Similar results on estimation of below-ground carbon sequestration following model simulation were reported by Woodall et al. (2008) where down and dead woody materials C stocks ranged from 2.55 MgC yr^{-1} in the northern Rocky Mountains to 15.5 in the sub-region Pacific Northwest, West of the Cascades. Kohl et al. (2008) also found that in the same test area, 8.9 MgC ha^{-1}were transferred from living trees to dead woody material by mortality (1.93 MgC ha^{-1}) and harvest residues (6.95 MgC ha^{-1}) over the observation period of 10 years.

Sierra et al. (2007) used a Monte Carlo analysis to calculate the uncertainty around mean estimate of total carbon stock in primary and secondary forests for both above and below-ground biomass. The results showed that the primary forests had significantly higher total carbon (383.7 ± 55.5 MgC ha^{-1}) as compared to secondary ones (228.2 ± 13.1 MgC ha^{-1}). Of this amount, soil organic carbon at 4 m depth represented 59 and 84% for primary and secondary forests, respectively. Estimated soil organic carbon up to 30 cm represented 42% and 37% up to 4 m in primary and secondary forests. Deforestation of 1 ha of the primary forests in the Porce region would cause the emission of about 155.8 ± 19.0 MgC $ha^{-1}$to the atmosphere and the estimated the amount of carbon emitted at the time of forest to pasture or agriculture was between 174.0 and 283.2 billion MgC. Further, methodologies have been enhanced on carbon estimation using remote sensing and ecosystem modelling techniques for a more complete and efficient simulation of forest ecosystem processes (Maselli et al., 2009).

2.7. Models for Estimation of Above-ground and Below-ground Carbon Sequestration in Forest Plantations

The growing of trees within agricultural landscapes in large scale has proved to be commercially viable including environmental credits, such as carbon credits and contributes greatly to environmental conservation when appropriately and sustainably managed. Studies have been carried out to estimate amount of carbon sequestered by different trees above-ground and below-ground in plantation forests. Paul et al. (2008), calibrated full carbon accounting model (FullCAM) for *Eucalyptus cladocalyx* and *Corymbia maculata* plantations and found that for both species, regardless of annual rainfall, throughout the rotation (stand average of 50 cm DBH), 37-50% of carbon sequestered in the total tree biomass was in stem, 18-27% in both branches and roots and the remainder in foliage or bark. However, the rate of accumulation of carbon was dependent on annual rainfall, with the average rate of sequestration of carbon in tree biomass and litter during the first rotation of *Eucalyptus cladocalyx* or *Corymbia maculata* increased from 3.68 to 4.72 MgC $ha^{-1}yr^{-1}$ as annual rainfall increased from 500 to 750 mm.

Paul et al. (2002) reviews studies on changes in soil carbon following afforestation and found that soil C increased or decreased particularly in young (< 10 years) forest stands due to variations in litter fall and decomposition of organic matter. On average, soil C in the <10 cm or <30 cm soil layers generally decreased by 3.46% per year relative to initial soil C content during the first five years of afforestation, followed by a decrease in the rate of decline and eventually recovery to C content found in agricultural soils at about age of 30 years. In plantations older than 30 years, C content was similar to that under the previous agricultural systems within the surface of 10 cm of soil. This was similar to Versterdal et al. (2002) and Dowell et al. (2009) who found that carbon concentration and storage increased in the upper 5 cm of the mineral soil but decreased in the 5-15 cm and 15-25 cm soil layers with increasing age following afforestation of former arable land and biomass production in short rotations.

Other important factors that affected changes in soil C were land use, whereafter afforestation, soil C tended to decrease on ex-pasture sites and increased on ex-cropping sites (Paul et al., 2002)). These findings were similar to those of Eaton and Lawrence (2009) who found that soil organic C in the top 1 m of soil was very high (155-394 MgC ha^{-1}) and tended to be higher on young forest stands, lower in middle aged and high again in older forests under different cycles of shifting cultivation. However, the number of cultivation fallow-cycles did not significantly affect soil organic carbon stocks.

The second factor was climate, where, it was observed that soil C accumulation increased with increasing mean annual precipitation, and soils with high moisture availability, rates of decomposition were directly related to the annual temperature and the converse was true. This again concurred well with Eaton and Lawrence (2009) who found that soil organic carbon was significantly lower in El Refugio, site which had least precipitation as compared to Arroyo Negro with most precipitation. The third factor was forest type established, where, the results showed that in surface soil (<10 cm or <30 cm), amounts of C increased under hardwoods (polar, mahogany, etc) and soft-woods (mixed pines, spruce, etc) yet changed little under eucalypts and decreased under *Pinus radiata*. However, in deeper soil layers (> 10 cm), C increased under eucalypts and other hardwoods and decreased under radiata pine and other soft-woods.

Lemma et al. (2007), using CO_2Fix model to determine factors controlling soil organic carbon (SOC) sequestration under exotic forest plantations (*Cupressus lusitanica*, *Eucalyptus grandis* and *Pinus patula*), found that SOC significantly varied between the species at age of 20 years. SOC sequestered was 32.7, 26.3 and 18.1 Mg C ha^{-1} under *Cupressus lusitanica, Pinus patula and Eucalyptus grandis*, respectively. These differences were as a result of different proportion of litter input and decomposition rate, since the trees were grown under the same edaphic and climatic conditions and management regime. Simulation using CENTURY and YASSO models on short and long term responses of SOC to harvesting in a northern hardwood forest indicated that SOC pools increased immediately after a harvest event and then decreased before beginning to accumulate where changes in dead wood and SOC pools were driven by changes in litter inputs, the rate of decomposition, management regimes, stand age, root activity, initial SOC, stand growth rates, site's biological carrying capacity, product utilization, among others (Johnson et al., 2010; Liski et al., 2005, Liski et al., 2002; Schulp et al., 2008; Stevens and Wesemael, 2008; Amichev et al., 2008).

Amichev et al. (2008) found that the average highest amount of ecosystem C on mined land was sequestered by pine stands (148 MgC ha^{-1}) followed by hardwoods (130 MgC ha^{-1}) and mixed stands (118 MgC ha^{-1}). Non-mined hardwood stands sequestered 62% higher than the average of all mined stands. Their mined land response surface models of carbon sequestration as a function of site quality and age explained 59, 39 and 36% of the variation ecosystem C in mixed, pine and hardwood, respectively. Pine and mixed stands, ecosystem C increased exponentially with increase of site quality, but decreased with age whereas in mined stands, ecosystem C increased asymptotically with age and was not affected with site quality. However, Jiang et al. (2002) in their simulation study found that at any specific site, the carbon stocks underwent large variations associated with each disturbance event like fire and harvest scenarios. The largest amount was found for intermediate rotation lengths with smaller changes in the short rotations. Essentially, lower carbon stocks were found with shorter rotations and relatively higher stocks in longer rotations.

Results from the ecosystem simulation model, FORECAST showed that carbon stored in soil represented a large, relatively stable pool and showed only minor long-term responses to harvesting activities. Tree biomass and litter pools, in contrast, fluctuated widely in concert with harvest cycle (clearcutting vs partial overstory retention, no harvest, single tree selection cutting, and 43 cm diameter limit cutting), however, total ecosystem carbon increased with rotation length regardless of the species and this was attributed largely to the changes in the live biomass pool (Seely et al., 2002; Alberti et al., 2008; Swanson, 2009; Davis et al., 2009).

The simulation carbon budget model of the Canadian forest sector for estimation of carbon stocks above-ground, forest floor and soil carbon for softwood and hardwood species resulted to nearly similar findings. Softwood constituted 75% of the total biomass for the inventory estimate and 80% of the total model estimate (Banfield et al., 2002). However, the study on the changes in forest biomass carbon storage in South Carolina Piedmont between 1936 and 2005, using allometric biomass regression equations and biomass expansion factors, showed that Piedmont forest had accumulated 81.84 billion MgC ha^{-1} due to forest expansion and re-growth, increasing from 57.36 billion MgC ha^{-1} in 1936 to 139.20 biilion MgC ha^{-1} in 2005, indicating forest carbon accumulation at a rate of 1.19 billion MgC ha^{-1}yr-1. Hardwood and softwood forest accounted for 74% and 26% of carbon accumulation during this period, respectively, with above-ground accounting for about 80% of total carbon pool (Hu and Wang, 2008).

Further, simulations using CO_2FIX and carbon accounting model on estimation of net carbon of open woodland and peatland afforestation, indicated that planted trees increasing C sink from the date of planting and about 87.0 MgC ha^{-1}would be sequestered after 70 years, which was pre-dominantly (46%) found within the stems. Soil carbon was the second largest C stock, with 26% of the total C followed by roots, with 14%, and the branches and foliage with 7% each (Gaboury et al., 2009; Hargreaves et al., 2003).

Studies have shown species substitution and short-rotation woody crop species plantations grow faster and are likely to sequester more carbon over short period of time frame. However, hardwood species have other desirable characteristics, which make them to store carbon for long period of time and enhance diversity (Jacobs, et al., 2009; Vallet et al., 2009; Stoffberg et al., 2010; Nabuurs et al., 2008). Similar results have been reported on agricultural practices with considerable differences in carbon sequestration between crop rotations and soil type or soil texture. Cumulic Anthrosols were found to sequester highest amount of carbon with Gleysols producing least due to high microbial activities in cumuli anthrosols (Gaiser et al., 2009; Billen et al., 2009). Elsewhere, carbon sequestration potential of major plantation species (*Pinus armandi, Pinus yunnanensis, Pinus kesiya var. langbianensis, Platycladus orientalis, Cunninghamia laceolata, Eucalyptus spp*) and others accounted for an increase of carbon stock from 12.474 billion MgC ha^{-1} in 2010 to 56.621billion MgC ha^{-1} in 2050 (Chen et al., 2009b). Similarly, in Swaziland, plantation forests which mainly constituted eucalyptus, pine and wattle trees were reported to have a higher carbon storage capacity than indigenous species and grasslands (Hassan and Ngwenya, 2006).

Forest management practices like harvests cycles, thinning, pruning, fertilizer application, control of pests and diseases, burn and slash, among others, affect carbon sequestration and greenhouse gas emissions (Waterworth and Richards, 2008). Increased biotic disturbances under climate change reduced C storage in the actively managed strategies (up to –41.0 t C ha^{-1}) over 100 year simulation period, whereas in the unmanaged control variant some scenarios even resulted in increased C sequestration due to a stand density effect (Seidl et al., 2008). Moderately thinned stands (560 trees ha^{-1}) of *Eucalyptus camaldulensis* produced highest above-ground carbon stock and storage at a rate of 4.2 MgC ha^{-1} yr^{-1} as compared to unthinned one whose carbon storage was about 1.6 MgC ha^{-1} yr^{-1} after 42 years (Horner et al., 2010). However, in Norway spruce, there was a significant decrease in above-ground tree including stump root system C storage of 27% and 22% due to thinning when the density was reduced to 820 and 1100 trees per ha, respectively, compared to the density of 2070 (Nilsen and Strand, 2008). Forests switch between being a source or a sink of carbon, depending on the succession stage, specific disturbance or management regime and activities (Masera et al., 2003).

2.8. Contribution of Nitrogen to Carbon Sequestration in Forestry Systems

Deposition of N on forests may increase C sequestration by increased growth and increased accumulation of soil organic matter (SOM) through increased litter production and /or increased recalcitrance of N-enriched litter, leading to reduced long-term decomposition rates of organic matter. SOM relates to nutrient cycling and carbon storage affecting soil physical and hydrological characteristics and forms substrate of soil biota. Relationship has been established between soil organic carbon (SOC) and labile forms of C and N and available P in the fine soil and long-term impact of fire and soil disturbance (Hopmans et al., 2005; Wamelink et al., 2009; Pelster et al., 2009). Some regression results for Scots pine and Norway spruce indicated relative change in stem volume growth per unit change was also an influencing factor. For example, a value of 0.01 and 0.02 for N deposition implied an increase of stem growth of 1.0% per kg N deposition of N ha^{-1} yr^{-1} for Scots pine and 2% for Norway spruce (de Varies et al., 2009; Wamelink et al., 2009).

Studies such as Vesterdal et al., 2008; Mol Dijkstra et al., 2009 have equally shown significant differences in forest surface soil C and N contents and C/N ratios among deciduous tree species with an increased trend of C and N down the soil profile. This was primarily attributed to large differences in turnover rates of foliar litterfall among others factors. However, it has been noted that stumps decompose slower than roots, branches and needles, but they constitute large proportion of C and N. For instance in Scots pine, Norway spruce and silver berch stumps, which had decomposed for 0, 5, 10, 20, 30 and 40 years after clear cutting in southern Finland, showed after 40 years of decomposition, the amount of N was 1.7 and 2.7 times higher than the initial amount in pine and spruce stumps, respectively. N was released from birch stumps but only after they had decomposed for 20 or more years. Their model predicted that birch, spruce and pine stumps began to release N when about 70, 80 and 95% of C was lost, respectively (Palviainen et al., 2010).

Knoepp and Clinton (2009) show that dissolved organic C and N did not respond to forest harvesting in either soil solution or stream samples. However, total C and N responses to forest harvest have been shown to vary considerably among studies (Knoepp and Swank, 1997; Johnson et al., 2002; Elliot and Knoepp, 2005; Hopmans and Elms, 2009). Johnson et al. (2002) examined the long-term impacts of whole –tree, complete tree, and sawlog harvest on total soil carbon content in sites across the southeastern US. They found initial soil carbon responses to harvest only on sites of intensive sampling schemes following harvest while other sites showed no response. All sites showed long-term changes in total C although they were not attributed to harvest treatment. Knoepp and Swank (1997) attributed rapid increase of total soil C and N content on the surface soil following clear-cut harvest in the southern Appalachians to root mortality and rapid decomposition of logging residue like leaves and small branches.

Elliot and Knoepp (2005) examined three different harvesting methods in similar forests (2-age regeneration, shelterwood and group selection) and found that there was no response in total soil C or N following harvest. However, Hopmans and Elms (2009) found levels of C and N declined during the second rotation of Pinus radiata and ratios of C/N in the surface soil increased from 27 to 30 in lower quality sites and from 24 to 26 in higher quality sites. Further, some studies on carbon sequestration by a jack pine stand in northeastern Ontario, Canada, following urea application showed that within the first five years of urea (N) application, there was a significant increase in C after which there was no further increase. Net C on fertilized plots were consistently lower than control plots for all treatments (Foster and Morrison, 2002).

2.9. Economic Analysis of Carbon Sequestered under different Scenarios of Tree Growing

The introduction of carbon budgets as an incentive in forest farming has led to the increase in the amount of carbon sequestered in the mitigation of climate change. This has become one of the major services among other environmental payment services (PES) that forests provide. Forest managers are thus faced with the task of optimizing the joint production of timber and carbon sequestration, and possibly other non-timber benefits. In this case, forest owners might find it profitable to give up some timber returns in exchange of CO_2 returns or modify forest management regulations in order to increase carbon sequestration (Liu et al., 2002; Pohjola and Valsta, 2007; Gene, 2007; Chladna, 2007; Bigsby, 2009). Pohjola and Valsta (2007) detennined by the optimal combination of thinnings and final harvest age for joint production of timber and carbon sequestration, when carbon uptake was subsidized and carbon release was taxed found different quantities of carbon and growth from Scots pine and Norway spruce. Thus changes in optimal silviculture for Scots pine increased carbon storage by 42 t CO_2/ha with carbon price of EURO 10/t of CO_2 and by 81 t CO_2/ha with carbon price of EURO 20/t of CO_2. In addition, carbon tax/subsidy programme was found to increase income to forest owners considerably.

Chladna (2007) developed real option model given certainties in the future wood and CO_2 price behaviour and found that optimal rotationperiods varied considerably with the type of price process, the way carbon income was defined and the selection of discount rates. Im et al. (2007), Lippke and Perez-Garcia (2008) examined potential impacts of carbon taxes on carbon flux and found simulated carbon tax led to reduced harvests and increased carbon stock in standing trees and understory biomass. Bigsby (2009) reviews the possibility of carbon banking by treating sequestered carbon in the same way the financial institutions treats capital. This provides opportunities for small forest owners with different types, age classes and management strategies to participate in carbon markets because payments would be based on the current carbon sequestered. Glenday (2006) showed a predicted carbon storage under suggested forest zonation scenario of which 0.5 Tg C or more would be increased. This translated to about $ 2.5 million at speculated carbon prices ($ 3-5/t C, under $ 18/t CO_2) over the course of the forest regeneration or plantation growth. If the said carbon was to be sequestered over a period of 50 years, credit sales could yield over $ 50,000/year.

Tree growing has enormous economic returns besides rehabilitating degraded areas and mitigation of climate change (Hoch et al., 2009). A study conducted by Rodriguez et al. (2009a) on changing contribution of forests to livelihoods found out that forest based income was at its highest accounting on average of 76% of household income. In addition, economic analysis of *Paraserianthes falcataria* in a mixed plantation other than in pure planting showed high profitability to community growers in East Java, Indonesia, even though their decisions to practise mixed plantations were influenced by amount of land owned, cost of mixed plantations, timber price and period of gaining income of harvesting that was difficult to cover monthly costs (Siregar et al., 2007).

Other studies such as Nath and Inoue, 2009; Medina et al., 2009 have shown that in forest-based settlement project and its impacts on community livelihood, participants, after receiving training and other skills on forest management, were able to sell their trees in markets which in turn provided income to meet family expenses. They revealed a significant difference in mean annual agro-forestry income and mean annual family income between villages of which the former was almost three times higher in the successful villages as compared to unsuccessful one.

Hill (2004) used a spreadsheet model to show the benefits and costs of various planting configurations and methods over a 30-year time span. The model assessed the monetary net costs /benefits of reducing recharge of a vegetation management proposal. The study indicated that under the assumption of electric fencing, block and alley planting were economically viable from the community's perspective, in that the quantified benefits exceed the quantified costs. Combination of carbon sequestration benefits and electric fencing resulted in improved cost /benefit ratios with alley planting also been economically viable providing carbon sequestration benefits of $2 and $10 per tone, respectively. All planting configurations were economically viable with a return of $60 per tonne for carbon sequestration. On the one hand, Sensitivity analysis indicated that the quantified annualised community benefits (i.e. excluding all private benefits) of tree planting were $112 per hectare while on the other hand ,costs exceeded benefits to the landholders in all but two cases by more than this amount.

2.10. Factors Influencing Establishment of Farm Forestry and Tree Retention

Farm forestry proves to be an important enterprise for small and large-scale farmers in low, medium and high potential areas across the world. For instance, in Ireland, the dramatic increase in farmer planting during the last 15 years reflected the economic realities of farming marginal land and uptake of attractive afforestation grants and annual premiums. To date, the focus has been on forest establishment, which has been driven to large extent by grant aid and ensures that high quality standards are achieved in new farm forests. These includes species selection, establishment practices and management to ensure high quality final tree crop. For example, to remain with most valuable trees for clear felling, trees were thinned at an appropriate age and size, normally on regular cycle which varied considerably from tree crop to tree crop, like *Sitka spruce* whose life cycle varies from 34-40 years and as compared to over 140 years for *Oak* and *Beech* (Teagasc Agriculture and Food Development Authority [TAFDA], 2007).

TAFDA (2007) points out that there has been great emphasis on environmental quality that meets national and international standards over the years and has led to new opportunities for expanding the role and use of forests for both the timber and non-timber products. Thus, farmers needed to develop additional skills and new supports and infrastructures must be put in place so that the returns to the farmer, community and country from the investment made in farm forests are optimised. Hence the future focus would be in the creation and maintenance of commercially viable forests delivering real environmental and social benefits and providing renewable energy solutions.

The decision to plant trees can be difficult for farmers as some do it as change in their lifestyle especially the older ones whereas others (younger ones) do it as part of career change by combining an off-farm job or business enterprise with farming to meet the family demand for increased income. This increases pressure on farmers who still have farms to manage making workloads to become invariably too much to handle hence singling out forestry which is not labour intensive and can free more time for work off the farm and for the family. Therefore, understanding the characteristics and behaviour of landowners who may be interested in the various agroforestry practices, extension programmes and policies could be better targeted to facilitate adoption (TAFDA, 2007; Valdivia and Poulos, 2009).

Studies like Valdivia and Poulos, 2009; Konyar and Osburn, 1990; Pattanayak et al., 2003; Moser et al., 2009 have further shown a set of factors that influence tree growing. These include but not limited to:farmer's age, farm size, land value, erosion rate, tenure system, expected net returns/resource endowment, site description/biophysical factors (hilly and rocky for row crops), recreation, aesthetic, ecosystem services, heritage value, bequest value of future generation, market incentives, risk and uncertainties, education level, farming experience, participation in organizations, conservation practices, contact with change agent, farmer's perceptions and others. These factors have been argued in different ways. According to Moser et al. (2009), farmers who invested in timber stand improvement could improve the value of a stand and subsequent income from harvesting. This could further suggest that forestland owners who derived significant income from their trees and view their forests as sources of income to be tapped periodically for income would engage in practices that would maintain or enhance income generating opportunities. Conversely, forestland owners who do not view their trees as a source of substantial income would have less incentive to invest in forestland.

In the same vein, land-owners who claimed to be interested in aesthetics or enjoying woods generally had higher volumes per hectare than those who owned woods as part of their farm. Forest-land-owners who salvage-harvested their forest-land a harvesting reason that was more reactive than proactive-exhibited lower volumes per hectare than those who harvested for more proactive product based reasons. Farmers with income generating harvest reasons had higher volumes per hectare than those who harvested for salvage purposes. For example, those farmers who were interested for posts harvested their trees at particular size and left smaller or large ones for other uses if any. Secure land tenure was found to be significantly associated with tree planting or agroforestry practices as renters were found to be less likely to adopt medium or long term conservation practices. (Moser et al., 2009; Arbuckle Jr et al., 2009).

Valdivia and Poulos (2009) in their study, on the one hand found that older farmers were less likely to be interested in riparian or stream bank plantings as compared to farmers who were more likely to be interested due to serious bank erosion problems. Similarly, habitus (future generations) was an important factor in considering tree planting. This was further evidenced by findings from the younger households who contemplated forest farming as an income generating activity. Hence mostly part-time farmers and non-traditional farmers would be interested in forest farming, as it was consistent with their rural life style.

On the other hand, the two authors found out while experimenting with field conservation agencies especially Conservation Reserve Programmethat the diversification on how many economic activities a landowner was pursuing had no effect on tree planting. While this was not expected in their study, they found that attitude matter was very critical, as even monetary motivations did not appear a driving factor in influencing tree farming as their data captured landowners who planted trees in the last 10 years. This was found to be consistent with other findings on the willingness to pay regardless of the existence of government support programmes (Workman et al., 2003).

TAFDA (2007) ina survey carried out in 2006 noted that in some cases there has been drop in tree planting among the land-owners. When farmers were asked to rank the biggest barrier to planting forests in their land, permanent nature of forestry, lack of knowledge and tradition of forestry, needed all land for agriculture, dislike forestry, among others were found to be the most highly ranked barriers in tree growing. This was further implied in Hoch et al. (2009) who found that donor funded programmes on tree planting widely ignored local capacities and knowledge. This reduced the uptake of tree growing, yet studies have shown that local knowledge significantly influences tree growing initiatives.

2.11. Summary of Literature Review and Knowledge Gaps

Generation of models has been found to be a useful exercise as it creates study of cause and effect relationships and could lead to insights regarding true mechanisms or drivers of forest cover change. This would in turn lead to better investment decisions by national governments seeking to manage their forests. The results of existing models are probably reasonable at the global level. However, the greatest weakness of the modelling approach continues to be the inadequacy of existing models when applied to specific countries. The process of deforestation is such a complex process, involving physical, climatic, political, and socio-economic forces, which are themselves very complex, that simple generalised models of forest change have so far not been developed.

Current models are oversimplified and yield similar predictions of forest cover change rates for countries, which are known to be very different. More complex models are yet to be developed and tested. Therefore, the reviewed studies show that no statistical modelling techniques have been applied on assessing recruitment, survival and growth of the selected plantation species in Kenya and most of other areas in Africa and other developing countries. Further, no studies have been conducted on carbon quantification of the most commonly grown plantation tree species in Kenya and their implication on carbon accounting system and payment of environmental services. Limited modelling techniques have been developed and applied on lifetime value of the farmer willing to retain trees on farm for improving cover and carbon sinks. Therefore, this study seeks to carry out statistical modelling of the determinants of forest cover and carbon sequestration in the country. This will contribute to the knowedge gap on suitable methodologies for estimating tree cover and carbon quantification.

CHAPTER THREE: MATERIALS AND METHODS

3.1. Introduction

This chapter describes the methodology of this study. It is divided into three distinct sections, namely; the description of study sites, the study design and data analysis. Each of these sections is further divided into different sub-sections explaining the approaches used. In the description of study sites, unique and different features are described in reference to the objectives ofthe study. The study design entails sampling techniques used, data sources and measurements. Lastly, Data analysis provides methods used in the analysis by first detailing the theoretical information and principles behind specific model application.

3.2. Description of Study Sites

This study was carried out in Kiambu and Nyeri Counties in the Central highlands forest zones. On the one hand, Kiambu County is comprised of Kikuyu, Thogoto, Muguga, Lari, Kinale, Uplands and Kerita forest stations. Of these, Muguga, Uplands and Kinale forest stations were used for collecting data on most commonly grown plantation species in Kiambu forest zone. In addition, Kiambu County comprises of Kikuyu, Kiambu East, Lari and Kiambu West districts of which, Kikuyu and Lari were used for collecting household and farm data. On the other hand, Nyeri County comprises of Kabage, Kiandogoro, Zaina, and Kabaru, Gathiuru, Hombe, Ragati, Naromoru, Chehe, Nanyuki forest stations in Aberdare range and Mt. Kenya respectively. Of these forest stations, Kabage, Kabaru and Naromoru were used for data collection of the commonly grown plantation species. Nyeri County also comprises of Nyeri South and Nyeri North districts, which were used for collecting household and farm data.

3.1.1. Kiambu County

In terms of size, Kiambu County covers an area of 1,323.9 Km^2 and is the smallest County in Central Kenya.Geographically, it borders Nairobi City and Kajiado County to the south, Nakuru County to the west, Nyandarua County to the northwest and Thika to the east. The County lies between latitudes 0°75′ and 1° 20′ south of Equator and longitudes 36° 54′ and 36° 85′ east. Its agro-ecological zone (AEZs) extend in a typical pattern along the eastern slopes of the Nyandarua (Aberdare) Range parallel to the isohypses. It has great potential for tea growing in Githunguri and Limuru, coffee, dairy farming and pyrethrum, among others. Vegetable is also grown above the limit (2300 m.a.s.l) due to small land size holdings and their proximity to Nairobi markets (Figure 3.1).

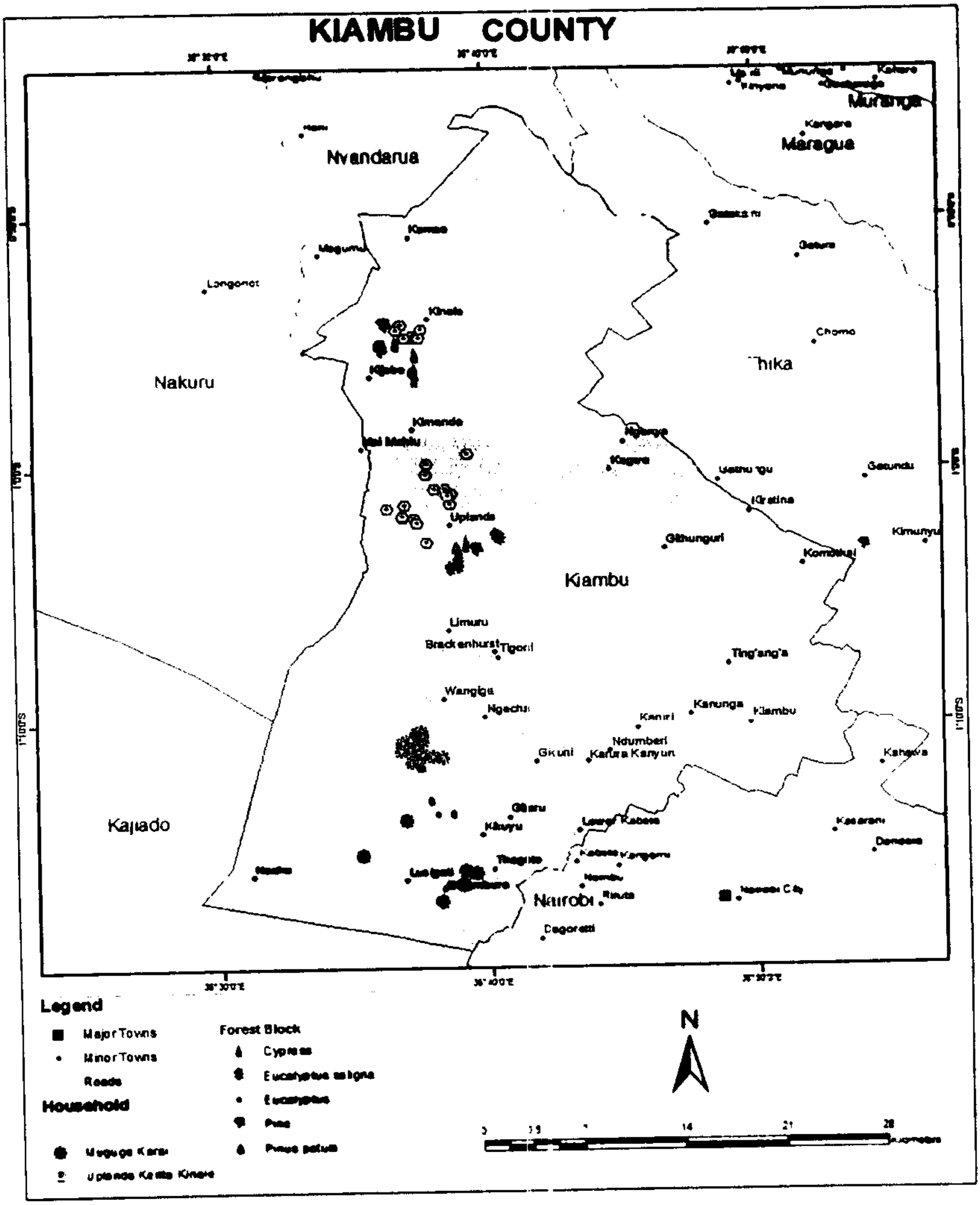

Figure. 3.1. Locations of the study sites in Kiambu County

In terms of population, it is the most densely populated area with a density of 562 persons per km^2 compared to 280 persons per km^2 in 1979, resulting in population growth rate of 8.4%. The 2009 national census based on the four districts within Kiambu County continued to show high growth of population. Kiambu East had a population density of 1,342 persons per km^2 as compared to 1,126 in Kikuyu district. Lari and Kiambu West districts had 282 and 466 persons per km^2 respectively (Kenya National Bureau of Statistics [KNBS], 2010; Jaetzold et al., 2006; Republic of Kenya, 2005a).

Lari district comprises of Uplands, Kerita, Kinale and Ragia forest stations. It lies on the upper highland AEZ one (UH 1) classified as sheep and dairy zone or vegetable zone with permanent cropping possibilities, with a long to very long cropping season followed by medium one. Kinale and Kerita are at 2591 m a.s.l receiving mean annual rainfall of 1150 to 1276 mm whereas that of Uplands is 2415 m a.s.l and 1210-1414 mm of annual rainfall. Kikuyu district which comprises of Muguga forest station lies on the lower highland AEZ two (LH 2) grouped as wheat/maize-pyrethrum zone with a medium to short and a (weak) short cropping season. It shows a good yield potential of wheat, linseed, sunflower, pyrethrum and good forage (0.6-1.0 ha) of secondary pasture of Kikuyu grass, high stocking capacity with Napier grass up to 2000 m a.s.l, fodder beets, among others. It is at 2067 m a.s.l receiving mean annual rainfall of 1000 mm. It extends to the drier area of Karai and Kikuyu escarpments. Overall, due to the combination of good soils, climate and proximity to Nairobi, the country's main market, this makes Kiambu County the most economic farming region in the country (KNBS, 2010; Jaetzold et al., 2006).

3.2.2. Nyeri County

This is one of the five Counties of Central Highland Conservancy and forms part of Kenya's eastern highlands. It is the most expansive covering an area of 3,266 km^2 and is situated between Longitudes 36° and 38° east and between the equator and Latitude 0° 38′ south. The County borders Laikipia County to the north, Kirinyaga County to the east, Muranga County to the south, Nyandarua County to the west and Meru County to the northeast (Figure 3.2).

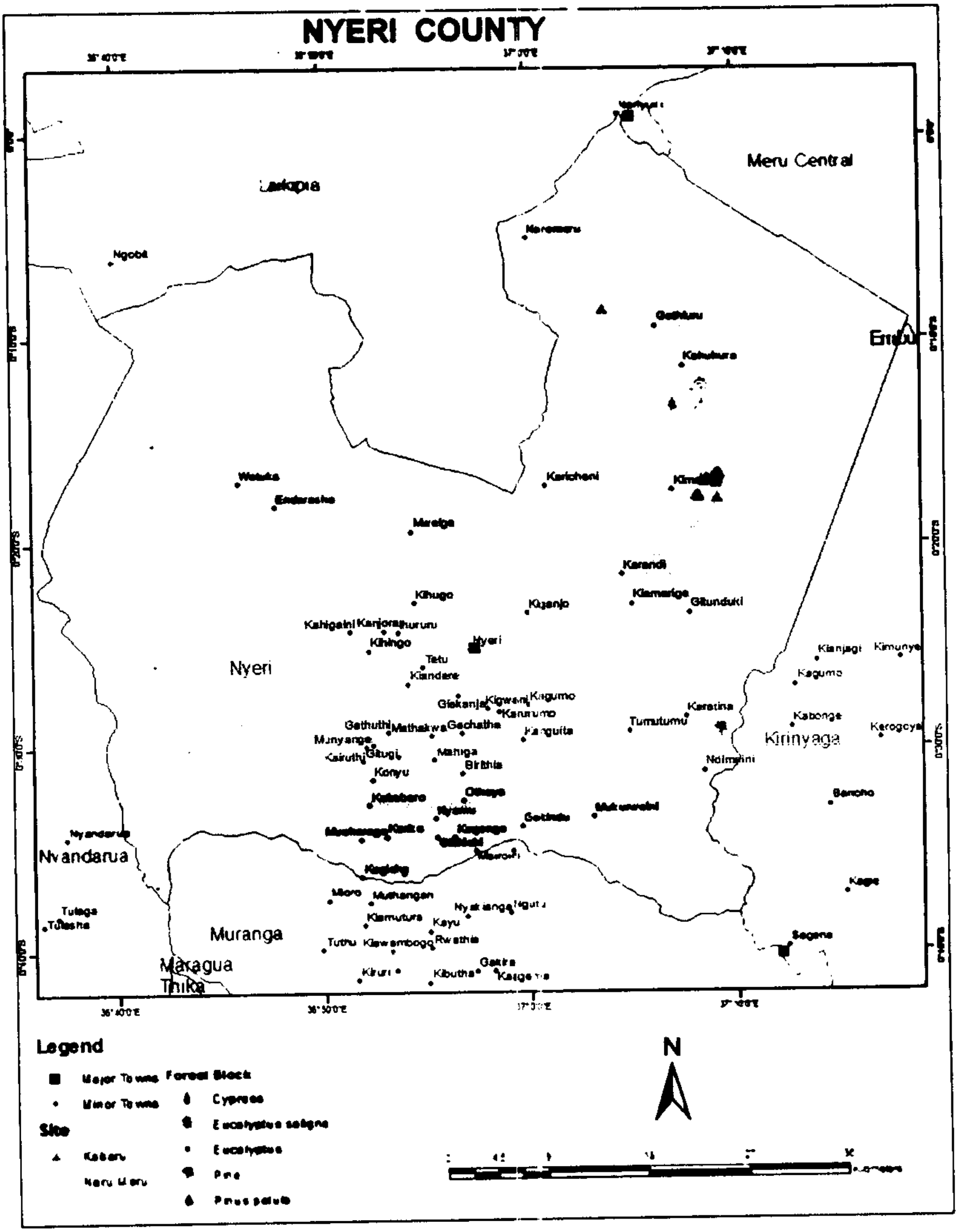

Figure 3.2. Location of study sites in Nyeri County

Its population increased from 148 in 1979 to 197 persons per km^2 according to the year 1999 national census. In 2009 national census, its population was presented under Nyeri North and Nyeri South whose densities were 142 and 351 persons per km^2, respectively (Kenya National Bureau of Statistics [KNBS], 2010; Republic of Kenya, 2005b). The main physical features of Nyeri County are Mt. Kenya (5199 m. a.s.l.) to the east and the Aberdare range (3999 m. a.s.l.) to the west. These mountains are of volcanic origin.They determine relief, climate and soils, and consequently, the agricultural potential of the district (Republic of Kenya, 2005b). The average annual rainfall ranges from 2200 mm on the most easterly exposed edge of the Aberdare range to 700 mm on the Laikipia Plateau. The economic livelihood of people in this County is dependent on agriculture as over 67% of the total area is arable land with main agro-ecological zones (AEZ) UM 2 (main coffee zone 2), LH 4 (Cattle-sheep-Barley Zone) and LH 5 (Ranching zone). In all divisions (Kieni West, Kieni East, Mathira, Mukurweini, Municipality, Tetu and Othaya) except Kieni W. and Kieni E., which are generally semi-arid, available agricultural land is less than 0.88 ha (Jaetzold et al., 2006).

Nyeri South district and Kabage forest station are on easterly exposed edge of the Aberdare Range on the upper highland agro-ecological zone one (UH 1). This zone is mainly for sheep-dairy farming and various vegetations (Tea bushes inclusive of Nyayo Tea Zones, agroforestry etc). It is at 2286 m a.s.l, receiving mean annual rainfall of 1424 mm. On the other hand, Kabaru forest station in Nyeri North district lies on the moist windward side of Mt. Kenya on the lower highland agro-ecological zone two (LH 2). It is at 2271 m a.s.l, receiving mean annual rainfall of 1004 mm. Naromoru forest station in Nyeri North district is on the drier western leeward side of Mt. Kenya on the lower highland agro-ecological zone three (LH 3). This zone is mainly for wheat/maize-barley with a weak (fully) medium to cropping season, intermediate rains, and a weak (fully) short one. It is at 2134 m a.s.l, receiving mean annual rainfall of 855 mm (Jaetzold et al., 2006).

3.3. The Study Design

This study was designed to collect data from commonly grown forest plantation species and determinants of tree retention on farm for improvement of forest cover in Kenya. According to Kenya Forestry Master Plan 1994, the commonly grown plantation species are *Pinus patula, Cupressus lusitanica, Eucalyptus grandis, Eucalyptus saligna* and *Juniperus procera*. These species are mainly grown in Central and Rift Valley highland Conservancies as well as in Western Kenya. The former conservancy was selected following simple random sampling.

3.3.1. Sampling Design and Primary Data Collection from Forest Plantation Species

A list of all forest stations managed by Kenya Forestry Service in Kiambu, Kirinyaga, Murang'a, Nyandarua and Nyeri Counties in Central highland Conservancy was obtained. Kiambu and Nyeri Counties were randomly selected out of the five Counties. The forest stations in each of these Counties were stratified and clustered on the basis of their AEZ and composition of plantation species. This resulted to the formation of four and three clusters in Kiambu and Nyeri Counties respectively. The first cluster of Kiambu County comprised of Thogoto and Muguga. The second one comprised of Uplands, Kerita and Kinale. The third cluster comprised of Ragia, Kamae and Kieni while the fourth one comprised of Kimakia. The first cluster of Nyeri County comprised of Kabage, Kiandongoro and Zaina. The second cluster comprised of Chehe, Hombe, Gathiuru and Kabaru while the third one comprised of Naromoru and Nanyuki.

The first and second clusters of forest stations in Kiambu County were randomly selected resulting to sampling of Muguga, Uplands and Kinale forest stations. On the other hand, due distinct locations of the three clusters in Nyeri County, where the first cluster is in Aberdare range, the second one is in the slopes of Mt. Kenya and the third one in the leeward side of Mt. Kenya, stratification and simple random sampling were used. Kabage, Kabaru and Naromoru forest stations were randomly selected in the first, second and third clusters, respectively (Figure 3.3).

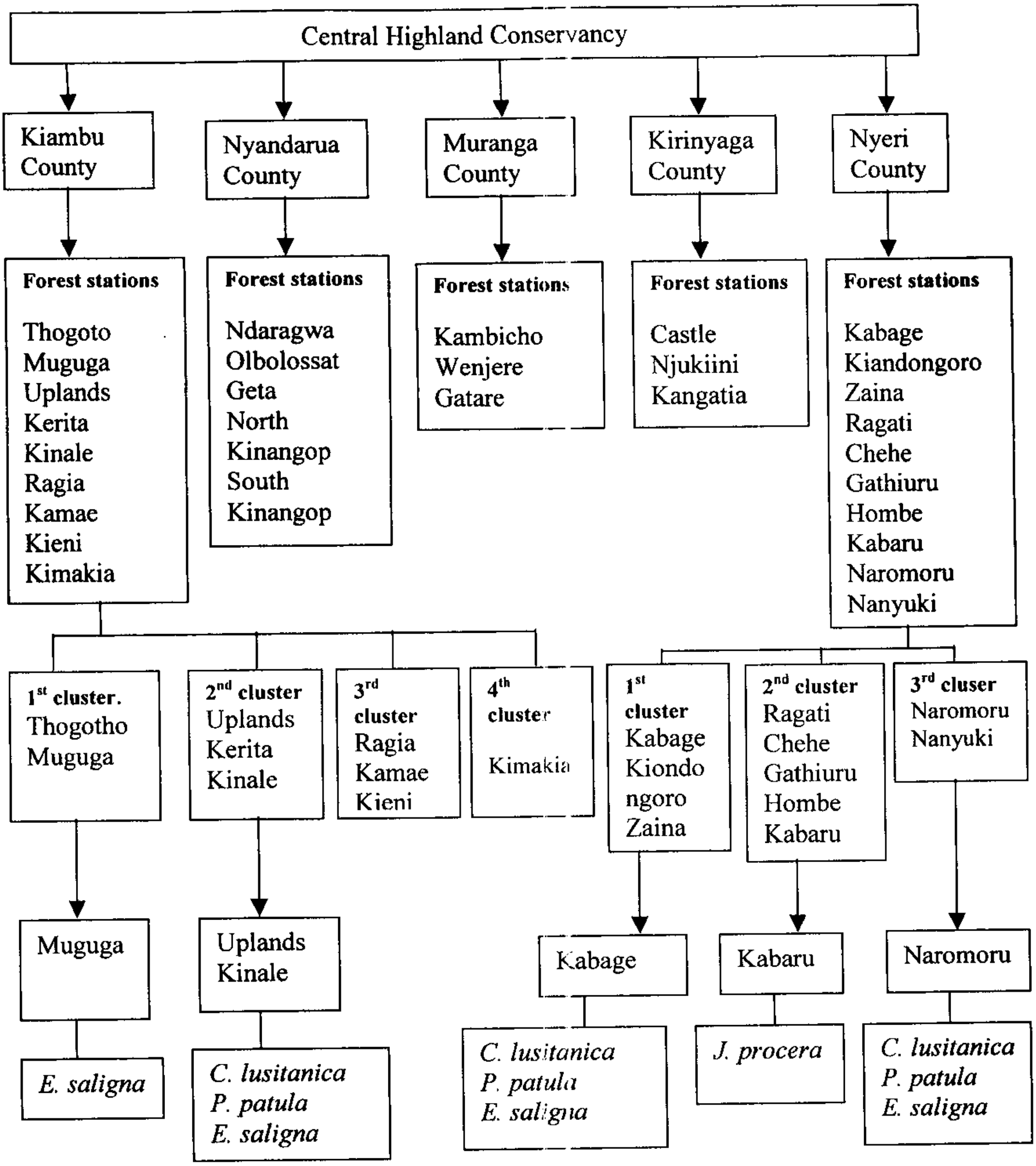

Figure 3. 3: Sampling design for selection of forest stations in Kiambu and Nyeri Counties

3.3.2. Tree Sampling from Forest Plantations and Measurements

A forest compartment register was used in selecting the plantation blocks depending on the age of the species, accessibility, secure from wild animals and previous management of the field. Rectangular plots measuring 20 m by 50 m of *Eucalyptus saligna* were established at Muguga, Uplands, Kinale, Kabage and Naromoru forest stations replicated three times for each age cateory. Also similar plot measurements were established for *Pinus patula* and *Cupressus lusitanica* at Uplands, Kinale, Kabage and Naromoru, replicated three times for each age category. The plots of the same measurements replicated three to eight times for each age category of *Juniperus procera* plantations were only established at Kabaru (Figure 3.1). This species was not planted in Naromoru while in other sampled stations it had poorly established and maintained. The rationale for plot measurements was based on other similar studies (Sierra et al., 2007; Williams et al., 2008; Paul et al., 2008; Alberti e al., 2008; Wang et al., 1996) which corroborated well with national inventory plots measuring 0.04 ha for large trees (> 10 cm DBH)and 0.02 ha for small trees (< 10 cm DBH) of high densities. The number of plots for each tree species studied varied depending on the total area planted, heterogeneity and homogeneity of the plantation compartments. In cases where the total area planted was large and fairly homogenous, distance between plots ranged from 80 m to 120 m apart.

Plantations that were relatively small in area and had important attributes for measurements, the distance between plots ranged from 30 m to 80 m. This sampling technique was found useful in providing data that was a true representative of the plantation under study. Within each plot, 10 trees were systematically selected and marked for measuring total height (H), diameter at breast height (DBH) at 1.3 m above the level ground, crown diameter and crown depth. The crown diameter was measured in four cardinal points and averaged out. The initial planting spacing of all these species was 2.5 m by 2.5 m.

3.3.3. Soil Sampling from Forest Plantation

Soil was sampled from six subplots of 4 m by 5 m established at the four edges and middle of the main plot of 20 m by 50 m (Figure 3.2) for all the selected tree species and age categories at different study sites. In each of the six subplots, central point was chosen where soil samples were collected at 0-20, 20-50 and 50-80 cm depth using soil augur. Any surface vegetation material was removed before soil augering was done. The collected soil samples from the six subplots of the same depth were thoroughly mixed and a composite sample of about one kg was packed into polythene bags for laboratory analysis of carbon, soil pH, nitrogen, phosphorous and potassium. Litter fall was collected from the same area of the soil sampling subplots, thoroughly mixed and about 300-500 g was packed into polythene bags for analysis on N and C.

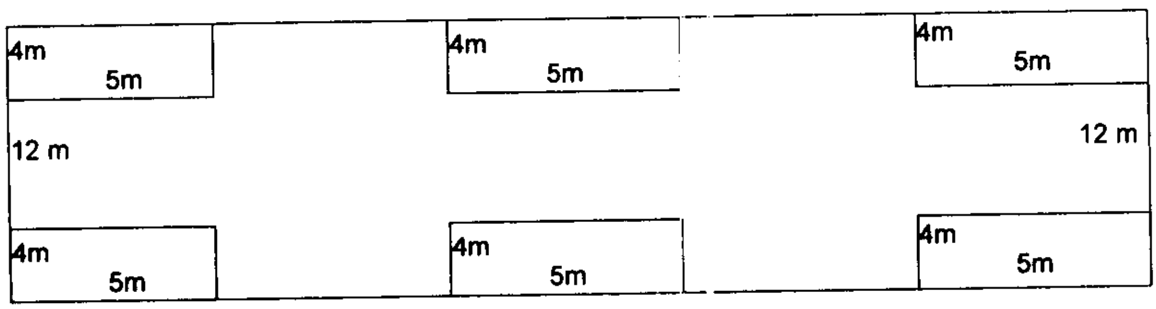

Figure 3.4: Layout of temporal forest plantation plots for soil sampling and tree measurements of various tree species and age categories

3.3.4 Sampling Farm Households

The farm household survey was conducted to establish the determinants of lifetime value of the farmer(s) willing to retain trees on the farm in improving forest cover and carbon sinks. A list of farmers who planted over one hundred trees or at least a quarter of an acre under woodlot or plantations was drawn from Nyeri South, Nyeri North, Kikuyu and Lari districts. Farmers were then stratified according to landsizes, tree planting densities and species diversity varying from intense boundary planting, woodlots to large plantations. To quantify the area under trees for cases of boundary planting, conversions were done to assume uniform area under trees, which was equated as either a woodlot or a plantation of 0.5 ha. In each stratum, simple random sampling was used to select farm-household respondents and proportional allocation of the questionnaires was used in each of the stratified category. Deliberate efforts were made during sampling to ensure that selected farm households were uniformly distributed across the study sites. Sixty five percent of the listed farmers within 20-25 km of the forest stations were selected resulting to 209 respondents. The type of questionnaire used to collect covered different measurements variables (Appendix 1). The enumerators were trained and pre-testing was done to ensure consistency, reliability and validity of the instrument

Table 3.1: Distribution of farm household questionnaire in Nyeri South, Nyeri North, Kikuyu and Lari districts

County	District	Sample size
Nyeri	Nyeri South	48
	Nyeri North	79
	Lari	48
Kiambu	Kikuyu	34
	Total	209

3.4 Secondary Data Sources

3.4.1 Seedling Distribution, Survival and Basic Wood Densities

Seedling distribution data of various species were obtained from head office, Central Conservancy, Kiambu forest zone and KEFRI nurseries. Data on growth and survival of commonly grown plantation species across ages were obtained from Kenya Forest Service (KFS) inventory records of 2009. Data on basic wood densities (ratio between oven-dry weight and green volume of wood) of major plantation species were obtained from KEFRI, forest product centre, Karura.

3.5 Data analysis and Description of Model Applications

3.5.1 Modelling Recruitment of Commonly Grown Tree Plantation Species

The entry of seedlings into the forestry system is what was referred to as recruitment process, which was likened to birth process in stochastic sense following the Markov chains that are often used to model the dynamics of various populations. Tree establishment and regeneration rates are largely stochastic, with maximum potential establishment rates constrained by the same environmental factors that modify tree growth. Time reversal of Markov chain could be used to estimate the distribution of time series since the last occurrence of some state of interest at appoint, given the current state of the point. Trend analysis based on time series models was used in forecasting the seedling recruitment on farm and gazzetted forests within Central highlands conservancy.

In particular, class of time series models used was Autoregressive Integrated Moving –Average models (ARIMA). These models are designed for the analysis of series of observations taken at regular intervals such as hourly or yearly and could describe the behaviour of a single series or relate one series to others (Digby et al., 1989). The autoregressive (AR) model used is of the form

$$X_t = \delta + \phi_1 X_{t-1} + \phi_2 X_{t-2} + \dots + \phi_p X_{t-p} + A_t \quad \text{......3.1}$$

where X_t is the time series, A_t is white noise, and

$$\delta = (1 - \sum_{i=1}^{p} \phi_i)\mu$$

with μ denoting the process mean and whereas p is the order of the AR model.

An autoregressive model is simply a linear regression of the current value of the series against one or more prior values of the series. The parameters were estimated using Least squares estimate (LSE) or by fitting a Box-Jenkins autoregressive model.

The moving average (MA) model is of the form

$$X_t = \mu + A_t - \theta_1 A_{t-1} - \theta_2 A_{t-2} - \dots - \theta_q A_{t-q} \quad \text{......3.2}$$

where X_t is the time series, μ is the mean of the series, A_{t-i} are white noise, and $\theta_1, \dots, \theta_q$ are the parameters of the model. The value of q is the order of the MA model.

ARIMA models were based on the following assumptions

i. Measurement data must occur at random from a fixed distribution of fixed location and fixed variation

ii. The data must be uncorrelated to one another where the random component has a fixed distribution.

iii. The deterministic component consists of only one constant and

iv. The random component has a fixed variation

The autocorrelations functions (ACF) displayed by correlogram were used for checking randomness of the data sets at varying time lags. For data measurements to be random, the autocorrelations should be near zero for any and all time lag separations. If non-random then one or more of the autocorrelations would be significantly non-zero. Partial autocorrelations functions (PACF) were useful in identifying the order of AR model.

Since the period was known, seasonal differencing for AR and MA models used was one, which was sufficient. Specifically, for an AR(1) process, the sample autocorrelation function should have an exponentially decreasing appearance. However, higher-order AR processes are often a mixture of exponentially decreasing and damped sinusoidal components. For higher-order autoregressive processes, the sample autocorrelation needs to be supplemented with a partial autocorrelation plot. The partial autocorrelation of an AR(***p***) process becomes zero at lag ***p*+1** and greater, so examination of the sample partial autocorrelation function to see if there was evidence of a departure from zero. This was usually determined by placing a 95% confidence interval on the sample partial autocorrelation plot.

The differences on the number of seedlings recruited of the commonly grown plantation tree species across the years among the sites and species were determined using mixed modelling approach which was given by

$$Y_{ij} = X_i\beta + Z_j u + \varepsilon_{ij} \quad \text{.........(3.3)}$$

where

Y is a vector of observations representing the number of seedling recruited from i^{th} site and j^{th} species,

β is a vector of unknown fixed effects,

X is a design matrix that relates observations to i^{th} sites

u is a vector of unknown random effects,

Z is a matrix that relates observations to j^{th} *species* random effects

ϵ_{ij} is a vector of residuals or random error term

3.5.2 Modelling Survival of Commonly Grown Plantation Trees Species

This was done using survival and hazard functions, which quantified the probability distribution of mortality in population (Muenchow, 1986). The survival function is defined as

$$S(t) = P(T \geq t), \quad \ldots\ldots 3.4$$

where $S(t)$ is the probability that a death occurs at some time T at least as great as time t, but not constrained except for being greater than 0 (Berkson and Gage, 1950; Cox and Oakes, 1984; Collet, 1994),

The hazard function is an instantaneous mortality rate and hence is a conditional probability (Cox and Oakes, 1984; Collet, 1994),

$$h(t) = \lim_{\delta t \to 0} \frac{P(t \leq T \leq t + \partial t / T \geq t)}{\partial t}, \quad \ldots\ldots 3.5$$

where $h(t)$ is the probability that death occurs exactly at time t, given that it has not occurred before then. The survival function may be estimated non-parametrically by using life table method (Cox and Oakes, 1984),

$$S(t_i) = \prod_{j=1}^{i-1} (1 - h_j) \quad \ldots\ldots 3.6$$

where for interval i, $S_{(ti)}$ is the survival probability at the start of time and h_i is the conditional probability of death. For $i = 1$ and hence $t_i = 0$, the survival probability is set to 1.

The proportional hazard models and other parametric survival models, namely, exponential, Weibull, Log-logistic and log-normal were used to determine the factors that influenced survival of commonly grown plantation tree species. Their descriptive forms are as defined below.

Proportional hazard model, also known as multiplicative hazard model or log-relative hazard model is given as

$\theta(t, X) = \theta_0 (t)\exp(\beta' X)=\theta_0(t)\lambda$ 3.7

where, θ_0 (t) is the baseline hazard function which depends on t but not on X. It summarizes the pattern of duration dependence assumed to be common to all tree species.

X is a set of explanatory variables (site, DBH, species, Thinning regimes and basal area expected to influence survival

$\lambda = \exp(\beta' X)$ is tree specific-non negative function of covariates X which does not depend on t and scales the baseline hazard function common to all tree species.

Weibull and exponential is defined as,

$\theta(t, X) = \alpha t^{\alpha-1} \exp(\beta' X) = \alpha t^{\alpha-1} \lambda$ 3.8

where $\lambda = \exp(\beta' X)$, $\alpha>0$ and exp(.) is the exponential function. The hazard rate rises monotonically with time ($\alpha>1$), falls monotonically with time ($\alpha<1$) or is constant. If $\alpha=1$, the special case of Weibull model becomes exponential model, α is the parameter shape.

Log-logistic model was given as

$\Psi= \exp(-\beta^{*\prime} X)$ 3.9

where $\beta^{*\prime} X = \beta_0+\beta_1 X_1+ \beta_2 X_2+ \beta_3 X_3+ \ldots\ldots\ldots\ldots\ldots\ldots + \beta_k X_k$

For example for the three sites, four species, four thnning regimes, basal area and DBH, the model becomes

$\beta^{*\prime}X = \beta_0+\beta_1$Kiambu+ β_2Nyeri South+ β_3Nyeri North+ β_4*Juniperus procera*+β_5*Eucalyptus saligna*+ β_6*Cuppressus lusitanica* + β_7 *Pinus patula* + $\beta_8$1st thinning + β_9 2nd thinning + β_{10}3rd thinning + β_{11}4th thinning + β_{12} DBH + β_{13} Basal area

Lognormal was given as

$$\theta(t, X) = 1/t\sigma\sqrt{2\pi}\, exp[-1/2\{ln(t)-\mu/\sigma\}^2]/1-\Phi(ln(t)-\mu/\sigma) \quad \text{......3.10}$$

where, $\Phi(ln(t)-\mu/\sigma)$ is the standard normal cumulative distribution function. The hazard rate is similar to that for the log-logstic model for the case $\gamma<1$. Both estimated parameters of the models were compared using –2loglikelihood ratio where the smaller the value, the better the model. The explanatory variables were DBH size, basal area, thinning intensity, study sites and tree species.

3.5.3 Modelling Carbon Sequestration of Commonly Grown Plantation Tree Species

The simulation modelling of the amount of carbon sequestered by commonly grown plantation tree species was done using CO2FIX V 3.1 framework. This is an eco-system-level simulation model that quantifies the C stocks and fluxes using full carbon accounting approach. It is divided into biomass, soil, products, bio-energy, financial and carbon accounting modules (Masera et al., 2003). The model considers the total carbon stored in most of the forest stand at any time (CT_i) to be,

$$CT_t = Cb_t + Cs_t + Cp_t(tC / ha) \quad \text{......3.11}$$

where

Cb_t is the total carbon stored in living (above plus below ground) biomass at any time t, in metric tones per ha;

Cs_t is the carbon stored in soil organic matter per ha and

Cp_t the carbon stored in wood products in tones per ha.

However, in this case, the interest was on the estimation of carbon stored in living biomass, which was estimated by 'cohort model' approach (Reed, 1980). Each cohort would be defined as a group of individual trees or species within the stand, which would be assumed to exhibit similar growth characteristics and which may be treated as a single entity within the model (Vanclay, 1989; Alder, 1995; Alder and Silva, 2000). These cohorts may be successional groups in natural forests, species in mixed forest and strata in a multi-strata agroforestry system. Then the carbon stored in living biomass (Cb_t) of the whole forest stand, can be expressed as the sum of the biomasses of each cohort

$$Cb_t = \sum Cb_t \left(\frac{tC}{ha}\right) \qquad 3.12$$

where :

Cb_t is the carbon stored in living biomass of cohort i(tC/ha).

Biomass expansion and conversion factor (BECF) of 1.3 was used for estimation of tree biomass above-ground and below-ground. This was based on root-shoot ratios which are used to expand above-ground biomass to total biomass as reported by FAO. These ratios range between 0.1 to 0.99 with an average of 0.29 which falls within the ranges provided by IPCC (2003) that reports global average root-shoot ratio of about 0.3 and an interval between 0.1 and 0.2 (Markuland and Schoene, 2006). In Africa the average BECF is 1.762. The stem biomass was obtained from wood density and local volume which was them multiplied by BCEF of 1.3 to obtain total biomass for above-ground and below-ground for carbon estimation.

In order to simulate Gb_{it},the model used input growth rate of stem volumes, which was derived from conventional yield tables. From the growth rate of stem volumes, growth rates of foliage, branches and roots were calculated using time-dependent allocation coefficients and actual crown measurements. Basically the model used stem volume growth in m^3 per ha per year as the main input, and allometric approach to derive net annual increment of the main biomass components from stem volume growth. Mathematically,

$$Gb_{it} = K_v Y_{ist}(1 + \sum(F_{ijt}))Mg_{it}(t / ha / yr) \qquad \text{3.13}$$

where:

K_v is a constant to convert volume yields into dry biomass (basic density, in kg dry biomass per $m^3$of fresh stemwood volume);

Y_{ist}, the volume yield of stem wood for each cohort "i" in m^3 ha−1 per year,

$Fijt$, the biomass allocation coefficient of each living biomass component "j" (foliage, branches, and roots) relative to stems, for each cohort "i" at time t (kg per kg) and

Mg_{it} is the dimensionless growth modifier due to interactions among and within cohorts.

Valkonen et al. (2000) reviewed the local formula for computing the stem volume of *Cupressus lusitanica, Juniperus procera, Eucalyptus saligna and Pinus patula* as follows: The volume equation of *Cupressus lusitanica* and *Pinus patula* is given by,

$$V=0.01722+0.0001937D^2+0.00005069DH+0.00002296\ D^2H \qquad 3.14$$

Whereas that of *Juniperus procera* is given by

$$\text{Log } V=-3.6321+2.2542\log D = -4.2224+0.9673\log D^2H \qquad 3.15$$

On the other hand the volume equation for *Eucalyptus saligna* is given by

$$V = 0.0368162+0.0000310D2H \qquad 3.16$$

The crown surface area and crown volume of *Cupressus lusitanica, Juniperus procera, Eucalyptus grandis and Pinus patula* was computed using the following equations;

$$\text{Crown surface area} = \Pi D/2\sqrt{(L^2+(D/2)^2)} \qquad 3.17$$

$$\text{Crown volume} = \Pi(D^2L/12) \qquad 3.18$$

The mean annual increment (M.A.I) was obtained by the difference between the highest age tree and least age during measurement divided by the number of years of growth.

3.5.4 Analysis of Soil Samples and Litterfall

Soil samples were analysed for C, N, P, K and pH. Litterfall was analysed for C and N. All analytical methods were conducted using the procedures as described by Okalebo et al. (2002). Statistical comparisons were done for C, N, P, K and pH under different soil depths and species using ANOVA and analysis of covariance. Comparisons of amount carbon sequestered below-ground and above-ground from each species across sites were done using analysis of covariance adjusted with age as a covariate. Pairwise comparisons were done using orthogonal contrasts. Total soil carbon estimated per ha was based on soil bulk density and percentage of carbon analyzed from soil samples. This was given by

*Total soil carbon (ha) = (Bulk density (kg/m³) * soil depth * %C)* 100* 3.19

Where the soil bulk density was determined using procedures as outlined by Okalebo et al. (2002). Mean comparisons of carbon sequestered were done using least significant difference (LSD), which was obtained by multiplying twice the standard error of difference (s.e.d) based on linear mixed model approach.

3.5.5 Analysis of Income from Sell of Carbon and Wood of Common Plantations Forest Species

Data on sell of carbon and wood from commonly grown plantation species were used in this analysis. Scenarios were created on assessing the postponement of harvesting times based on different products in demand mainly firewood, poles and posts in reference to timber under standard management. The prices for wood sale were obtained from Kenya Forest Service 2010/2011 finanancial year. Mean sale comparisons were carried out using linear mixed model techniques, analysis of variance (ANOVA) and regression.

3.5.6 Modelling Lifetime Value of Farmer Willingness to Retain Trees on Farm

The likelihood of the farmer willing to retain trees on farm would be influenced by a number of explanatory factors. To explore the relationship or association of these explanatory variables chi-square was used, Non-parametric tests, namely, Kruskal-Wallis H and Mann-Whitney U were used to compare mean rank differences among and between variables of lifetime value of the farmer willing to retain treesrespectively. In order to examine the probability and extent at which the farmer was willing to retain trees on farm, a dummy variable was created categorizing farmers as 'not likely', 'less likely' and 'most likely' to retain trees on farm. This was a dependent variable regressed against the independent or explanatory variables. The binary logistic ('not likely/likely') and multinomial logistic regression models were used and a comparison was drawn among the models. The multinomial logistic regression model with j categories of dependent variable was expressed as:

$$ln\left[\frac{p_j}{1-p_j}\right] = P(LTV) = \frac{1}{1+exp\{-(\beta_0+\beta_1X_1+ \ldots\ldots\ldots+\beta_nX_n)\}} \ldots\ldots\ldots\ldots\ldots\ldots 3.20$$

where:

j = 3 (1=not likely, 2=less likely and 3= most likely),

$P(LTV)$= the probability of lifetime value of the farmer willing to retain trees,

$0 \leq LTV \leq 1$ β_0 = intercept

$\beta_1 + \cdots + \beta_n$ = set of n regression coefficients,

$X_1 + \cdots + X_n$ = set of n (n=17) predictors and exp = base of the natural logarithm. In particular X_1=major occupation, X_2=Age of the household head, X_3=Education level of the household head, X_4=Marital status of the household head, X_5= number of members in the household, X_6=monthly income of the household, X_7=Type of land ownershipe, X_8=household land size, X_9=land use, X_{10}=Purpose of planting trees, X_{11}=Acquisition of technical skills in tree management, X_{12}=labour, X_{13}=extension services, X_{14}=Havesting regulation, X_{15}=Forest association, X_{16}=Market of forest products and X_{17}=economic motivation of tree planting.

When j=2, (1=not likely and 2=likely) the multinomial logistic model was an estimate of binary logistic regression model. Both multinomial and binary logistic regression models assumed that there exists an index/a desire or intent by the farmer to retain trees on farm which was a linear function of the vector of predictors expressed as

$$I_t = X_t\beta \quad \text{.......... 3.21}$$

where

I_t = (1×1) latent variable that is unobservable or index of intent/desire to retain trees by farmer t;

X_t = $(1 \times k)$ vector of observations on k independent variables for farmer t;

and

β = $(k \times 1)$ vector of coefficients.

If this index exceeds the individual threshold, retention of trees occurs. Similarly, extend of retaining was also a function of the predictors, through the index. Thus the greater the intend/desire to retain trees on farm, the greater the extent of retaining:

$$y_t = 0 \; if \; I_t < I_t^* = I_t - I_t^* \; if \; I_t > I_t^* \quad \text{.......... 3.22}$$

where:

y_t = (1×1) dependent variable representing extent of retaining trees on farm by farmer t;

I_t^* = (1×1) critical threshold or limiting factor for famer t.

Essentially, each farmer may have a different value. For instance, if extension services is a predictor variable, then more of the extension services may be required to push one farmer over his/her threshold than that required to induce another farmer's retaining ability. Since individual threshold differ, at any given index value, there will be both a concentration of zeros (for non-retaining) and a distribution of positive extents of retaining (for those who would retain). Therefore the probability of retaining, given a particular index value, is

$$Prob\left\{y > \frac{0}{I}\right\} = Prob\left\{I^* < \frac{1}{I}\right\} = F\left(\frac{I}{\delta}\right) \qquad 3.24$$

and

$$Prob\left\{y = \frac{0}{I}\right\} = Prob\left\{I^* > \frac{1}{I}\right\} = 1 - F\left(\frac{I}{\delta}\right) \qquad 3.25$$

where:

$F\left(\frac{I}{\delta}\right)$ is the value of the standard normal cumulative distribution at $\frac{I}{\delta}$. Expected extend of the retaining, given a particular index value is

$$E\left(\frac{y_t}{I_t}\right) = IF\left(\frac{I_t}{\delta}\right) + \delta F\left(\frac{I_t}{\delta}\right) \qquad 3.26$$

where:

$F\left(\frac{I_t}{\delta}\right)$ is the value of the standard normal density distribution at $\frac{I_t}{\delta}$. Estimation of β and δ is accomplished through maximum likelihood, since the functional form is non-linear.

The criterion used to group farmers as 'not likely', 'less likely' and 'most likely' to retain trees on farm for longer period of time included age (old and young), land size, species diversity, nature of planting (continuous and planted in last twelve months), motivational factors of tree planting, whether the farmer would prioritize to clear fell trees if faced with financial constraints, member of tree based organization, land use systems, priorities of given extra land, overall plans of land use, hindrances on tree growing and reasons for growing trees. The details and definitions of variables were as in Table (3.2).

The model was validated using chi-square test in which percentage prediction of the variables between observed and expected were used to determine the validity of the model.

The higher the correct percentage (>70%) of prediction in the model the better were the estimates of the explanatory variables.

Table 3.2: Definitions and description of modelling variables

Variables	Description	Dummy description
Dependent variable: Retaining trees on farm	Farmers' lifetime value to retain trees on farm for certain period of time	0=not likely; 1=less likely 3= most likely
Explanatory variables:		
Occupation (X_1)	Main occupation of the household head	1=Formal or non-formal 0=otherwise
Age (X_2)	Age of the household head	
Education (X_3)	Education level of the household head	1=schooled primary to university 0=otherwise
Marital status (X_4)	Marital status of the head of household	1=yes 0=otherwise
Number household (X_5)	Number of members of the household	
Income (X_6)	Income of the household head	
Land (X_7)	Land ownership of the household head	1=owns 0=otherwise
Land size (X_8)	Land size owned by household members	
Landuse (X_9)	Proportion of land under trees	1=yes 0=otherwise
Tree use (X_{10})	Purpose of trees planted on farm	1=yes 0=otherwise
Technical skills (X_{11})	Provision of technical skills on tree management	1=yes 0=otherwise
Labour (X_{12})	Labour involvement on tree management	1=yes 0=otherwise
Extension services(X_{13})	Accessing regular extension services	1=yes 0=otherwise
Regulation (X_{14})	Regulation by KFS on tree harvesting	1=yes 0=otherwise
Forest association (X_{15})	Existence and participation on forest organization	1=yes 0=otherwise
Marketability (X_{16})	Knowledge and access to markets and policies	1=yes 0=otherwise
Economic motivation (X_{17})	Economic returns from tree growing	1=yes 0=otherwise

The data were captured and checked in Ms-excel 2003 and analyzed using General Statistics (Genstat V12), Statistical Package for Social Scientists (SPSS V17) and Gretl for time series analysis. Statistically significant differences were declared at 1% (highly significant) and 5% (significant) levels of significant, unless stated otherwise

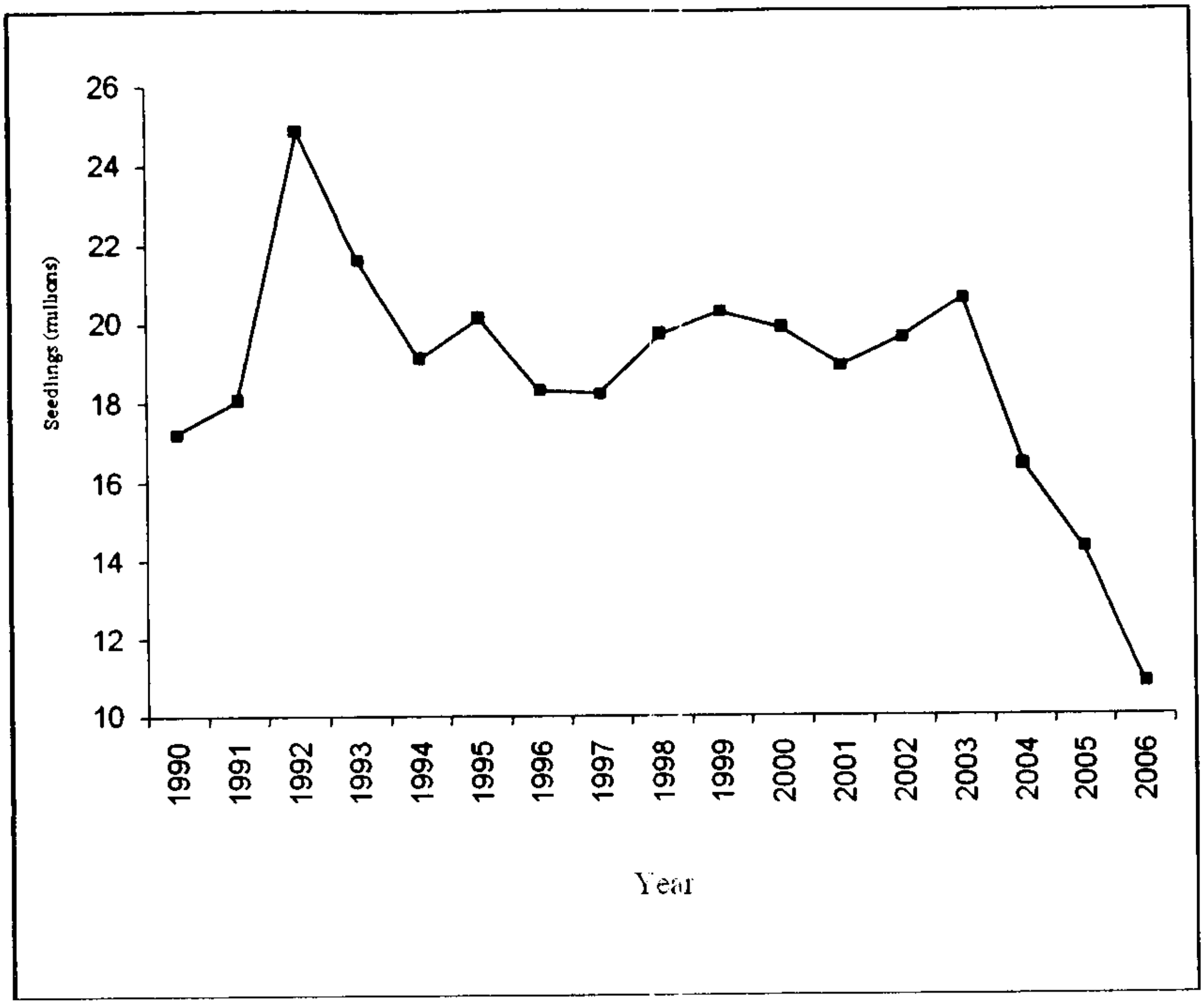

Figure 4.1: Seedlings recruitment in gazetted forest and farms in Central Kenya between 1990 and 2006

In addition, there was high peak of the number of established nurseries in 1992 and thereafter started to decline slightly between 1993 and 1994, after which it was constant till 2006 (Figure 4.2).

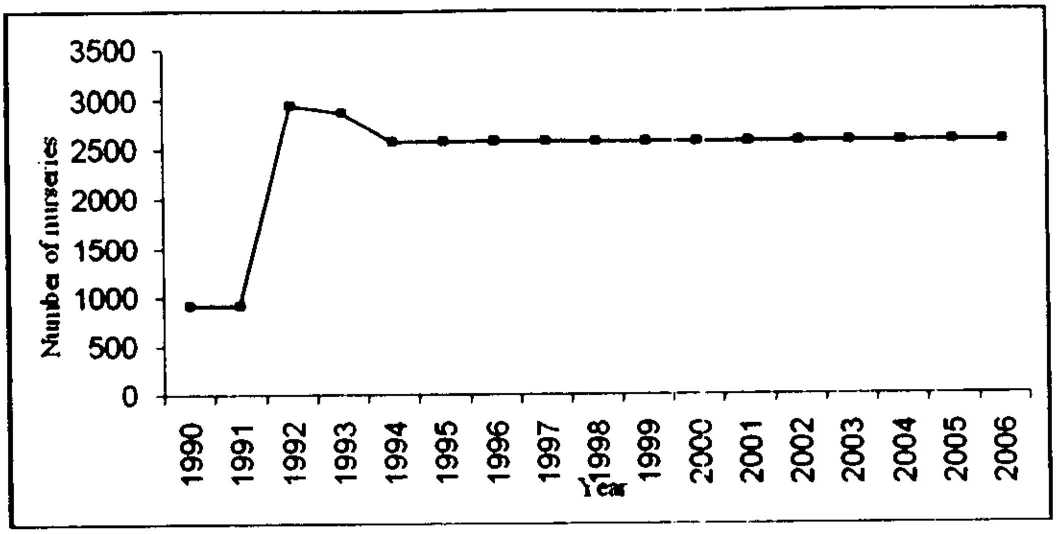

Figure 4.2: Number of established nurseries between 1990 and 2006 in Central Kenya

The sharp increase of seedling recruitment in 1992 may have been as a result of expulsion of squatters from the forest that started in 1988 and continued to 1991. During this period, there were many open places in the forest as a result of demolishing settlement structures and bare land that was initially converted into agriculture. Therefore, the foresters took an opportunity to carry out planting of trees before the invasion of other unwanted species on land that was initially under agriculture. There were also aggressive campaigns by village communities on re-afforestation programmes that were also initiated by NGOs. This corresponded well with the high peak of the number of tree nurseries in 1992 (Figure 4.2). However, the significant decline from 2003 to 2006 may be attributed to change of governance in Kenya. In 2003, the National Rainbow Coalition (NARC) government took over from Kenya African National Union (KANU) and aggressively addressed tree planting programme in all forest stations. During this time, most of the open areas in the forest were planted. Moreover, it was on the same year that the NARC government suspended all the foresters which significantly affected all planting programmes in most of the forest stations.

Nevertheless, the declining trend of seedling recruitment (Figure 4.1) painted a gloomy scenario in reference to the status of forest/tree cover in Central Kenya. This may be associated with the ban on industrial forest harvesting which took effect from 1999 implying that before the ban year, trees that had reached their economic rotations were clearfelled and replanting was carried out in sustainable manner. This might have led to an almost consistent trend of seedling recruitment from 1994 till 1999. Trees that had reached their maturity age for harvesting and were delayed due to the log ban may further explain the sharp drop as indicated in 2006. This implied that there is a limited area for industrial forests to undertake reforestation programmes other than rehabilitation of degraded forest areas. Overall, industrial plantation forests continued to dictate seedling recruitment in most forest stations of Central Conservancy.

Fitting the ARIMA model to the seedling recruitment data, the model with one Autoregressive parameter (ARp), one order of differencing and moving average significantly ($p<0.05$) fitted the data better than the other two models (Table 4.1). This was based on the Akaike information criterion (AIC) for model selection, where the smaller the AIC value the better is the model and higher the statistical significance. Forecasting the number of seedling recruited using the estimated parameters for the next five years from 2007 to 2011, the results showed some increasing trend (Figure 4.3). This was further evidenced with autocorrelation and partial correlation coefficients functions (ACF and PACF) at various time lags. The results showed that most coefficients were near zero, indicating that seedling recruitment was at random and fitting of the ARIMA model with specified parameters was correctly identified. Also the results based on partial correlation coefficients suitably identified the order of AR model the point at which the PACF essentially became zero. The 95% confidence intervals of the coefficient parameters were within estimated range for both ACF and PACF (Figure 4.4).

Table 4.1: Model selection for forecasting seedlings recruitment in Central Kenya based on Akaike criterion and log-likelihood ratio

ARIMA model with	Parameters coefficient	s.e	Z	p-value	Log-likelihood ratio	Akaike criterion
AR only	0.676	0.226	2.999	0.003	-39.54	85.08
AR and MA	0.417	0.561	0.743	0.458	-39.25	86.50
	0.383	0.620	0.619	0.536		
AR, Difference and MA	0.673	0.326	2.062	0.039	37.21	82.49
	-1.000	0.196	-5.106	<0.001		

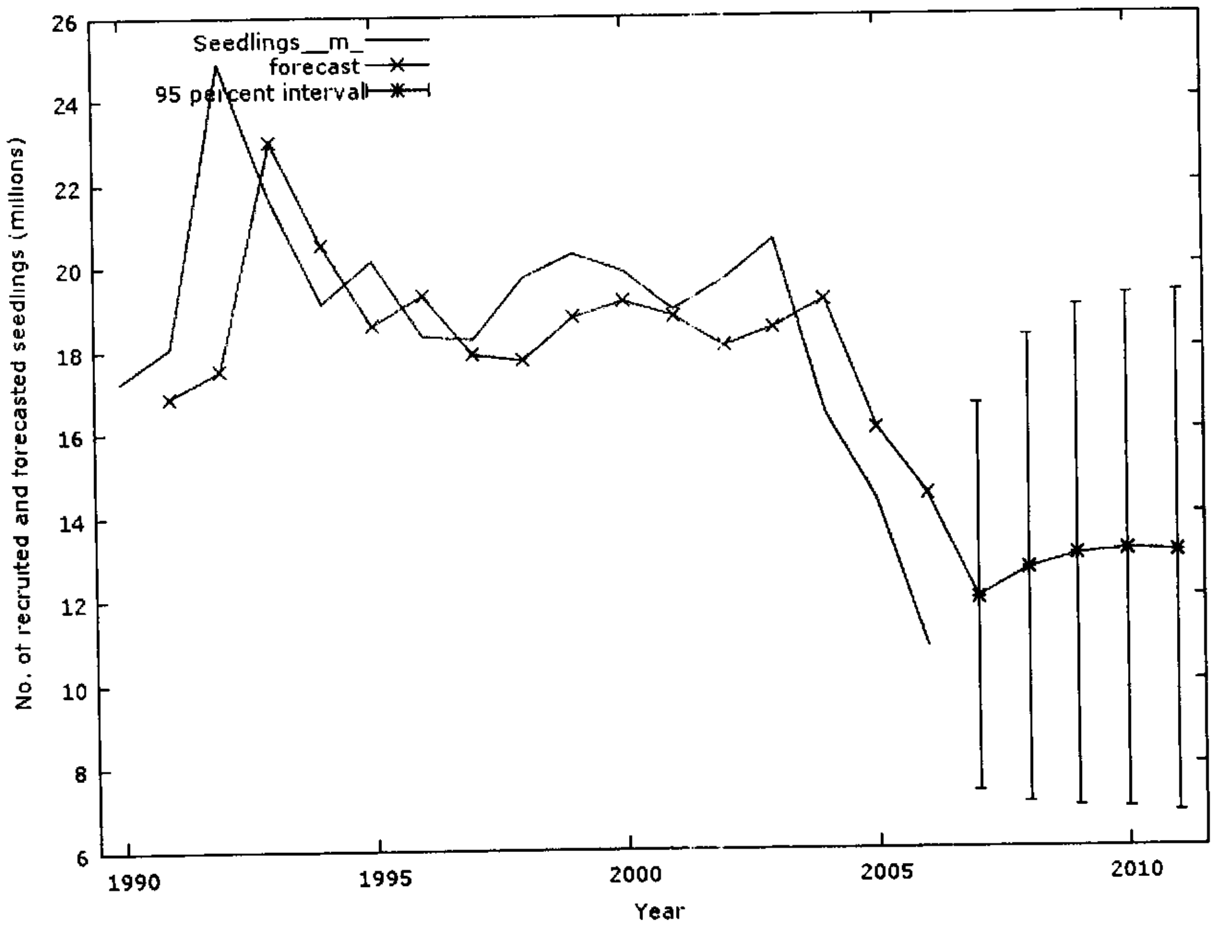

Figure 4.3: Forecasting recruitment of seedlings (millions) in Central Kenya

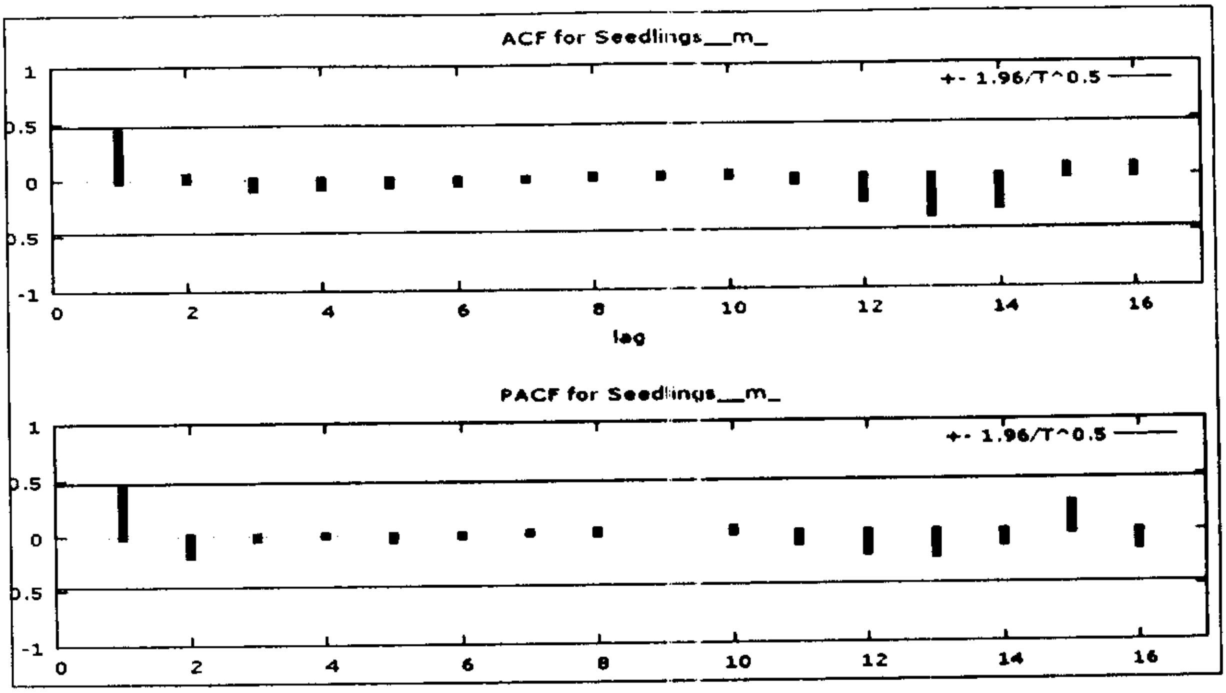

Figure 4.4: Autocorrelation and partial correlation coefficients (ACF/PACF) of seedling recruitment in Central Kenya

Forecasting of seedling recruitment using ARIMA model based on different parameters indicated an increase of seedling recruitment between 2007 and 2011. This demonstrated the power of time series analysis in projecting the likely scenario of seedling recruitment for improvement of tree cover. Other studies like Prior et al., 2009 have underscored the importance of understanding the demographic processes determining tree cover, namely; tree recruitment, growth and mortality. The techniques of time series analysis have been commonly applied in sales, weather stations, economic forecasting, budgetary analysis, census, stock market, yield projections, inventory studies, monitoring industrial processes or tracking corporate business metrics, among others. It usually requires more data points taken overtime at equally spaced interval in order to identify autocorrelation, trend and seasonal variation. This forms a critical component when modelling time series data following autoregressive order, differencing and moving averages in order to correctly forecast the likely scenario in the future. Therefore, the limited data points in this study led to use of time series analysis for forecasting seedling recruitment for only five years (2007-2011). This further implies that with availability of data taken at equal interval, modelling of time series analysis data would be very instrumental on tracking the status of forest/tree cover in Central Kenya, among other areas of the country.

4.2.2 Modelling Seedling Recruitment of Tree Species in Farmers' Fields

There was a significant difference (Wald statistic = 50.72; $F_{(1, 753)} = 50.72$; $p<0.001$) between exotic and indigenous tree species recruited in farmers' field between 2003 to 2010. This resulted to a total of 1,263,780 and 254,785 seedlings for exotic and indigenous trees, respectively, summing to 1,518,565 in a span of 8 years (Figure 4.5). Further, of the exotic tree species; *Grevillea robusta* (210,901), *Cupressus lusitanica* (152,546), *Eucalyptus saligna* (134,553), *Casuarina equistifolia* (127,438) were dominant seedlings whereas indigenous tree species, namely; *Markhamia lutea* (53,224), *Prunus africana* (25,436), *Acacia* spp (25,219), *Podocarpus* spp (17,684) *Croton megalocarpus* (16,830) and *Juniperus procera* (12,635)were most dominant .

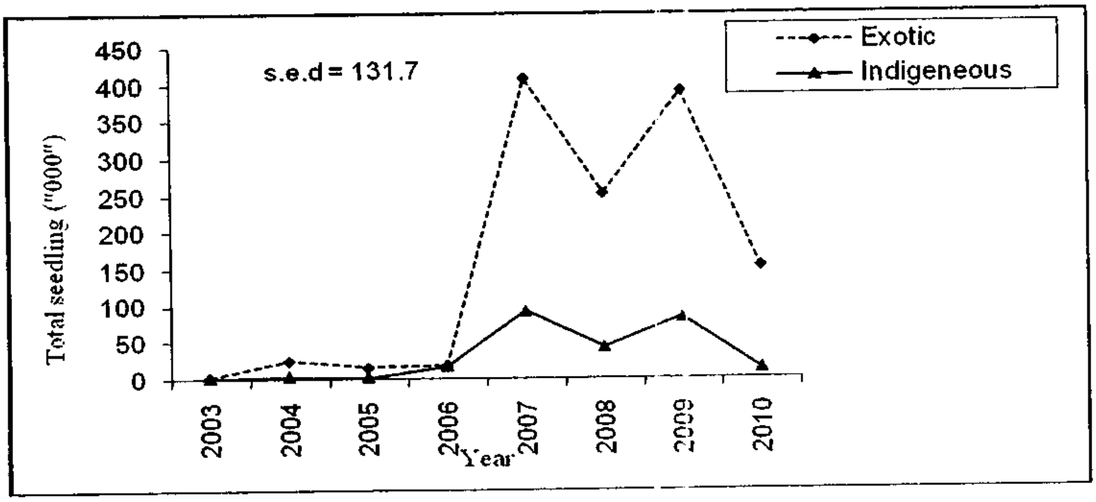

Figure 4.5: Total recruitment of seedlings from selected nurseries across sites

The high take of seedlings in 2006 may be associated with tree planting campaigns by various environmental groups/community based organization, good market of tree products, ban on tree harvesting by the government hence farmers need satisfy household woodfuel from their farms among other possible reasons. The preference of exotic tree species over indigenous ones by various tree nurseries may be associated with the demand and fast growing linked with multiple uses of such species. For example, *Grevillea robusta* intercrops well with agricultural crops and provide less competition on soil nutrients. This might explain why the recruitment of this species was high as compared to others. In addition, the management and uses of this species has been well documented within the Central Kenya region and the adoption level is high. This explains further its valuable role in improving forest/tree cover in Central Kenya as compared to other tree species. The slow growth, inadequate of quality seeds, low adoption of propagation methods and other tree improvement technologies of indigenous tree species such as *Markhamia lutea*, *Prunus africana*, *Podocarpus* spp, *Croton megalocarpus* and *Juniperus procera* may explain why most nurseries supply a limited number of such seedlings. Astrup et al. (2008) reports that seed source availability, seedbed substrate, over storey structure and time, affected the seedling recruitment of the dominant tree species in various forest types.

Moreover, a significant increase ($F_{(1,30)}$ = 8.36; p=0.007) in the number of Eucalyptus hybrid seedlings recruited in Central Kenya accrued from 780,000 in 2003 to 1.1 million in 2005 (Figure 4.6). This continued to demonstrate the significant contribution of Eucalyptus hybrid clones in improving the status of forest cover in Central region. For instance the increasing uptake trend of clones from 2003 to 2006 may be associated with wide publicity on the advantages of growing clones which included, fast growth, early maturity to different products such as construction posts within five years, transmission poles with seven years and timber within 10 years. These tree products are in high demand leading to high uptake. Eucalypts are known to grow fast and suitable for fuelwood, construction and transmission poles, among other uses (Oeba et al., 2009). This makes eucalypts popular species especially for farmers who had large land area for commercial even though of recent it has received lot of negative publicity on water use and competition with food crops. This resulted to uprooting of eucalypts from some farms in Central Kenya. However, the decreasing may be associated with failure of farmers to realize the associated benefits from the eucalyptus clones and land availability among others.

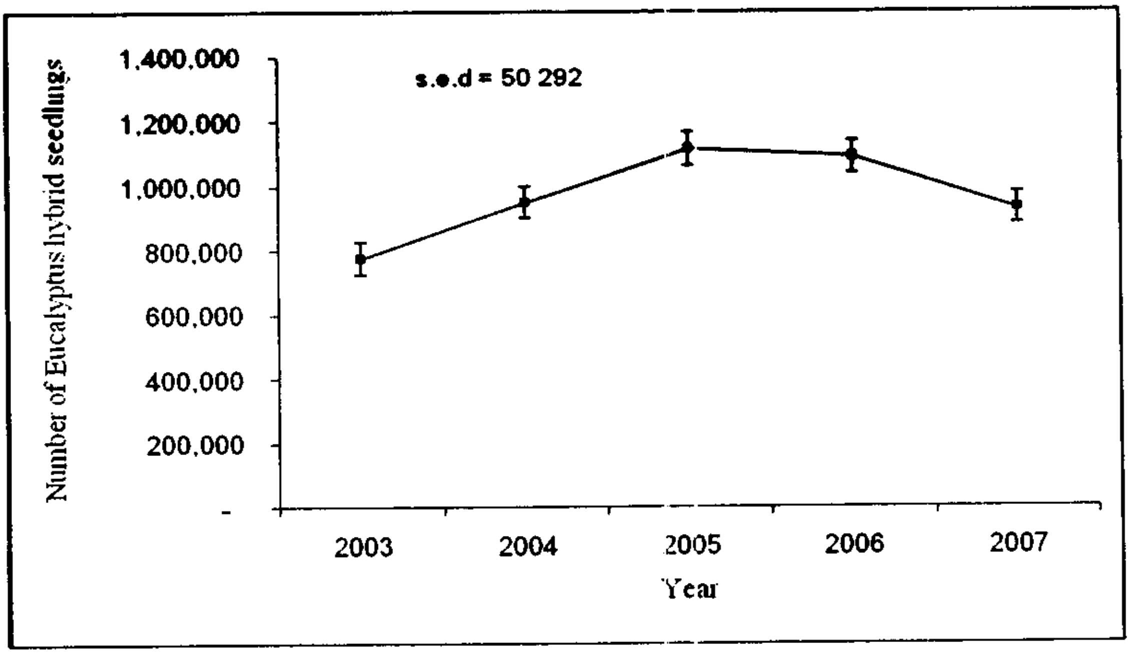

Figure 4.6: Number of Eucalyptus hybrid seedlings recruited in Central Kenya between 2003 and 2007

Fitting the ARIMA model to the data, only two Autoregressive parameters (ARp) with no order of differencing and moving averages significantly ($p<0.01$) fitted the model better with negative correlation of -0.89. They had least residual and innovation deviance whose coefficients parameter estimates were 1.743 and -0.942 with s.e of 0.723 and 0.571 for first and second ARp, respectively. This implied that the two ARp had better improvement of the model as compared to other alternating parameters (Order of differencing for stationarity and Integrated Moving Averages). They had also better standard error (s.e) of estimates that were used for forecasting seedling recruitment as shown in Figure 4.7.

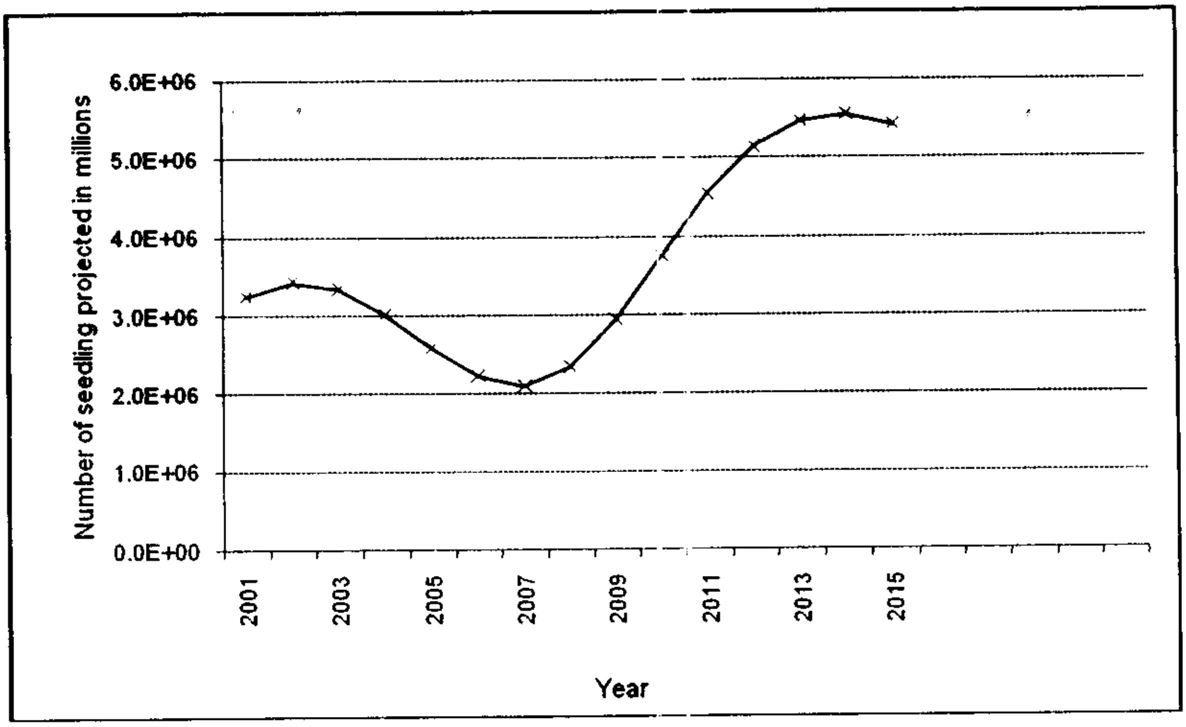

Figure 4.7: Forecasts of the number of seedling recruited of eucalyptus hybrid clones in Central Kenya

4.2.3. Seedling Recruitment of Commonly Grown Plantation and Other Integrated in Gazzetted Forests

There were significant differences (Wald statistics = 9.32; $F_{(3, 23)}$ = 3.09; p=0.047) in the quantity of the seedling recruited among sites for planting in various gazzeted forests. Similarly, there were significant differences (Wald statistics = 557.72; $F_{(9, 624)}$ = 61.97; p<0.001) in the predicted quantity of seedling recruited per species in various gazzeted forests in Central Kenya. There were also significant interaction effect (Wald statistics = 42.82; $F_{(18, 622)}$ = 2.38; p=0.001) between the districts and species recruited (Table 4.2). This implied that some species recruited were site specific.

Table 4.2: Mean number of seedlings recruited annually of common plantations and other integrated species in gazzetted forests of Kikuyu, Lari, Nyeri South and Nyeri North districts

Species type	Kikuyu	Lari	Nyeri North	Nyeri South	Total
Common plantation species					
Pinus patula	30000	71677	52279	58211	60263
Eucalyptus saligna	26667	57636	36934	37714	44305
Cupressus lusitanica	57500	137866	112958	101362	117705
Juniperus procera	26667	16000	26111	23684	22545
Other integrated species					
Bischofia		17500	10000	10000	15294
Casuarina equistifolia	15000	20000	21667		20000
Eucalyptus grandis			75000	55000	65000
Makharmia lutea			30000		30000
Podocarpus falcatus		10000		10000	10000
Prunus africana		10000	23333	10000	15714
Vitex keniensis	20000	12083	37407	10000	23898
Total	31579	71737	61046	58667	63626

*s.e.d of sites (districts) =4741; s.e.d of tree species = 7732

Mean comparisons of total number of recruited seedlings among districts and tree species, showed that there were significant differences ($p<0.05$) between Kikuyu and Lari, Kikuyu and Nyeri North, Kikuyu and Nyeri South. However, no significant differences ($p>0.05$) were found between Lari, and Nyeri North. Similarly, no significant differences ($p>0.05$) were found in the number of seedling recruitment between Nyeri North and Nyeri South. In addition, there were significant differences ($p<0.05$) in the number of seedlings recruited of *Cupressus lusitanica* and the rest of the tree species. Also significant differences ($p<0.05$) were obtained on the mean number of seedlings recruited between all combinations of commonly grown plantation species. Similarly, for integrated tree species, there were significant differences ($p<0.05$) in the mean number of seedling recruited between *Eucalyptus grandis* and *Markhamia lutea*. On the other hand, there were no significant differences ($p>0.05$) among *Bischofia, Casuarina, Juniperus procera, Markhamia lutea, Vitex keniensis, Podocarpus falcatus* and *Prunus africana*.

The variation in the number of seedlings recruited in this study among the sites may be explained by the sample sizes of the forest station per district and the targeted area for re-forestation and afforestation programmes carried by KFS. For instance, Lari had nine forest stations as compared to two in Kikuyu, five in Nyeri South and seven in Nyeri North. This in turn has a direct bearing of species diversity and frequency of tree planting. The high dominance of *Cupressus lusitanica* and *Pinus patula* seedling recruitment may be attributed to the nature of their uses (sawn timber) in Central Kenya. These species were primarily introduced for industrial plantation forestry to cater for such specific needs of the country. They are the most promoted exotic tree species in most forest plantations. Eucalyptus were recently introduced to cater for firewood even though of recent they are also grown for timber, construction posts, transmission poles and beams, among other needs of wood and non-wood products also in numbers after the ban of cedar and demand by the Kenya Power Lighting Company (KPLC).

Indigenous tree species like *Juniperus procera* are mainly grown for fencing posts whereas *Vitex keniensis*, *Podocarpus falcatus* and *Markhamia lutea* are being considered as potential plantation tree species leading to their limited recruitment in major forest plantations. Essentially, most indigenous tree species have been mainly used for rehabilitation of degraded forest areas and enrichment planting. Overall, the afforestation and re-forestation programme undertaken by KFS plays a significant role in improving tree cover in Kenya. The massive seedlings recruited through forest plantations underpin this importance. Farwig et al. (2009) reported a convergence of recruiting seedling communities in different forest management types suggesting that tree plantations might buffer forest loss to a certain extent and may have the potential to develop into more natural forest overtime.

In addition, the planting area significantly varied from site to site. Lari had the highest total area (9137 ha) re-forested and afforested for a period of 10 years followed by Nyeri North (8028 ha), Nyeri South (4505 ha) and lastly Kikuyu (300 ha). The availability of the planting area has generally been found to be one of the important determinants influencing forestry activities (Arbuckle et al., 2009; Volker and Waibel, 2010). This was further evidenced with a significant relationship (Wald statistics = 14,186; $F_{(1,531)}$ = 14,186; $p<0.001$) between the number of seedlings recruited and the area targeted for planting across all tree species and districts between 2001 and 2010 (Figures 4.8 and 4.9).

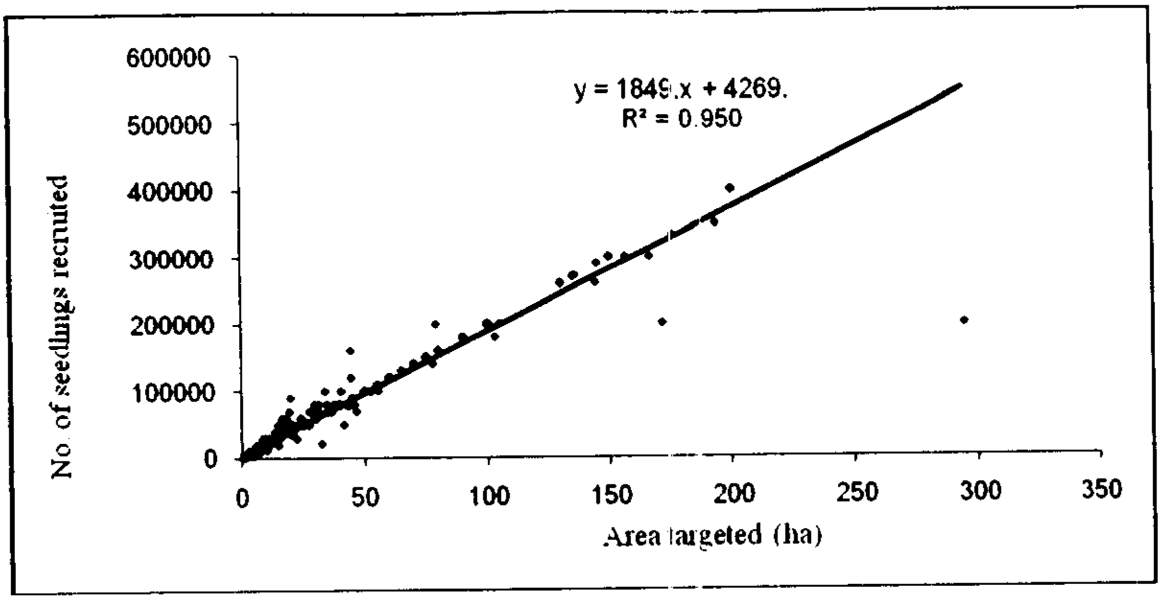

Figure 4.8: Relationship between number of seedling recruited and area targeted for planting in gazetted forests of Central Kenya

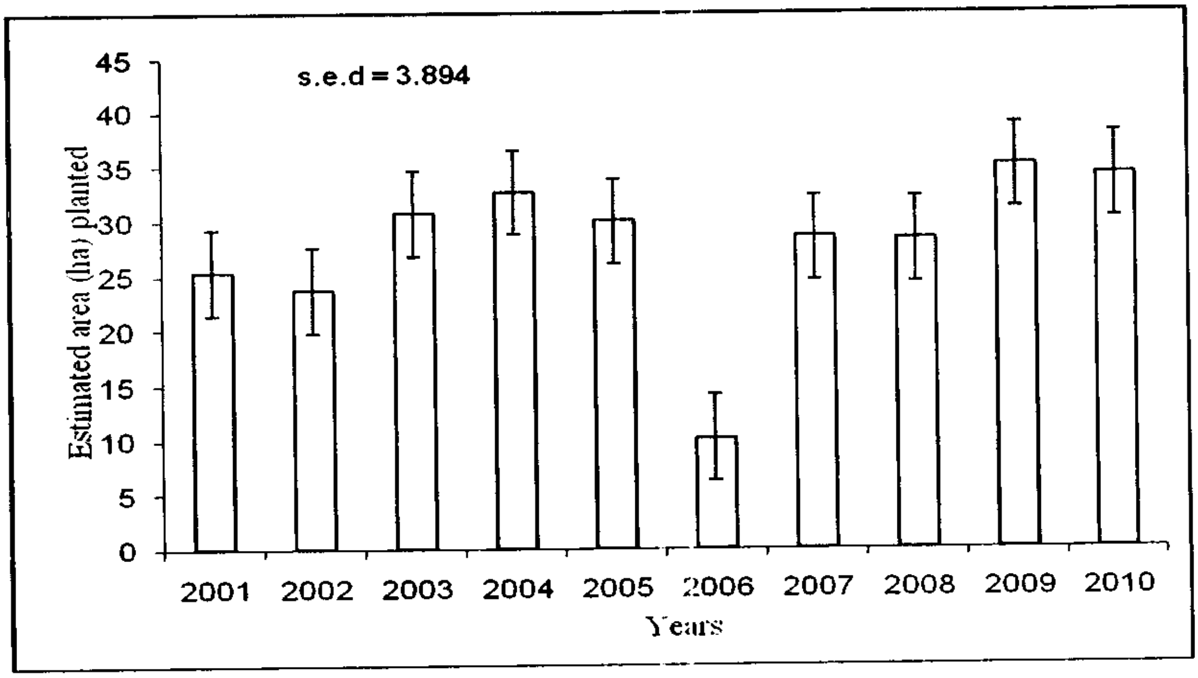

Figure 4.9: Estimated area (ha) planted per tree species by KFS between 2001 and 2010 in gazzetted forests of Central Kenya

4.2.4 .Modelling Survival of Common Plantations Species

Based on Kaplan-Meier estimate, there was a decreasing trend of survival among *Juniperus procera*, *Eucalyptus saligna*, *Pinus patula* and *Cupressus lusitanica* across all ages and sites. *Juniperus procera* showed a substantial drop in the likelihood of survival (43.5% censored) with increasing age followed by *Eucalyptus saligna* (41.2%), *Cupressus lusitanica* (19.2%) and *Pinus patula* (11.2%, Figure 4.10). Non-parametric tests on equality of survival curves for each tree species showed high significant difference (Log-rank = 5060.472, d.f = 3, $p<0.01$); Wilcoxon (Breslow) = 3745.84, d.f. =3, $p<0.01$; Tarone-Ware = 4524.94, d.f. =3, $p<0.01$ and Wilcoxon (Peto-prentice) = 4100.65, d.f =3, $p<0.01$) on tree species survival.

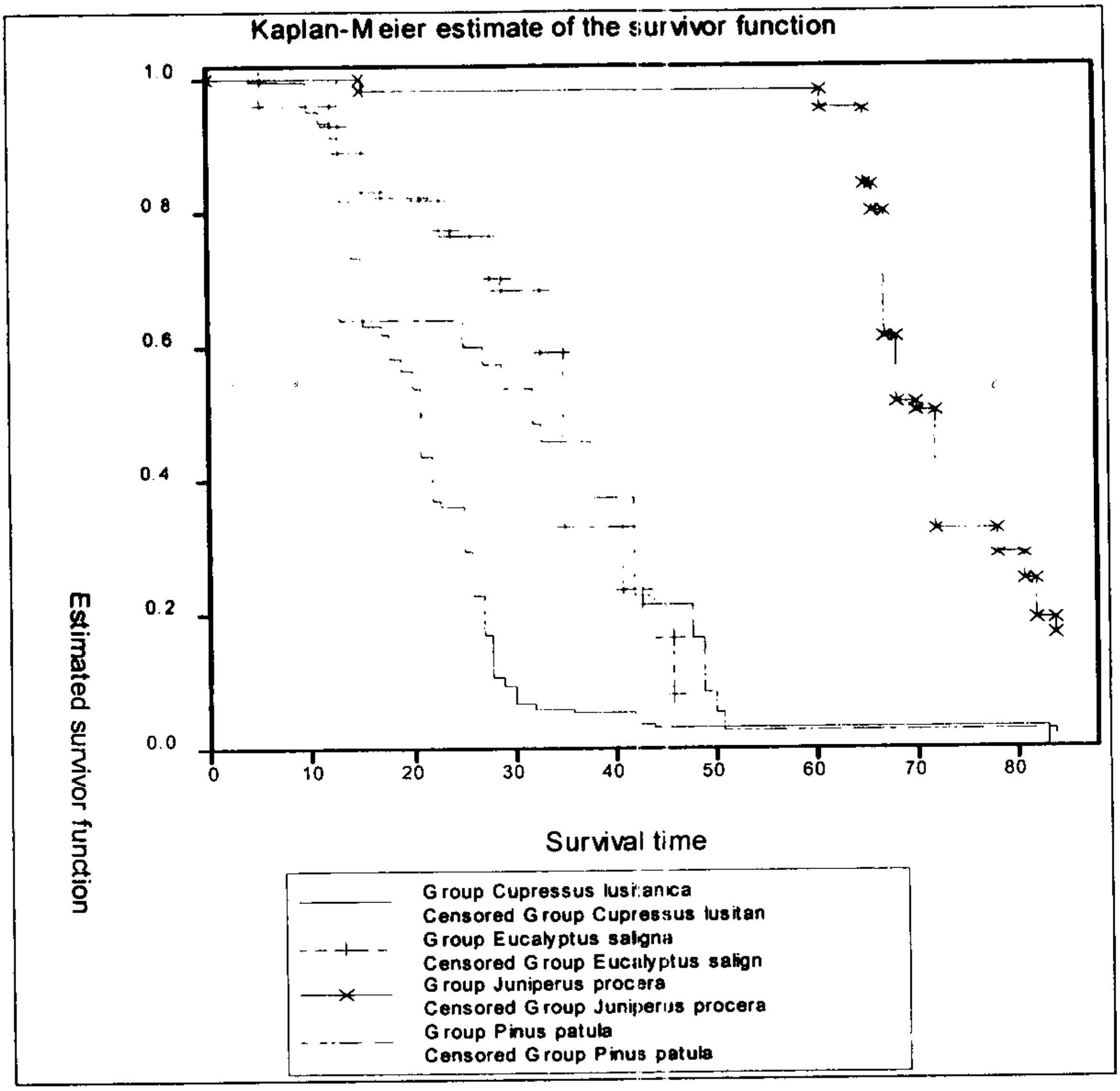

Figure 4.10: Kaplan-Meier estimate of the survivor function of commonly grown plantation species across ages and sites

All species (Figure 4.10) had an equal chance of survival at tree recruitment across sites. However, with increase in age, likelihood survival dropped in the order; Nyeri South (38.6% censored), Kiambu (Lari and Kikuyu, 32.9%) and Nyeri North (25%) districts (Figure 4.11). This was found to be significantly different (Log-rank = 45.47, d.f = 2, p<0.01); Wilcoxon (Breslow) = 267.66, d.f. =2, p<0.01; Tarone-Ware = 150.15, d.f. =2, p<0.01 and Wilcoxon (Peto-prentice) = 209.87, d.f =2, p<0.01) among survival curves in each site.

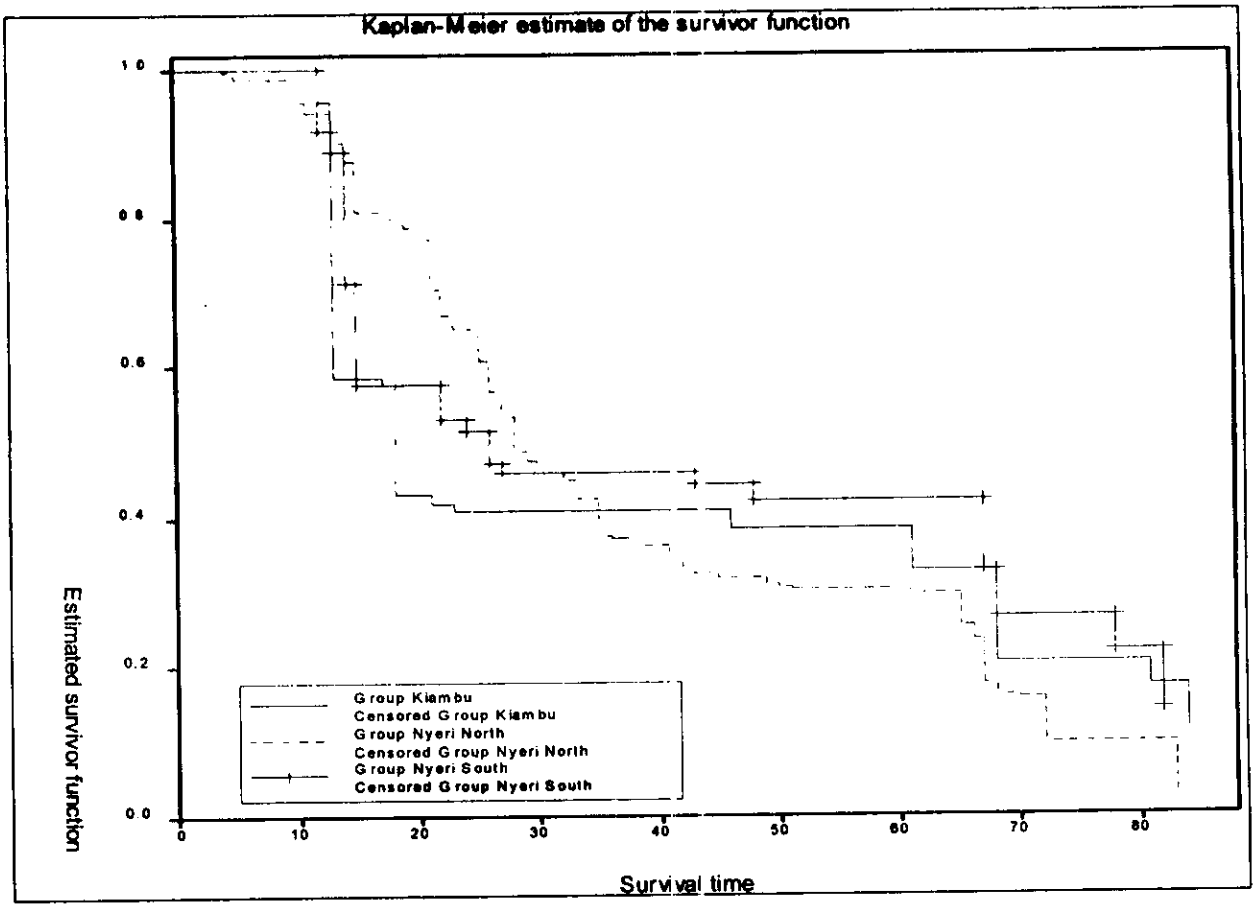

Figure 4.11: Kaplan-Meier estimate of the survivor function of major plantation tree species accross all ages at Kiambu, Nyeri South and Nyeri North

Poor establishment of *Juniperus procera* due to edaphic factors especially in Kiambu (Lari and Kikuyu) and Nyeri South districts may explain the significant variation of survival among other commonly grown plantation species. Most of *Juniperus procera* blocks at Kabage and Lari were poorly maintained and logging was evident due to high value of *Juniperus procera* posts for fencing. At Nyeri North district, a number of *Juniperus procera* plantations were well established especially at Kabaru and Ndathi forest blocks other than incidents of animal destruction especially elephants from Mount Kenya. On the other hand, high mortality rates of *Eucalyptus saligna* across all sites may be explained by various uses: fuelwood, beams, rails, poles, fencing and construction posts at age of 5-6 years as well as transmission poles at age of 10-12 years. This in essence means chances of some sections of *Eucalyptus saligna* tree plantation harvested for such uses are quite high. This was evident during data collection as some in compartments, specific trees were marked for clearfelling. Most of eucalypts plantations were not well maintained especially after clearfelling of respective trees from the earmarked compartment.

The low mortality of *Pinus patula* and *Cupressus lusitanica* may be attributed to good establishment and maintenance of these plantations. This was also observed during data collection as majority of compartments of these two species were accessible and free from shrubs/bushy undergrowth. The low rotation age of these species without log ban may also explain the low mortality rates. In addition, *Pinus patula* and *Cupressus lusitanica* have a long history in Central Kenya gazzetted forests. They are mainly grown for sawn timber and the management has been tailored for this end use. However, there were delays of thinning and clearfelling due to government ban since 1999. Ultimately, some plantations were therefore likely to have high density beyond the expected standard ones as stated by forest management schedules or technical orders.

4.2.5. Modelling Survival Determinants of Commonly Grown Plantation Species

Modelling survival of *Juniperus procera, Eucalyptus saligna, Pinus patula* and *Cupressus lusitanica* using age as time points, both parametric and non-parametric models determined; site, thinning regime, diameter increase and local basal area as significant ($p<0.01$) determinants influencing survival status. Significant differences ($p<0.01$) were also observed in survival among tree species. Proportional hazard model had the highest –2log-likelihood ratio (95,651) followed by parametric Exponential model (58,251), Log-normal (46,249), Log-logistic model (41,973) and least with Weibull distribution model (41,223). The corresponded shape parameters for Weibull distribution, Log-logistic and Log-normal models were $\alpha = 6.758$, $\delta = 0.104$ and $\delta = 0.285$, respectively (Table 4.3).

Comparisons among various survival parameters showed chances of tree survival at Nyeri North were significantly higher ($p<0.01$) than Kiambu (Kikuyu and Lari) and Nyeri South district. Similary, the findings of Weibull distribution, Log-logistic and Log-normal on survival differences among commonly grown plantation species were consistent with non-parametric test as indicated by Kaplan-Meier estimate of the survival function. Thinning management significantly ($p<0.01$) influenced survival of commonly grown plantation tree species, except for *Eucalyptus saligna* that was harvested selectively at different times for firewood, transmission poles, construction posts, among others. As number of thinnings increased there was a corresponding decrease of survival function (Table 4.3 and Figure 4.12). Equally, differences on DBH and basal area significantly ($p<0.01$) affected the survival of *Juniperus procera*, *Eucalyptus saligna*, *Pinus patula* and *Cupressus lusitanica* across ages and sites (Table 4.3 and Figure 4.13).

Table 4.3: Comparison of models on survival of commonly grown plantation species across ages and sites

	Proportional hazard model			Exponential model			Weibull model			Log-logistic model			Log normal model		
Parameter	β	s.e(β).	t(*)	β	s.e(β).	t(*)	β	s.e(β).	t(*)	β	s.e(β).	t(*)	β	s.e(β).	t(*)
Nyeri North	0.17	0.046	3.61	-0.01	0.04	-0.2	0.49	0.04	10.9	-0.01	0.07	-0.08	0.04	0.01	5.20
Nyeri South	-0.02	0.057	-0.32	-0.10	0.05	-1.9	0.25	0.06	4.4	0.01	0.09	0.09	0.05	0.01	4.32
Cupressus lusitanica	9.96	0.134	74.28	2.02	0.05	43.2	11.63	0.05	237.3	-1.74	0.07	-23.99	-1.73	0.01	-202.31
Pinus patula	10.33	0.145	71.1	2.04	0.06	31.5	12.24	0.06	195.3	-1.73	0.11	-16.37	-1.72	0.01	-121.39
Eucalyptus saligna	3.60	0.079	45.7	1.34	0.05	28.6	5.01	0.05	107.0	-0.91	0.09	-10.55	-1.08	0.01	-124.36
2nd thinning	-1.85	0.073	-25.41	-0.34	0.05	-6.7	-2.07	0.05	-40.5	0.30	0.08	3.95	0.29	0.01	24.52
3rd thinning	-3.62	0.085	-42.53	-0.69	0.05	-14.0	-3.77	0.05	-73.9	0.55	0.07	7.34	0.54	0.01	48.62
4th thinning	-6.86	0.122	-56.37	-1.20	0.07	-16.5	-9.43	0.06	-146.0	1.01	0.14	7.45	1.04	0.02	61.32
None	2.28	0.080	28.52	0.33	0.05	7.1	1.64	0.05	34.4	-0.26	0.07	-3.68	-0.28	0.01	-27.32
DBH_cm	0.11	0.003	35.24	0.11	0.00	36.5	0.11	0.00	34.6	-0.02	0.00	-3.94	-0.03	0.00	-112.21
Basal_area (m^2)	-17.31	0.688	-25.16	-17.9	0.67	-26.8	-17.92	0.67	-26.8	2.99	0.97	3.08	4.30	0.05	90.54
-2log-likelihood	95,651.052			58,251			41,223			41,973			46,249		

Reference: Site-Kiambu; Tree species-*Juniperus procera*, Thinnings-1st ; DBH cm –Unit increase; Basal area, unit increase

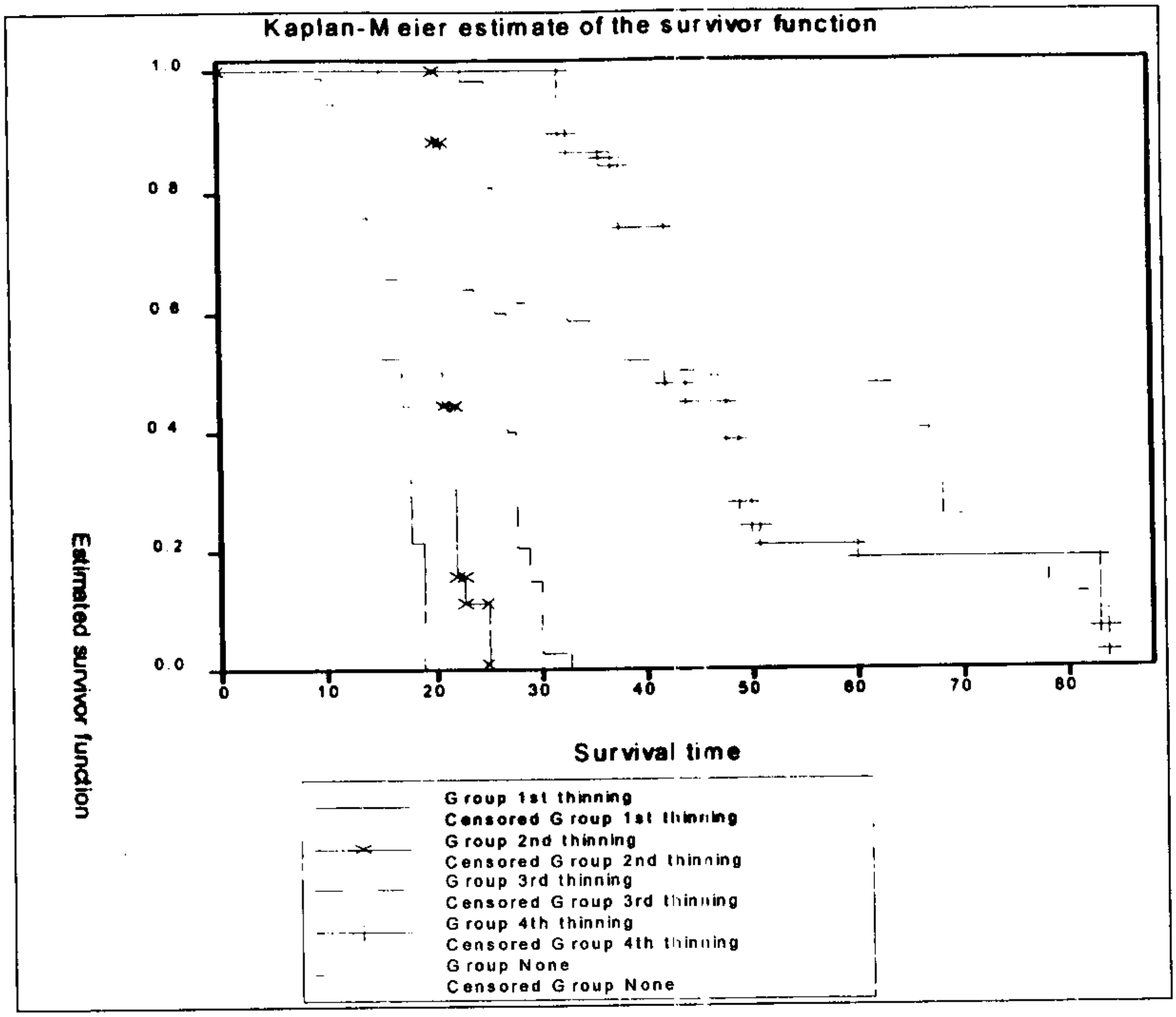

Figure 4.12: Kaplan-Meier estimate of the survival function of commonly grown plantation species across ages under different thinning management

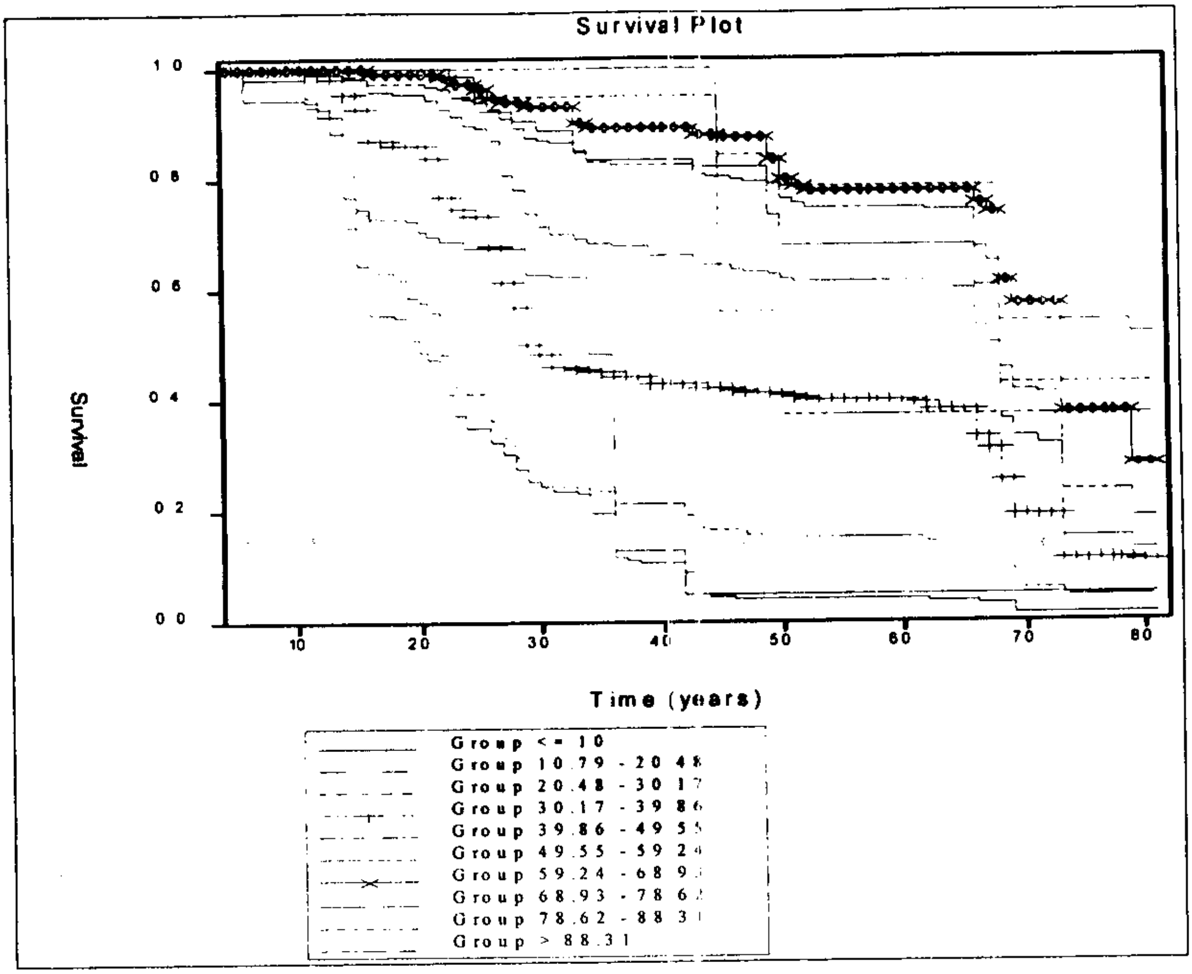

Figure 4.13: Survival estimate based on DBH classes of commonly grown plantation species across ages and sites.

The significant effect of DBH on survival of *Juniperus procera, Eucalyptus saligna, Pinus patula* and *Cupressus lusitanica* indicated that an increase in DBH in a given class demonstrated substantial drop in the likelihood of survival to the next DBH class. This was evident to trees of large DBH classes where the height and width between steps in Kaplan-Meier estimate of survivor function were high implying variations in survival. Essentially, DBH and age are interrelated meaning an increase in tree age has a corresponding increase in DBH improving the likelihood of end use of a tree if grown for commercial purposes. For example, at the age of 20-30 years, *Pinus patula* is clearfelled for sawn timber at an average

DBH of 37±3 cm whereas at about 35 years, it is clearfelled for plywood at an average DBH of 51 cm. On the other hand, at an average DBH of 48 cm, *Cupressus lusitanica* is clearfelled for sawn timber at a rotation age 30 years which, can be extended to 40 years. In addition, at an average DBH of 13.1-20 cm, *Eucalyptus saligna* would be clearfelled for building posts, 10-20 cm for beams, 9.1-13 cm for fencing posts, 7.1-9 cm for poles, 5.1-7 cm for rails and less than 5 cm for withies.

Overall, the growth of trees follows a sigmoid curve implying, that as age increases, the probability of survival decreases as some would die and others clearfelled for specific end uses. This underscored the contribution of DBH and basal area, which has a direct derivation from the DBH in influencing survival of trees in an ecosystem. Teck and Hilt (1990) used logistic regression approach and found that the survival rates decreased with increasing competition of basal area for a given DBH and site index. The authors also found out that survival rates increased with increasing DBH for a given basal area. This was consistent with Lynch et al. (1999) who reported similar factors influencing survival of trees.

Karlsson and Norell (2005) also used logistic regression model in fitting DBH, thinning intensity, thinning quotient, number of thinnings among other predictors and found that they significantly influenced the survival of trees. Kariuki (2008) also used logistic and multilevel regression analysis and found that tree survival, growth and thinning response were functions of tree species, size and age. However, Teck and Hilt (1990) warned that logistic model would not be suitable for young stands unless the data were large and in instances where high mortality is likley, the model may tend to overpredict the survival.

This thus calls for other survival models such as Weibull, Lognormal, proportional harzard, log-logistic and exponential that were used in this study.

Consequently, the findings on survival of trees following the use of such survival techniques in analyzing forest data demonstrated the power of survival analysis, which has been predomininantly, used in medical and other industrial research fields. Forest scientist have hitherto focused on developing individual tree mortality models for incorporation in growth and yield models (Woodall et al., 2005). In this study, Weibull model estimated the survival parameters for tree species, sites, thinning regimes, DBH and basal area better than proportional hazard model, exponential model, lognormal and log-logistic models. This was based on –2log-likelihood where the smaller the –2log-likelihood the better the model. Also the shape parameter was more than one showing that the hazard rate raised monotonically with time and likely to decrease monotonically with large sample size resulting to almost a normal distribution pattern of the data. The Weibull shape parameter is also known as a slope, which shows how the Weibull probability plot changes with the parameter. The shape parameters for Log-logistic and lognormal were less than one but greater than zero implying that the hazard rate monotonically rose with time and then falls monotonically.

The use of Kaplan-Meier estimate survivor function and life-table as non-parametric estimates also showed the strength of this technique in survival analysis of forest data. Woodall et al. (2005) in their study used elementary life table estimation procedure as a first attempt to apply survival analysis techniques to large-scale forest inventories. They found out that tree species, DBH classes, site and tree size significantly influenced the tree a mortality, ascenario that corroborated well with findings of the current study. Guinto et al. (1999) in their study reported that tree mortality depended on diameter and fire and hence smaller trees had lower chance of survival. Breguel et al. (2010) also found that tree survival correlated well with diameter and growth heights in all study sites.

4.3. Estimation of Above-ground and Below-ground Carbon Sequestered by Commonly Grown Plantation Species

The data of *Eucalyptus saligna* from Kikuyu District was presented together with that of other commonly grown plantation species at Lari and grouped Kiambu site. The output of regression model of the unbalanced design and linear mixed model when age was fitted as a covariate showed a significant difference ($F_{(4,23)} = 4.80$; Wald statistic = 19.13; $p=0.006$) in the amount of carbon sequestered above-ground and below-ground among the species; *Cupressus lusitanica, Eucalyptus saligna* and *Pinus patula* in Kiambu, Nyeri North and Nyeri South sites (Table 4.4). *Eucalyptus saligna* had the highest amount of carbon (247.9 ± 44.4 MgC ha^{-1}) sequestered above-ground and below-ground in Nyeri South district followed by *Pinus patula* (145.6 ± 44.4 MgC ha^{-1}) in Nyeri North district and lastly *Cupressus lusitanica* (98.4 ± 44.4 MgC ha^{-1}) in Lari district.

Table 4.4: Estimation of above-ground and below-ground carbon sequestered by commonly grown plantation species in Kiambu, Nyeri North and Nyeri South

Site	Tree species	Above-ground and below-ground (ABG) (MgC ha^{-1})
Kiambu (Lari & Kikuyu)	*Cupressus lusitanica*	98.4
	Eucalyptus saligna	79.9
	Pinus patula	87.2
Nyeri North	*Cupressus lusitanica*	62.5
	Eucalyptus saligna	55.5
	Pinus patula	145.6
Nyeri South	*Cupressus lusitanica*	91.8
	Eucalyptus saligna	247.9
	Pinus patula	72.7
s.e.d		44.4

Multiple mean comparisons in the amount of carbon sequestered above-ground and below-ground by *Eucalyptus saligna* adjusted for age as a covariate across sites, showed a significant difference ($p<0.05$) among Kiambu, Nyeri North and Nyeri South. However, there were no significant differences ($p>0.05$) in the amount of carbon sequestered above-ground and below-ground by *Eucalyptus saligna* at Kiambu and Nyeri North. *Cupressus lusitanica* at Kiambu, Nyeri South and Nyeri North and by *Pinus patula* significant differences were not found among the sites.

Comparisons within study sites showed no significant differences ($p>0.05$) among the species in the amount of carbon sequestered above-ground and below-ground for Kiambu site. This was in contrast to Nyeri North and Nyeri South of which there were significant differences ($p<0.05$) among the species within each of the sites. However, no significant differences ($p>0.05$) in the amount of carbon sequestered above-ground and below-ground were found between *Eucalyptus saligna* and *Cupressus lusitanica* in Nyeri North and between *Pinus patula* and *Cupressus lusitanica* in Nyeri South.

The significant difference in the amount of above-ground and below-ground carbon sequestered among species and sites would be explained by the nature of respective tree species. Eucalypts are generally known to grow fast and accumulate more biomass than *Cupressus lusitanica* and *Pinus patula* resulting in high amount of carbon sequestered within the same period. Eucalypts are also known to be self pruning thus demanding less silvicultural management as compared to *Cupressus lusitanica* and *Pinus patula,* which require such operations at specific time of growth to improve on their stem quality and total biomass. Delays of such operational management are more likely to affect the diameter growth, which is a key parameter on tree volume that has direct relationship on the estimation of the total biomass from the stem density. This resonates well with the findings of Paul et al. (2008) who used Full Carbon Accounting Model on *Eucalyptus cladocalyx* and *Corymbia maculata* plantations and found that 37-50% of carbon sequestered in the total tree biomass was in stem, 18-27% in both branches and roots and the reminder in foliage or bark.

Furthermore, it was noted in the foresters' records and personal communications from all forest stations that most plantations of *Cupressus lusitanica* and *Pinus patula* had two to four delays in pruning and thinning as a result of government ban on logging and inadequate labour to support forestry activities in each forest station. It was also observed that some forest stations had started to engage the community in pruning as well as other forest management activities. Waterworth and Richards (2008) reported forest management practices like harvest cycles, thinning, pruning, fertilizer application, control of pests and diseases, burn and slash, significantly affects the amount of carbon sequestration and greenhouse gas emissions. The low stand densities per ha of *Eucalyptus saligna* as observed in the field during data collection across ages and sites as compared with other species could further explain high differences in the amount of carbon sequestered. This is further associated with less competition among trees resulting to more biomass accumulation over time. Horner et al. (2010) reported moderately thinned stands (560 trees ha^{-1}) of *Eucalyptus camaldulensis* produced highest aboveground carbon stock and storage rate of 4.2 MgC per year as compared to unthinned stands at 1.6 MgC per year after 42 years. Glenday (2008) also observed that differences in carbon sequestration among levee, evergreen and transitional forests/woodlands were as a result of higher stem densities and large DBH.

Consequently, the age effect could also explain differences in the amount of carbon sequestered in above and below-ground. The minimum and maximum ages measured for *Eucalyptus saligna*, *Pinus patula* and *Cupressus lusitanica* were 2, 6, 5 years and 33, 32, 24 years, respectively. This might further give evidence as to why *Pinus patula* was second in total amount of carbon sequestered besides being a fast growing tree species compared to *Cupressus lusitanica*. Environmental site effects like types of soil, rainfall and altitude could also explain further differences in the amount of carbon sequestered above-ground and below-ground among species across the sites.

For instance, Nyeri South (Kabage forest station) at 2286 m a.s.l receives mean annual rainfall of 1424 mm as compared to Nyeri North (Naromoru forest station) at 2134 m.a.s.l, which receives mean annual rainfall of 855. Kiambu (Kinale forest stations) at 2591 m.a.s.l receives mean annual rainfall of 1150 to 1276 mm. Similarly, Uplands forest station in Kiambu, at 2415 m.a.s.l receives mean annual rainfall of 1210 to1414 as compared to Muguga forest station on 2067 m.a.s.l, which receives a mean annual rainfall of 1000 mm (Jaetzold et al., 2006). Such rainfall differences would significantly affect the growth rate of tree species resulting to variations in the amount of biomass. Paul et al. (2008) reported that the rate of accumulation of carbon was dependent on annual rainfall.

4.3.1. Estimation of Above-ground and Below-ground Carbon Sequestered by Commonly Grown Plantation Species across Ages and Sites

There were significant differences ($F_{(15, 62)} = 114.31$; $p<0.001$) in the amount of carbon sequestered across ages of *Cupressus lusitanica*, *Pinus patula* and *Eucalyptus saligna* in Kiambu, Nyeri North and Nyeri South sites. This accounted for 70% of the total variations in the amount of carbon sequestered. Similarly, significant differences among sites ($F_{(2, 62)}$ = 34.58; p<0.001) , tree species ($F_{(2, 62)}$ = 30.01; p<0.001) and interaction between sites and species ($F_{(4, 62)}$ = 30.93; p<0.001), sites and age ($F_{(8, 62)}$ = 39.58; p<0.001), tree species and age ($F_{(1, 62)}$ = 97.86; p<0.001) were observed. This accounted for 3, 3, 5, 13 and 4%, of total variation respectively with only 3% remaining unexplained. The amount of carbon sequestered by *Cupressus lusitanica* in Kiambu increased from 10.4 ± 15.98 MgC ha^{-1} at age 5 to 228.2 ± 15.98 MgC ha^{-1} at age 24 while that of *Pinus patula* in Nyeri North increased from 67.5 ± 15.98 MgC ha^{-1} at age 8 to 265.3 ± 15.98 MgC ha^{-1} at age 30 respectively. Equally, the amount of carbon sequestered by *Cupressus lusitanica* at 24 years among sites was significantly higher at Kiambu as compared to Nyeri North and Nyeri South sites. Other tree species had varied amount of carbon sequestered among sites (Table 4.5).

This undercscores the significance of age in biomass accumulation resulting to higher levels of carbon sequestered by different tree species. Other studies on white forests pine like Peichl and Arain, 2007 reported stem wood as a major above ground biomass pool increased with age and variation of canopy biomass at advanced ages. Similar findings were also found by Onyekwelu (2004) on *Gmelina arborea* plantations where stem biomass accounted for 83.6% of the above-ground biomass, which increased from 83.2 t ha^{-1} in 5 years to 394.9 t ha^{-1} in 21 years stand. Similarly, Guo et al (2010) reported biomass carbon stock varied with forest ages, site quality and stand density.

Table 4.5: Estimated above-ground and below-ground carbon sequestered by commonly grown plantation species at across ages and sites

Site	Tree species	Age	Stand density per (ha)	MgC ha^{-1}
Kiambu	*Cupressus lusitanica*	5	960	10.4
		8	800	45.8
		14	590	102.8
		24	532	228.2
	Eucalyptus saligna	2	671	11.3
		5	758	21.1
		7	1238	125.9
		10	250	26.1
		12	150	95.4
	Pinus patula	6	550	65.4
		10	200	60.0
		13	506	161.5
		32	60	95.6
Nyeri North	*Cupressus lusitanica*	5	1100	2.2
		8	1050	63.0
		13	1000	85.1
		24	525	89.1
	Eucalyptus saligna	8	780	70.0
		19	525	73.6
		33	150	105.8
	Pinus patula	8	600	67.5
		17	640	166.5
		30	425	265.3
Nyeri South	*Cupressus lusitanica*	5	1000	8.3
		8	1100	73.3
		14	1000	180.3
		24	235	98.8
	Eucalyptus saligna	7	700	120.3
		8	840	337.0
		14	390	244.3
	Pinus patula	5	999	50.3
		10	750	99.4
		26	200	74.5
s.e.d				21.03

There were significant differences ($F_{(10, 26)}$ = 127.04; p<0.001) in the amount of carbon sequestered by *Cupressus lusitanica* (CL), ***Pinus patula*** (PP) and ***Eucalyptus saligna*** (ES) across ages in Kiambu. Of the total variations in the amount of the above-ground and below-ground carbon sequestered, 88% was accounted by age as compared to 10% by species leaving about 2% unexplained (Figure 4.14). This demonstrated the significance of age in biomass increase at a given site and concurs with other research findings (Peichl and Arain, 2007; Onyekwelu, 2004).

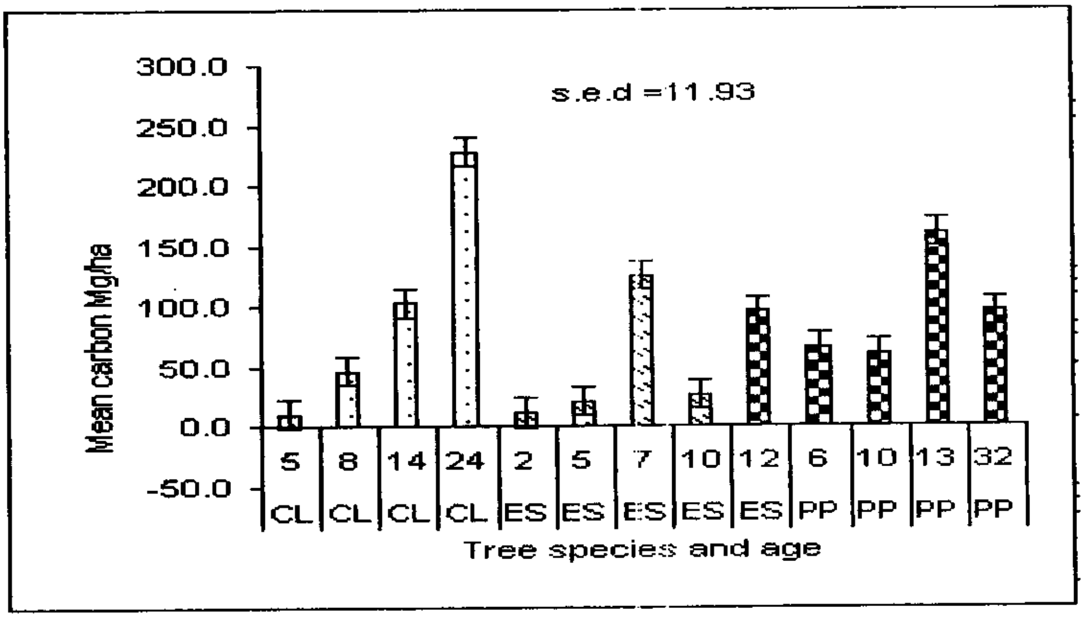

Figure 4.14: Amount of carbon sequestered above-ground and below-ground across species and ages in Kiambu site

Similarly, there were significant differences ($F_{(7, 20)} = 75.07$; $p<0.001$) in the amount of carbon sequestered above-ground and below-ground by *Cupressus lusitanica*, *Pinus patula* and *Eucalyptus saligna* across ages in Nyeri North. Age and tree species accounted for 54% and 44%, respectively of the total variations in the amount of carbon sequestered leaving about 2% unexplained (Figure 4.15).

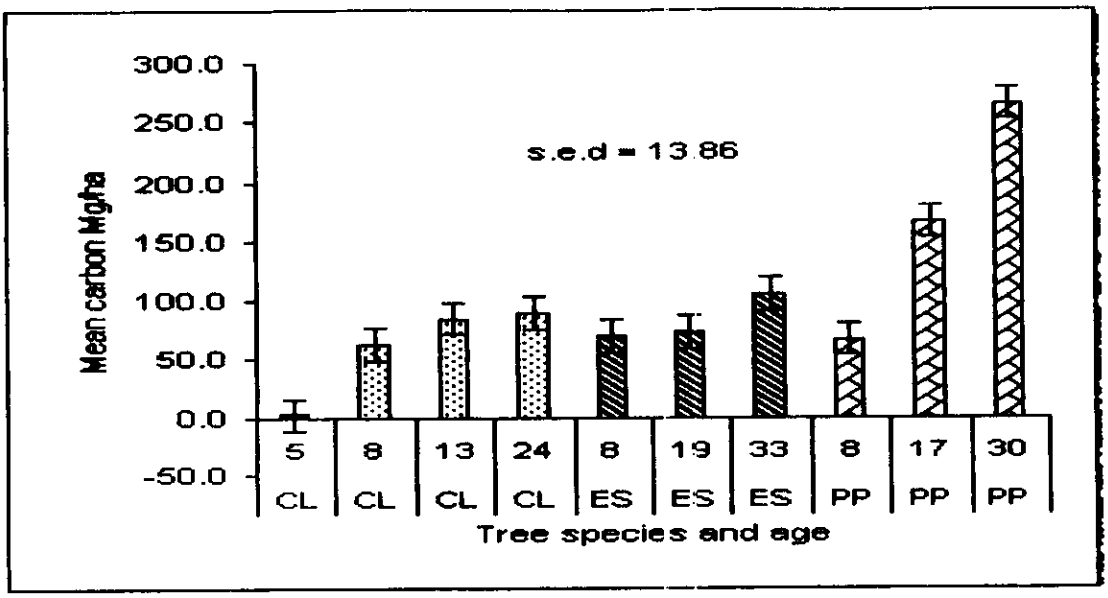

Figure 4.15: Amount of carbon sequestered among species across ages in Nyeri North

There were also significant differences ($F_{(6, 16)} = 28.77$; $p<0.001$) in the amount of carbon sequestered above-ground and below-ground by *Cupressus lusitanica*, *Pinus patula* and *Eucalyptus saligna* across ages in Nyeri South. The total variation in the amount of carbon sequestered was explained by tree species (44%), age (41%) and the interaction effect (12%) leaving 3% unexplained (Figure 4.16).

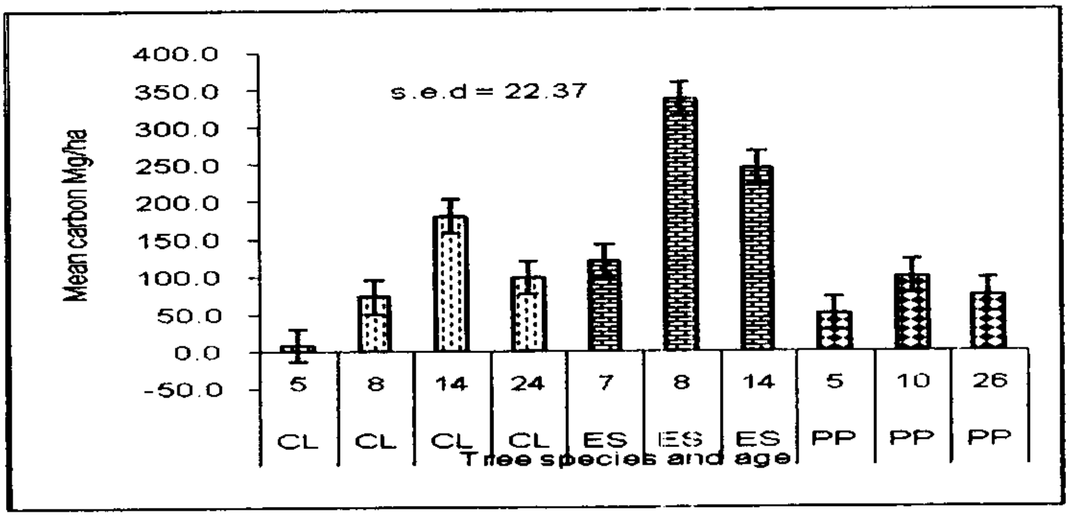

Figure 4.16: Amount of carbon sequestered among species across ages in Nyeri South

On the other hand, the mean amount of carbon sequestered above-ground and below-ground by *Juniperus procera* at age 19, 65 and 70 was 55 ± 28.7 MgC ha^{-1}, 199 ± 28.7 MgC ha^{-1}, 204 ± 28.7MgC ha^{-1}respectively. This varied significantly ($F_{(2,10)}$ = 14.03; p=0.001) with age accounting for 74% of the total variability. Mean comparisons of carbon sequestered between ages showed significant differences ($p<0.05$) in the amount of carbon sequestered above-ground and below-ground between 19 and 65 years, 19 and 70 years. However, no significant differences ($p>0.05$) in the amount of carbon sequestered were observed between 65 and 70 years.

There was a strong significant relationship ($p<0.01$) between the amount of carbon sequestered by *Cupressus lusitanica* and *Pinus patula* at different ages of growth at Kiambu, Nyeri North and Nyeri South (Figures 4.17). However, there were inconsistencies of carbon sequestration for *Eucalyptus saligna* across different ages of growth among the sites (Figure 4.18).

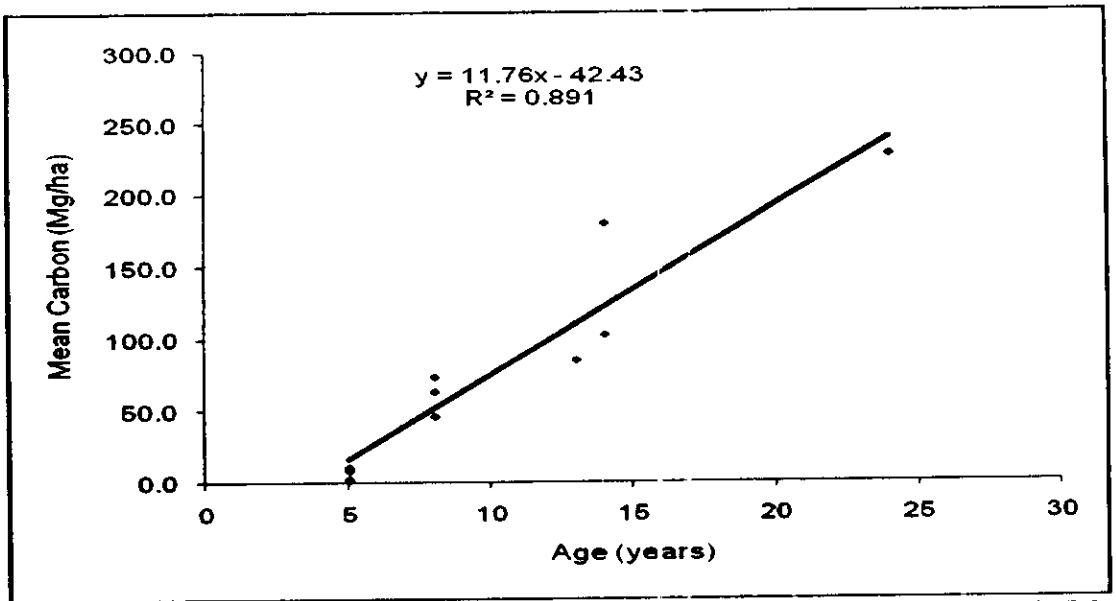

Figure 4.17: Relationship between age and amount of carbon sequestered (Mg/ha) by *Cupressus lusitanica* in Kiambu, Nyeri North and Nyeri South sites

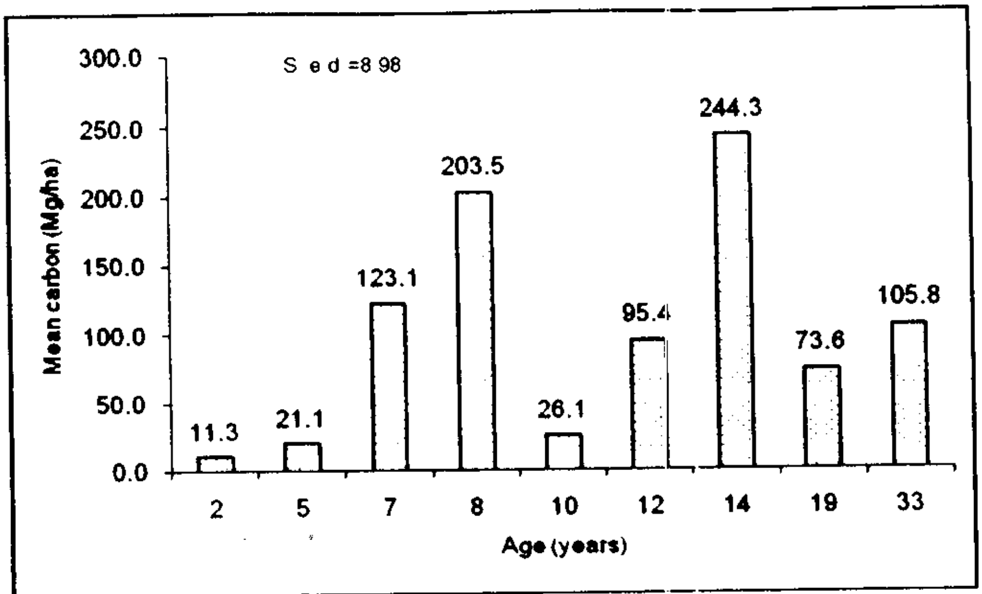

Figure 4.18: Age and mean amount of carbon (Mg/ha) sequestered by *Eucalyptus saligna* in Kiambu, Nyeri North and Nyeri South site

The inconsistence of *Eucalyptus saligna* in the amount of carbon sequestered across ages and sites could be explained by the harvesting cycles of the species. Some stands were at first planting and others were 1st, 2nd, 3rd and 4th coppice regimes. For example, the highest amount of carbon was observed at ages 7, 8, 12 and 14 because there were at first planting while at age 5, 10, 19 and 33 were on the third coppice whilst at age 2 was on first coppice. Even though some stands were on the same coppice, they had different amount of carbon sequestered. This was as a result of site effects that had a significant effect on biomass accumulation other than age. *Eucalyptus saligna* accumulated more biomass at first planting and if left over a long period of time would significantly sequester substantial amount of carbon compared to other tree species.

4.3.2. Relationship among Tree Parameters of Various Species and Carbon Sequestration across ages and sites

There were significant positive correlation ($p<0.001$) among DBH, tree height, crown surface area, crown volume and estimated above-ground and below-ground biomass for *Eucalyptus saligna, Pinus patula* and *Cupressus lusitanica* of different ages at Kiambu, Nyeri North and South. Diameter at breast height was the main parameter that had high significant correlation with tree biomass and crown volume (Table 4.6). The DBH had a near exponential fit with estimated tree biomass best fitted with polynomial function of degree two (Figure 4.19).

Table 4.6: Correlation among growth parameters of *Eucalyptus saligna, Pinus patula* and *Cupresus lusitanica* in Kiambu, Nyeri North and Nyeri South sites

Tree parameters	DBH (cm)	Height (m)	Crown surface area (m^2)	Crown volume (m^3)
Diameter at breast height (cm)	-			
Height (m)	0.79	-		
Crown surface area (m^2)	0.47	0.32	-	
Crown volume (m^3)	0.76	0.59	0.36	-
Total biomass (kg)	0.87	0.72	0.3	0.83

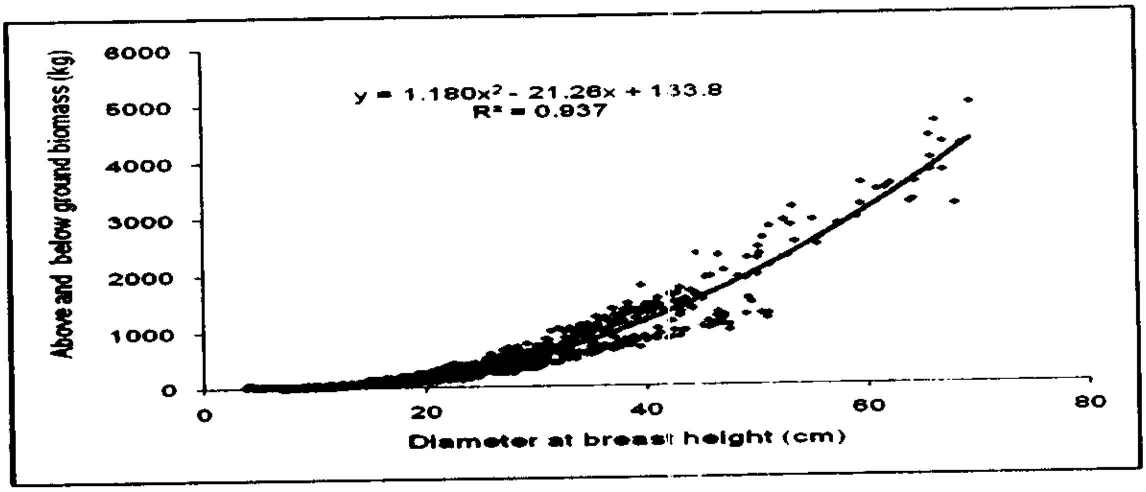

Figure 4.19: Relationship between DBH and tree biomass for commonly grown plantation species at Kiambu, Nyeri North and Nyeri South

Similarly, there were high significant ($p<0.001$) positive correlations among various tree parameters across ages for *Juniperus procera* at Nyeri North. DBH and height were the main parameters that significantly contributed to total estimated biomass followed by crown surface area and crown volume (Table 4.7). This was further demonstrated when the best fit line tended to be more exponential in polynomial equation of degree two (Figure 4.20).

Table 4.7: Correlation among tree parameters of *Juniperus procera* in Nyeri North

Tree parameters	DBH (cm)	Height (m)	Crown surface area (m^2)	Crown volume (m^3)
Diameter at breast height (cm)	-			
Height (m)	0.89	-		
Crown surface area (m^2)	0.73	0.59	-	
Crown volume (m^3)	0.74	0.59	0.36	-
Total biomass (kg)	0.98	0.85	0.74	0.73

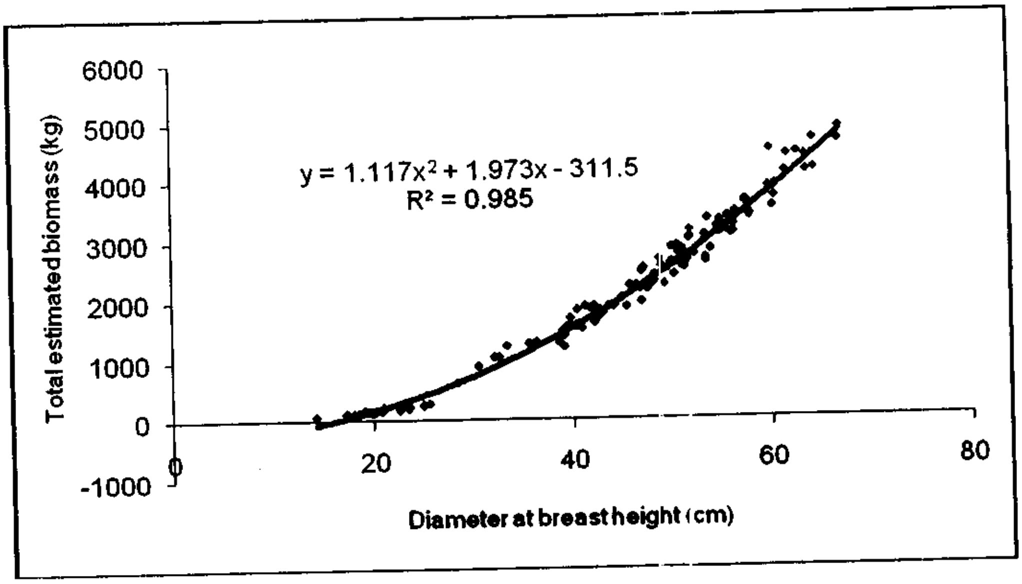

Figure 4.20: Relationship between DBH and tree biomass for *Juniperus procera* for different ages at Nyeri North

In addition, there were significant differences in crown surface area ($F_{(4, 1087)}$ = 132.14; $p<0.001$) and crown volume ($F_{(4, 1088)}$ = 10.63; $p<0.001$) among the tree species between and within sites. In each of the tree species within study sites, an increase of the crown surface area resulted to an increase of crown volume leading to an increase on the amount of carbon sequestration. This also varied with age among the sites and tree species as well as tree stand density (Table 4.8).

Table 4.8: Estimated stand density, area, mean crown area, mean crown volume and carbon sequestered

Site	Tree species	Age	Density/ha	Area (ha)	DBH (cm)	Crown area (m^2)	crown volume (m^3)	$MgCha^{-1}$
Kiambu	*C. lusitanica*	5	960	7.8	11.2	31.8	22.3	10.4
		8	800	13.8	19.3	65.1	63.8	45.8
		14	590	10.3	28.2	95.0	110.5	102.8
		24	532	2.5	38.9	162.6	268.6	228.2
	E. saligna	2	671	3.54	5.9	29.4	14.6	11.3
		5	758	3.56	9.3	33.8	18.9	21.1
		7	1238	5.2	18.5	59.3	44.4	125.9
		10	250	2	20.2	67.3	64.4	26.1
		12	150	9.8	38.0	266.7	464.4	95.4
	P. patula	6	550	2.3	19.3	36.0	23.4	65.4
		10	200	4.2	28.6	63.0	53.8	60.0
		13	506	20.5	28.9	84.3	84.4	161.5
		32	60	11.1	59.0	450.4	963.0	95.6
Nyeri North	*C. lusitanica*	5	1100	5	6.6	102.4	17.1	2.2
		8	1050	5	20.1	319.0	53.2	63.0
		13	1000	19.4	21.9	515.9	86.0	85.1
		24	525	10.1	27.4	769.0	128.2	89.1
	E. saligna	8	780	5	19.1	44.0	30.6	70.0
		19	525	25	23.3	124.3	157.1	73.6
		33	150	3.6	42.7	271.2	485.3	105.8
	P. patula	8	600	5	18.6	471.1	78.5	67.5
		17	640	5	26.5	794.6	132.4	166.5
		30	425	5.4	36.3	1555.0	259.2	265.3
Nyeri South	*C. lusitanica*	5	1000	5	9.8	137.1	22.9	8.3
		8	1100	3.5	19.6	492.4	82.1	73.3
		14	1000	16.3	27.9	886.7	147.8	180.3
		24	235	30.4	40.1	1801.1	300.2	98.8
	E. saligna	7	700	1.5	22.5	264.4	44.1	120.3
		8	840	4.5	30.7	177.9	29.7	337.0
		14	390	4	36.5	850.8	180.9	244.3
	P. patula	5	999	4.4	15.7	185.0	30.8	50.3
		10	750	16	22.9	867.1	144.5	99.4
		26	200	12	35.6	1459.7	243.3	74.5
		s.e.d			2.56	37.27	18.49	21.03

Also, there were significant differences in the crown surface area ($F_{(2,137)} = 70.58$; $p<0.001$) and crown volume ($F_{(2,137)} = 70.58$; $p<0.001$) across ages of *Juniperus procera* in Nyeri North. Crown surface area and crown volume increased with age and this corresponded to the increase in the amount of carbon sequestered. Mean comparisons on crown surface area and crown volume showed significant differences ($p<0.05$) between 19, 65 and 70 years (Table 4.9).

Table 4.9: Mean amount of carbon sequestered by *Juniperus procera* and associated tree parameteres in Nyeri North district

Age	Stand density per (ha)	Area sampled (ha)	Mean DBH (cm)	Mean crown surface area (m^2)	Mean crown volume (m^3)	Mean carbon $Mgha^{-1}$
19	587	4	20.6	224	37.3	55
65	175	30.5	47.1	565	94.2	199
70	150	3.4	50.3	1287	214.5	204
s.e.d			1.594	97.2	19.53	28.7

The positive correlation between DBH, crown surface area and crown volume implies that as the DBH increases, crown surface area over crown volume ratio increases as well. This leads to more biomass due to photosynthesis process and more carbon is sequestratered at different stages of tree growth. The variations in crown surface area and crown volume among species could be explained by the differences in age across species and sites, stand density and some silvicultural management operations such as pruning and thinning. Essentially, pruning of the lowest branches regulates branching habit and crown base. Other studies have shown that tree height, crown height and crown diameter growth rates were highest in the young trees and decrease with tree age. The rate of decrease however, differs among species and growth parameters. Relatively larger crown diameter growth compared to tree height and crown height might suggest that older trees may have reached near asymptotic tree height growth levels while still growing laterally in tree crowns (Stoffberg et al., 2008).

4.3.3. Estimation of Soil Carbon Sequestration among Commonly Grown Plantation Species

There were significant differences ($F_{(4,271)}$ =8.08; $p<0.001$) in the amount of soil carbon sequestered by commonly grown plantation species adjusted for age in Kiambu, Nyeri South and Nyeri North sites. *Pinus patula* had the highest amount of soil carbon (191.1 ± 12.55 MgC ha^{-1}) followed by *Cupressus lusitanica* (169.3 ± 12.55 MgC ha^{-1}) in Kiambu, Lari district. *Eucalyptus saligna* had the least amount of soil carbon in Kiambu and Nyeri South except in Nyeri North (Table 4.10).

Table 4.10: Estimation of soil carbon sequestered by commonly grown plantation species in Kiambu, Nyei North and Nyeri South sites

Site	Tree species	Mean soil carbon (MgC ha^{-1})
Kiambu (Lari & Kikuyu)	*Cupressus lusitanica*	169.3
	Eucalyptus saligna	109.7
	Pinus patula	191.1
Nyeri North	*Cupressus lusitanica*	70.1
	Eucalyptus saligna	83.2
	Pinus patula	70.2
Nyeri South	*Cupressus lusitanica*	104.4
	Eucalyptus saligna	62.3
	Pinus patula	135.4
s.e.d		12.55

Moreover, mean comparisons in the amount of soil carbon sequestered by the species among sites showed a significant difference ($p<0.05$) in the quantity of carbon sequestered by *Cupressus lusitanica* and *Pinus patula* in Kiambu, Nyeri North and Nyeri South.

Similarly, there were significant differences ($p<0.05$) in the amount of soil carbon by *Eucalyptus saligna* among the sites but no significant differences ($p>0.05$) were obtained between Nyeri North and Nyeri South. *Eucalyptus saligna* had generally lower amount of soil carbon sequestered among the sites as compared to *Pinus patula* and *Cupressus lusitanica* except in Nyeri North. Subsequently, mean comparisons of soil carbon sequestered by commonly grown plantation species within each site, significantly differed ($p<0.05$) among the species in Kiambu and Nyeri South. However, no significant differences ($p>0.05$) were observed among species in Nyeri North.

The differences of soil carbon sequestered by *Pinus patula* as compared to other two species could be associated with a lot of litter fall that was found on the plots. The lignin content of *Pinus patula* leaves is low followed by *Cupressus lusitanica* and highest in eucalyptus leaves affecting the rate of decomposition. This was further evidenced by analyzed samples of litter collected where the findings showed highest amount of carbon in litter of *Pinus patula* (46%) as compared to *Cupressus lusitanica* (41%) and *Eucalyptus saligna* (43%). This would be associated with moisture content in the soil that enhanced micro-organisms decomposition of such litter fall. For instance, the dry part of Nyeri North had the least soil carbon as compared to other sites, which might be attributed to unfavourable environmental conditions for microbial activities in carbon fixation and mineralization of soil nutrients.

This corresponds with the findings of Lemma et al. (2007) who reported that differences on soil organic carbon among exotic plantations (*Cupressus lusitanica, Eucalyptus grandis* and *Pinus patula*). *Cupressus lusitanica* had highest amount of soil C followed with *Pinus patula* and least with *Eucalyptus grandis* due to litter quality input and rate of decomposition. Similar arguments have been advanced by Johnson (2010), Eaton and Lawrence (2009), Schulp et al. (2008), Stevens and Wasemael (2008), Amichev et al. (2008), Liski et al. (2005) and Liski et al. (2002) following simulation in CENTURY and YASSO models. The authors indicated that accumulation of soil organic pools were driven by changes in litter inputs, rate of decomposition, management regimes, root activity, stand growth rates among others.

4.3.4. Estimation of %C and Selected Soil Elements across Depths and Common Plantation Species

The overall %C in Kiambu, Nyeri North and Nyeri South were 3.48, 2 and 2.6% with standard error difference of 0.153, respectively. This varied significantly ($F_{(2, 271)}$ = 52.88; p<0.001). Also significant differences ($F_{(2, 271)}$ = 25.51; p<0.001) were obtained among the tree species with a standard error difference of 0.151, at an average of 2.82, 2.11 and 3.09% SOC for *Cupressus lusitanica*, *Eucalyptus saligna* and *Pinus patula*, respectively.

The variation in the amount of soil carbon under different tree species indicated the potential of different trees species to sequester carbon based on the amount of litter fall in a given period of time and rate of decomposition. *Pinus patula* plantations across the years and among sites had highest amount of carbon. This suggested high amount of litterfall and high rate of decomposition enabling the soil to improve soil organic matter and high carbon sink. This was similar to *Cupressus lusitanica*, which had high amount of carbon as compared to *Eucalyptus saligna*. Palviainen et al. (2010) in their study reported Scots pine had higher amount of C on decomposing wood and bark as compared to spruce and birch in Finland. Plantation managements like pruning, thinning and clear felling could also bring the variations on the amount of C as leftovers would decompose differently depending on the site characteristics and on the litter quality of the material.

In addition, regardless of study sites and species, and with the exception of *Junierus procera*, the average soil carbon at 0-20, 20-50 and 50-80 cm were 3.59, 2.48 and 2.01%, respectively. This varied significantly ($F_{(2, 271)} = 65.98$; $p<0.001$) with a standard error difference of 0.149. Overall, there were significant differences ($F_{(8, 271)} = 3.91$; $p<0.001$) in the amount of soil carbon across study sites and soil depths for commonly grown plantation tree species (Table 4.11).

Table 4.11: Mean soil carbon sequestered (MgC ha^{1}) at different soil depths by commonly grown plantation species in Kiambu, Nyeri Noth and Nyeri South sites

		Mean soil carbon sequestered (MgC ha^{-1}) at different soil depths		
Site	Tree species	0-20 cm	20-50 cm	50-80 cm
Kiambu	*Cupressus lusitanica*	84.8	180.2	245.4
	Eucalyptus saligna	69.1	125	136.4
	Pinus patula	96.9	193.8	285.4
Nyeri North	*Cupressus lusitanica*	60.2	74.7	75.9
	Eucalyptus saligna	53.3	79.2	117.9
	Pinus patula	57	100.3	54
	Juniperus procera	29.4	48.1	74.4
Nyeri South	*Cupressus lusitanica*	78.3	91.5	143.9
	Eucalyptus saligna	29.4	56	102.4
	Pinus patula	56.1	141.5	211
	s.e.d		21.55 (14.22)	

* In parenthesis is the s.e.d for *Juniperus procera*

The significant variations of the %C across soil depths, decreased with, increasing soil depth. This implied that more C is concentrated in the top layer of the soil where there is high organic matter due to high litter fall. These findings were consistent with other studies (Dowell et al., 2009; Weishampel et al., 2009; Eaton and Lawrence, 2009; Sierra et al., 2007; Paul et al., 2002; Versterdal et al., 2002) who reported C storage and concentration increased in the upper layers of the soil and decreased with soil depths among hardwood and softwoods tree species. This was also found to vary with age of tree where young forest stands had higher soil carbon as compared to middle aged. Overall, quantification of soil carbon among different soil depths showed an increasing trend due to multiplier of soil depths and bulk density. The bulk density increased with increase of soil depth in most of the commonly grown plantation species. Kaumbutho and Simalenga (1999) reported bulk density normally tends to increase with soil depths due to low organic matter, poor structure, low moisture and roots penetration as well as pressure exerted by overlying layers.

Furthermore, there were significant differences ($F_{(2, 224)}$ = 79.22; $p<0.001$) in the levels of soil pH among the sites. Kiambu soils were slightly acidic (6.11) as compared to Nyeri North (5.14) and Nyeri South (5.15), which were strongly acidic with a standard error difference of 0.093 (Table 4.12). However, there were no significant interaction effect ($F_{(8, 224)}$ = 0.98; p=0.455) in soil pH between sites, tree species and soil depths (Table 4.12). Overall, the soil pH in all the study areas was mainly acidic. The levels of acidity varied among species, between and within sites from very strongly acidic to very slightly acidic (Table 4.12). *Cupressus lusitanica* exhibited almost same soil pH at Kiambu, Nyeri North and Nyeri South similar to *Eucalyptus saligna*. However, *Pinus patula*, which is known to grow well in acidic conditions, had low amount of acidity in the soil in Kiambu as compared to Nyeri North and Nyeri South districts. This may be explained by incidences of fire outbreak resulting to increase of ashthat is rich in exchangeable bases, which leads to the reduction of soil acidity. Antibus and Linkins III (1992) reported the effect of lime in shifting the ectomycorrhizas in red pine plantations. Ectomycorrhizas are significant component of the forest floor in red pine plantations and produce high levels of surface acid phosphate activity. Therefore induced lime has the potential to alter the mineralization of organic P and P nutrition of the host.

Table 4.12: Mean estimates of %C and major soil elements across soil depths and commonly grown plantation species at Kiambu, Nyeri North and Nyeri South sites

Site	Tree species	Soil depth (cm)	pH	% C	% N	P_ppm	K_ppm	Bulk density (g/cm³)
Kiambu	*C. lusitanica*	0-20	6.08	4.52	0.74	7.29	407.4	0.94
		20-50	6.23	3.67	0.62	1.68	406.5	0.97
		50-80	6.14	3.12	0.49	3.02	435.7	0.98
	E.saligna	0-20	5.87	3.4	0.59	3.23	605.5	1.05
		20-50	5.91	2.18	0.45	2.39	597.7	1.16
		50-80	5.88	1.48	0.31	0.51	563.9	1.14
	P. patula	0-20	6.27	5.12	0.83	8.90	397.4	0.94
		20-50	6.30	3.81	0.60	4.42	317.4	1.03
		50-80	6.28	3.49	0.50	4.08	313.9	1.02
Nyeri North	*C. lusitanica*	0-20	5.59	3.11	0.58	18.90	326.2	0.99
		20-50	5.42	1.52	0.41	9.18	376.0	1.00
		50-80	5.42	0.91	0.27	8.27	363.4	1.02
	E. saligna	0-20	4.51	2.93	0.62	14.04	214.7	0.90
		20-50	5.00	2.31	0.36	9.16	167.6	0.96
		50-80	5.02	1.77	0.39	7.94	137.1	0.92
	P. patula	0-20	4.85	2.92	0.42	9.73	288.3	0.96
		20-50	4.85	1.98	0.34	8.06	323.0	1.04
		50-80	5.34	0.67	0.24	4.79	265.3	1.06
	J. procera	0-20	6.07	1.46	0.52	7.85	457.6	1.04
		20-50	5.74	0.94	0.45	8.41	346.4	1.03
		50-80	5.63	0.93	0.28	11.04	317.2	1.00
Nyeri South	*C. lusitanica*	0-20	5.35	4.38	0.57	6.65	544.9	0.89
		20-50	5.21	2.05	0.44	7.48	557.5	0.89
		50-80	5.03	2.08	0.43	5.75	475.5	0.86
	E. saligna	0-20	5.74	1.76	0.43	3.10	357.0	0.85
		20-50	5.15	1.22	0.35	4.76	308.0	0.91
		50-80	5.03	1.38	0.74	7.10	303.2	0.91
	P. patula	0-20	4.89	3.44	0.75	5.58	254.1	0.83
		20-50	4.98	3.28	0.65	4.70	254.7	0.88
		50-80	4.93	3.30	0.49	5.22	262.9	0.83
	s.e.d		0.274	0.456	0.098	2.46	93.79	0.058

On the other hand, the interaction effects between sites and species were significant ($F_{(4, 271)} = 12.62$; $p<0.001$) with respect to %C. Also there were significant interaction effect in %C ($F_{(8, 271)} = 2.08$; p=0.037) between environmental sites, tree species and soil depths (Table 4.12). This was however different for *Juniperus procera* whose interaction effect was only between age and depth albeit non significant ($F_{(4, 48)} = 0.23$; p=0.918).

Furthermore, there were significant interaction effect ($F_{(8, 221)}= 2.00$; p=0.047) in the amount of soil nitrogen between sites, tree species and soil depths (Table 4.12). This was however different for *Juniperus procera* whose significant interaction effect was only between age and depth ($F_{(4, 24)} = 4.86$; p=0.005). Similarly, the amount of soil nitrogen differed significantly ($F_{(2, 221)}= 13.66$; p<0.001) among sites with Kiambu having the highest at 0.57% followed by Nyeri South (0.54%) and Nyeri North (0.41%) with a standard error difference of 0.470. Equally, there were significant differences ($F_{(2, 221)}= 3.52$; p=0.031) in the amount of nitrogen among the tree species with *Pinus patula* having highest amount (0.55%) followed with *Cupressus lusitanica* (0.52%) and *Eucalyptus saligna* (0.47%) with a standard difference of 0.033.

The significant amount of N in *Pinus patula* as compared to *Cupressus lusitanica* and *Eucalyptus saligna* may be explained by effect of forest floor leading to large differences in turnover rates of litterfall and the amount of soil organic matter accumulated in the soils. For instance, the rate at which forest litter decomposes forms an important aspect of assessing past, current and future carbon and N responses of forests under changing climate conditions (Zhang et al., 2008). N comes mainly from three sources, namely; uptake from the soil, foliar uptake of atmospheric deposition and internal reallocation from one organ to another (Wamelink et al., 2009). The authors reported increased N deposition causes an increased rate of soil organic matter. Also in the study by Palviainen et al. (2010) on carbon and nitrogen release from decomposing Scots pine, Norway Spruce and silver birch stumps found that N was released considerably more slowly from the stumps than from the stems and branches. However, Foster and Morrison (2002) reported forests respond to increased N availability by increase in stand leaf area and net photosynthesis and increased stem growth.

Consequently, amount of nitrogen varied significantly ($F_{(2, 221)}$= 22.80; p<0.001) across soil depths. The highest (0.63%) was observed at 0-20 cm followed by 20-50 cm (0.48%) and 50-80 cm (0.43%) with a standard error difference of 0.032. There were also significant differences on the interaction effect ($F_{(4, 221)}$= 6.05; p<0.001) of N between environmental sites and tree species, sites and soil depths (Table 4.12). The high %N in the upper soil layer (0-20 cm) could be explained by litterfall among tree species. This concurs with Vesterdal et al. (2008) who reported mineral soil N status among tree species were strongly related to literfall N status and was significantly higher in 0-30 cm of soil depth.

In contrast, there were no significant interaction effect ($F_{(8, 219)}$= 0.86; p= 0.552) between environmental sites, tree species and soil depths in the amount of phosphorous (Table 4.12). This was however different for *Juniperus procera* whose interaction effect was only between age and depth albeit non significant ($F_{(4, 24)}$ = 0.08; p=0.989). However, there were significant differences ($F_{(2, 219)}$= 35.29; p<0.001) across sites in decreasing order; Nyeri North (10.22 ppm), Nyeri South (5.68 ppm) and Kiambu (3.97 ppm) with a standard error difference of 0.829. Similary, P significantly varied ($F_{(2, 219)}$= 3.50; p=0.032) among the species with *Cupressus lusitanica* having the highest P (7.16 ppm) followed by *Pinus patula* (6.13) and *Eucalyptus saligna* (5.34 ppm) with a standard error difference of 0.819. There were however, significant differences ($F_{(2, 219)}$= 12.83; p<0.001) in amount of P across soil depths, which reduced with increase in depth, 0-20 cm (8.51 ppm), 20-50 cm (5.40 ppm) and 50-80 cm (4.90 ppm) with a standard error difference of 0.800.

Significant differences ($F_{(2, 259)}$= 13.39; p<0.001) with respect to K (ppm) among sites were observed with Kiambu having the highest (447.4 ppm) followed by Nyeri South (385.8 ppm) and Nyeri North (281.6 ppm) with a standard error difference of 31.44. Equally, significant differences ($F_{(2, 259)}$= 10.01; p<0.001) in K were found in area under *Cupressus lusitanica* (412.3 ppm), *Eucalyptus saligna* (368.8 ppm) and *Pinus patula* (302. 8 ppm) with standard error difference of 31.24. In contrast, no significant differences ($F_{(2, 259)}$= 0.57; p=568) of K were found across soil depths. On the other hand bulk density significantly differed ($F_{(2, 271)}$= 35.71; p<0.001) across sites with Kiambu having the highest (1.01 g/cm^3) followed by Nyeri North (0.98 g/cm^3) and Nyeri South (0.87 g/cm^3) with a standard error difference of 0.019. Bulk density also significantly differed across soil depths, 0-20 cm (0.94 g/cm^3), 20-50 cm (0.99 g/cm^3) and 50-80 cm (0.98 g/cm^3) with a standard error of 0.019.

In addition, regardless of the sites, tree species and soil depths, there were positive significant correlations (ρ=0.26; p<0.001) between soil pH and % carbon and potassium. Also there were negative significant correlation (ρ=-0.17; p=0.0067) between soil pH and phosphorous. Similarly, there were high positive significant correlations (ρ=0.61; p<0.001) between %C and %N. However, there were no significant correlations (ρ=0.08; p=0.245) between soil pH and N, C and P (ρ=0.05; p=0.411), N and P (ρ=0.11; p=0.085), K and N (ρ=-0.06; p=0.372) as well as P and K (ρ=-0.1; p=0.120). Correlation among soil elements under *Juniperus procera* showed a positive correlation (ρ=0.60; p<0.001) between C and soil pH. There was also positive correlation between K and soil pH (ρ=0.55; p<0.001) and C and K (ρ=0.67; p<0.001) but negative significant correlation (ρ=-0.35; p=0.052) between P and K. There were no significant correlations (ρ=0.21; p=0.260) between C and N; C and P (ρ=-0.09; p=0.635), N and P (ρ=-0.22; p=0.226) as well as N and K (ρ=0.32; p=0.07)

The soil parameters findings concurred with soil classifications within Central Kenya, which are known to be largely nitisols. These are characterized by pH <5.5 due to leaching of soluble bases and high clay content >35% (Gachene & Kimaru, 2003). Therefore the correlation of soil pH with P indicated the levels at which this elements would be available to plants to support the plant growth and accumulation of biomass for enhancement of carbon sequestration. Both sites, C, N, P and K were high. This indicated high amount of precipitation and soil mobilization as influenced by different trees species, thus availability of major nutrients for tree uptake/forest productivity. Soil pH usually has a big influence on the uptake of minerals (Gachene & Kimaru, 2003). Thus soils with high acidity do not provide good conditions for the microorganisms that are very valuable with litter decomposition and other dead wood for nutrient fixation and carbon sinks.

The positive relationship between C and N showed available N could also be used as an indicator of soil carbon sequestration. This is because deposition of N on forests may increase C by increased growth and accumulation of soil organic matter through increased litter production or N-enriched litter. This leads to reduced long term decomposition rates of organic matter. Other studies have shown such relationship between C and N and offered appropriate explanations including large differences in turnover rates of foliar litterfall, forest management, different tree species among others (de Varies et al., 2009; Wamelink et al., 2009; Hopmans et al., 2005; Pelster et al., 2009; Mol Dijkstra et al., 2009). In general, this showed that soils in various plantation forests in Central Kenya had a huge potential of soil carbon stocks for mitigation of climate change. For instance, Hopmans and Elms (2009) found levels of soil C and N declined during the second rotation of *Pinus radiata* and ratios of C/N in the surface soil increased from 27 to 30 in lower quality sites and from 24 to 26 in higher quality sites.

4.3.5. Estimation of Carbon dioxide Equivalent from Commonly Grown Plantation Species across Ages and Sites

The amount of carbon dioxide equivalent (CO_2e) removed from the atmosphere by commonly grown plantation species below-ground, above-ground and soil significantly ($F_{(4,86)} = 6.03$; $p<0.001$) varied across ages and sites (Table 4.13). Age as a covariate was highly significant ($F_{(1,86)} = 17.55$; $p<0.001$) in the amount of CO_2e among tree species (Table 4.13). Similarly, amount of CO_2e significantly differed ($F_{(2,86)} = 14.73$; $p<0.001$) among the sites with Kiambu having highest amount followed by Nyeri South and Nyeri North (Figure 4.21). There were also significant interaction effect between age and sites for CO_2e among species above-ground and below-ground as well in soil (Table 4.13). There were also significant differences in the amount of CO_2e ($F_{(2, 9)} = 12.42$; $p = 0.003$) above-ground and below-ground across ages of *Juniperus procera*. However, no significant differences ($F_{(2, 9)} = 2.65$; $p = 0.125$) were found in the amount of CO_2e in soil (Table 4.14).

Table 4.13: Estimation of CO_2e AGB and soil across tree species and sites at different ages

Site	Tree species	Stand density	Age in years	CO_2e t ha^{-1} (AGB)	CO_2e t ha^{-1} (soil)	CO_2e t ha^{-1} (total)
Kiambu	C. lusitanica	960	5	38.1	459.3	497.3
		800	8	168.0	560.5	728.5
		590	14	377.1	750.7	1,127.8
		532	24	836.7	793.5	1,630.2
	E. saligna	671	2	41.6	479.4	521.1
		758	5	77.2	376.5	453.8
		1238	7	461.5	419.1	880.6
		250	10	95.6	405.8	501.4
		150	12	349.7	484.0	833.7
	Pinus patula	550	6	239.9	574.1	814.0
		200	10	220.0	644.7	864.7
		506	13	592.3	946.6	1,538.9
		60	32	350.4	693.5	2,247.0
Nyeri North	*C.lusitanica*	1100	5	7.1	233.0	240.0
		1050	8	231.1	342.1	573.2
		1000	13	312.1	203.2	515.2
		525	24	326.7	239.0	565.6
	E. saligna	780	8	256.7	315.0	571.7
		525	19	269.9	307.6	577.5
		150	33	387.9	271.5	659.3
	P. patula	600	8	247.7	299.3	547.0
		640	17	610.5	177.3	787.8
		425	30	972.8	170.2	1,143.0
Nyeri South	*C. lusitanica*	1000	5	29.9	418.4	448.3
		1100	8	268.8	365.7	634.4
		1000	14	661.1	360.8	1,021.9
		235	24	362.4	421.3	783.7
	E. saligna	700	7	441.2	183.1	624.3
		840	8	1,203.0	216.8	1,419.8
		390	14	895.7	290.6	1,186.2
	Pinus patula	999	5	184.4	363.6	548.1
		750	10	364.6	731.5	1,096.1
		200	26	273.0	297.7	570.7
		s.e.d		83.86	63.97	118.4

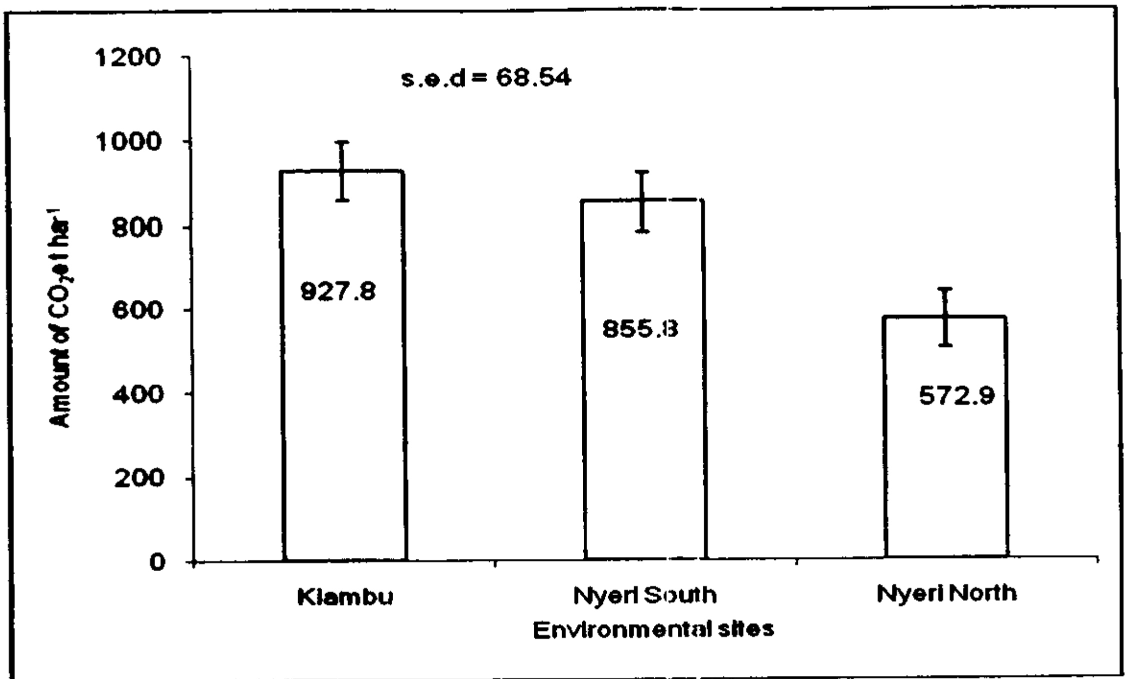

Figure 4.21: Amount of CO2e at Kiambu , Nyeri South and Nyeri North among commonly grown plantation species adjusted for age

Table 4.14: Estimation amount of CO_2e above-ground, below-ground (AGB) and soil across ages of *Juniperus procera* in Nyeri North

Age	Stand density	CO_2e t ha^{-1} (AGB)	CO_2e t ha^{-1} (soil)	CO_2e t ha^{-1} (total)
19	587	199.9	95.6	295.4
65	175	730.3	93.4	823.7
70	150	738.0	258.7	996.7
	s.e.d	111.3	97.9	152.1

The differentials obtained on CO_2e among the commonly grown plantation tree species could be attributed to their differences in architectural and genetic composition for biomass accumulation in trunks, branches, foliage, roots and in soils as influenced by site. For instance, *Pinus patula*, *Eucalyptus saligna* and *Cupressus lusitanica* were found to grow faster in Kiambu and Nyeri South as compared to Nyeri North, which is on the leeward side of Mt. Kenya and receiving limited amount of rainfall. Also, the significant variation of CO_2e between age 19 and 65 for *Juniperus procera* may be explained by the age difference in response to growth. This species is known to grow slowly accumulating significant amount of biomass over time as compared to faster growing exotic species in this study.

Stable factors such as soil texture, slope aspect and fluctuates levels do not change appreciably during the life of a tree, but transient factors such as climate and competition among organisms change erratically during the life cycle of a tree (Husch et al., 2003). This implied that in order to continue promoting the role of trees in the mitigation of climate change through carbon sequestration, it would be preferable to plant such fast growing tree species in specific sites to enhance carbon sinks and within the wood. This would counter carbon emissions from deforestation, burning of fossils, changes in land use and other human activities, thus resulting to promotion of carbon credits within and between nations.

Stand density, site quality, management schedules and age had a direct effect in the total biomass variation resulting to variation on the amount of CO_2e among *Pinus patula*, *Eucalyptus saligna*, *Cupressus lusitanica* and *Juniperus procera*. For instance, Liu et al. (2002) reported young age (36.2) years of Ontario's boreal forests indicated a great potential for C sequestration and storage. The less stand density from the expected standard stands, trees would have less competition for nutrients and light hence higher photosynthetic process resulting in more biomass accumulation and removal of carbon dioxide from the atmosphere. It is during the photosynthesis process trees combine carbon dioxide with light and energy to form sugar which is converted into complex compounds that increases dry solid plant substance for continued growth to final maturity. When the supply of carbon dioxide is cut off or reduced, the complex plant cell structure cannot utilize the sun's energy fully and growth or development. Studies have shown that plants would stop growing when CO_2 decreases below 150 ppm and even at 200 ppm. It is also known that young trees grow faster and therefore their ability to sequester carbonn is high, as they require more nutrients for their growth.

Soils have also been found to be good carbon sinks. The ability of a tree to sequester carbon is also influenced by soil nutrients that support tree growth. In return, the decomposition of litter fall, dead roots, among others, are converted into temporal and stable humus stabilizing soil carbon. Therefore, estimation of CO_2e from soils is very valuable as a measure of ameliorating climate change.

4.4. Evaluation of Sell of Carbon Credits and Wood of Commonly Grown Plantation Species

The major output of this objective was to determine the amount of income that tree investors were likely to get from the sale of carbon sequestered by commonly grown plantation tree species in comparison with the sale of wood. These were considered as incentives for tree farming in improving forest cover and mitigation of climate change. Carbon trading is essentially known as administrative approach to control pollution by providing economic incentives for reductions in the emissions of greenhouse gases. Carbon pricing was estimated at minimum of US \$10/tCO_2 (Ksh.800/tCO_2) and a maximum of US \$30/tCO_2 (Ksh.2400/tCO_2) with an average of US \$20/ tCO_2 (Ksh. 1600/tCO_2) based on the literature (Stern, 2006). Unit prices of different wood products/wood volume per m^3 were obtained from plantation and inventory sections of Kenya Forestry Research Institute and Kenya Forest Service respectively.

4.4.1. Estimation of Income from Sell of Carbon Credits and Wood of Commonly Grown Plantation Species

The analysis of data was based on the minimum DBH cm for clearfelling and thinning as per the end product of each commonly grown plantation species. This was compared with expected carbon income at an average of US \$20/tCO_2. The stumpage royalty for *Cupressus lusitanica, Eucalyptus saligna, Pinus patula* and *Juniperus procera* were estimated in Ksh/m^3 within the threshold of the DBH as per KFS price list of 2010/2011 financial year. The costs for poles/beams/construction posts were estimated as per KEFRI plantation price list for 2010/2011 financial year. The prices for minimum and maximum DBH for clearfelling and thinning are as summarized in Table 4.15a.

Table 4.15a. Stumpage royalty at clearfelling and thinning of selected plantation tree species

Tree species	DBH size for clearfelling and thinning	DBH (cm) size	Stumpage royalty (Ksh.per m^3)
Cupressus lusitanica	Minimum for clear fell	15	2375
	Maximum for clearfell	>100	3108
	Minimum for thinning	15	1972
	Maximum for thinning	55	2423
Pinus patula	Minimum for clear fell	20	2222
	Maximum for clearfell	100	2797
	Minimum for thinning	20	1844
	Maximum for thinning	55	2180
Eucalyptus saligna	Minimum for clear fell	20	1975
	Maximum for clearfell	>100	2490
Juniperus procera	Minimum for clear fell	24	5043
	Maximum for clearfell	>56	10,284
	Minimum for thinning	24	4136
	Maximum for thinning	56	8433

Source. KFS stumpage royalty for 2010/2011 financial year

The data based stumpage royalty and average carbon sale showed there were significant differences ($F_{(2, 208)} = 83.81$; $p<0.001$) in the expected amount of income to be realized from AGB and clearfelling among commonly grown plantation species across ages and sites (Table 4.15b). Overall, the amount likely to be realized from sale of carbon from AGB was lower as compared to sale of wood implying that there would be less likelihood of carbon sale uptake . Additionally, age was a significant factor ($F_{(1, 208)} = 17.90$; $p<0.001$)

on variation of the amount of income likely to be realized from the sell of carbon and clearfelling. This was also obtained within and between sites of each tree species. For instance, expected income to be realized from sell of carbon and clearfelling of *Cupressus lusitanica* at age 24, almost at economic age rotation of about 30 years, was significantly high ($p<0.05$) at Kiambu as compared to Nyeri North and Nyeri South. However, this was not significantly different ($p>0.05$) between Nyeri South and North. Similar evidence was found for *Pinus patula* at almost economic age rotation of about 30 years among sites. In addition, there were significant differences in the expected amount of income to be realized from sell of carbon credit and wood among the environmental sites ($F_{(2, 208)} = 13.80$; $p<0.001$), interaction between sites and tree species ($F_{(4, 208)} = 23.26$; $p<0.001$) and interaction between environmental sites and levels of sales ($F_{(4, 208)} = 6.15$; $p<0.001$;Table 4.15b).

Table 4. 15b: Expected income from sell of carbon and clearfelling of commonly growth plantation tree species in Kiambu, Nyeri North and Nyeri South sites

Site	Tree species	Stand density ha^{-1}	Age (years)	Income (Ksh) from AGB $tCO_2e\ ha^{-1}$	Income (Ksh) from clearfelling m^3ha^{-1}
Kiambu	*C. lusitanica*	800	8	268,859	323,694
		590	14	603,330	775,773
		532	24	1,338,740	1,821,856
	E. saligna	1238	7	738,409	947,738
		250	10	152,913	185,515
		150	12	559,470	581,266
	P. patula	550	6	383,774	420,315
		200	10	352,055	358,023
		506	13	947,698	966,042
		60	32	560,638	636,229
Nyeri North	*C. lusitanica*	1050	8	369,711	458,267
		1000	13	499,287	613,798
		525	24	522,693	669,351
	E. saligna	780	8	410,647	449,974
		525	19	431,857	448,683
		150	33	620,625	662,592
	P. patula	600	8	396,260	462,196
		640	17	976,847	981,120
		425	30	1,556,449	1,648,599
Nyeri South	*C. lusitanica*	1100	8	430,007	516,736
		1000	14	1,057,701	1,360,948
		235	24	579,876	793,698
	E. saligna	700	7	705,840	688,454
		840	8	1,924,801	1,932,723
		390	14	1,433,083	1,488,358
	P. patula	750	10	583,303	577,178
		200	26	436,820	462,401
		s.e.d		177,918	

There were significant differences ($F_{(1, 20)} = 92.08$; $p<0.001$) between the amount of income to be realized from clearfelling (Ksh. 3.8 m ± 0.29) and the sale of carbon credits (Ksh. 1 m ± 0.29) for *Juniperus procera* at Kabaru forest station, Nyeri North.. Moreover, age was found to be a significant factor ($F_{(2, 20)} = 16.29$; $p<0.001$) in influencing the expected amount of income to be realized from growing *Juniperus procera*. However, at ages 65 and 70, no significant differences on the amount of income expected to be realized from clearfelling and sale of carbon credits (Table 4.16). Of the total variation in the expected amount to be realized, cleafelling and sale of carbon credits contributed 58% followed with age (21%), interaction between age and sources of sale (8%) leaving 13% unexplained.

Table 4.16: Expected income (Ksh. Million) from clearfelling and sale of carbon of *Juniperus procera* in Nyeri North

Age-yrs	(Ksh. million) clearfelling	(Ksh. million) AGB $tCO_2e\ ha^{-1}$
19	0.7	0.3
65	4.2	1.2
70	4.5	1.2
s.e.d	0.588	

The findings on expected income to be realized from sell of carbon indicated there was enormous potential of tree growing in improving the Kenya's economy through payment of environmental services. Carbon offsetting has gained some appeal and momentum mainly among consumers in western countries who have become aware and concerned about the potentially negative environmental effects of energy-intensive lifestyles and economies. In 2009, 8.2 billion metric tons of CO_2e changed hands worldwide, up by 68% from 2008, according to the study by carbon-market research firm Point Carbon, of Washington and Oslo. But at EUR 94 billion, or about $135 billion, the market's value was nearly unchanged compared with 2008, with world carbon prices averaging EUR 11.40 a ton, down about 40% from the previous year (Sweet, 2010). Consequently, World Bank (2010) put overall value of the market at $ 144 billion, but found that a significant part of this figure resulted from manipulation of a VAT loophole.

Carbon market is currently a global concern where the carbon prices significantly vary from a group of nations to individual nations and voluntary market. Pohjola and Valsta (2007) used EURO 10 and 20/tCO_2 to estimate expected amount of income to be realized from sale of carbon credits of Scots pine and Norway spruce stands in Finland. They found that for Scots pine stands, lengthening the rotation age had a minor impact with value used of carbon prices. Currently, the carbon market is dominated by the European Union, where companies that emit greenhouse gases are required to cut their emissions or buy pollution allowances or carbon credits from the market, under the Eurpean Union Emssion Trading Scheme (EU-ETS). Europe, which has seen volatile carbon prices due to fluctuations in energy prices and supply and demand, will continue to dominate the global carbon market for another few years, as the United States (U.S) and China, the world's top polluters, have yet to establish mandatory emission-reduction policies. The U.S. market remains primarily a voluntary market, but multiple cap and trade regimes are either fully implemented or near imminent at the regional level. The first mandatory, market-based cap-and-trade programme to cut CO_2 in the U.S., called the Regional Greenhouse Gas initiative (RGGI), kicked into gear in Northeastern states in 2009, growing nearly tenfold to $2.5 billion, according to point carbon.

Nevertheless, to counter such market fluctuations and difficulties, Bigsby (2009) presented alternative system of carbon sequestration termed as carbon banking where carbon sequestered is treated in the same way the financial institution treats capital. It follows the arguement that forest owners deposit carbon in exchange of annual payment and those who need carbon offsets-borrow carbon by making annual payment. This would provide opportunity for small forest owners with different types, age classes and management strategies to participate in carbon markets because payments are based on current carbon sequestered. It also allows participants in the carbon market to receive current value for carbon rather than what effectively represents the capitalized value of the future benefits of sequestering carbon, thus removing some uncertainty about locking into the wrong value of carbon. This approach is currently envisaged by the government of Kenya in the Ministry of Finance where carbon unit has been established to oversee aspects of carbon trading and how best it would be incorporated in Nairobi Stock exchange, once the National Carbon Accounting System (NCAS) and REDD for establishing reference scenario are in place.

4.4.2. Projection of Mean Annual Increament and Income from Sell of Carbon Credits and Wood of Commonly Grown Plantation Species

On the other hand, data on projection for the volume increase showed significant differences ($F_{(2, 86)} = 7.98$; $p<0.001$) on mean annual increment (M.A.I) for *Cupressus lusitanica* (16.7 ± 3.4), *Pinus patula* (21.3 ± 3.4) and *Eucalyptus saligna* (32.3 ± 3.4) across sites and ages. However, comparisons of M.A.I for *Cupressus lusitanica, Pinus patula* and *Eucalyptus saligna* within Kiambu and Nyeri North were not significantly different ($p>0.05$) other than at Nyeri South where *Eucalyptus saligna* had significantly higher ($p<0.05$) M.A.I as compared to *Cupressus lusitanica* and *Pinus patula* (Table 4.17). In this analysis, age as a covariate was also significant ($F_{(1, 86)} = 6.17$; $p=0.015$) in influencing the mean annual increment among the major plantation tree species.

Table 4.17 : **Mean annual increment (M.A.I) in m^3ha^{-1} of commonly grown plantation tree species across sites and ages**

Site	Treespecies	M.A.I m^3ha^{-1}	Site M.A.I m^3ha^{-1}	Age
Kiambu	Cupressus lusitanica	18	19	5, 8, 14, 24
	Eucalyptus saligna	19		2, 5, 7,10, 12
	Pinus patula	21		6, 10, 13, 32
Nyeri North	*Cupressus lusitanica*	13	18	5, 8, 13, 24
	Eucalyptus saligna	16		8, 19, 33
	Pinus patula	24		8, 17, 30
Nyeri South	*Cupressus lusitanica*	20	35	5, 8, 14, 24
	Eucalyptus saligna	67		7, 8, 14
	Pinus patula	19		5, 10, 26
	s.e.d	5.97	3.455	

In addition, the projections based on the M.A.I assuming the same density, site quality and other environmental factors kept constant, a tree investor of *Cupressus lusitanica* at Kiambu would be expected to realize an income of Ksh 3.2 m ha^{-1} from sale of carbon credit and Ksh. 3.8 m ha^{-1} from clearfelling at economic rotation age of 30 years. Similarly, the expected income to be realized from *Pinus patula* at economic rotation age of 30 years on the same site through sale of carbon credits would be about Ksh 3.8 m ha^{-1} and Ksh. 4.4 m ha^{-1} from clearfelling. There was no estimation projected for *Eucalyptus saligna* at Kiambu due to inconsistencies of age variations as a result of coppices. Overall, the projected income from clearfelling was higher for both tree species followed with income from sale of carbon above-ground and below-ground biomass other than soil carbon (Figure 4.22).

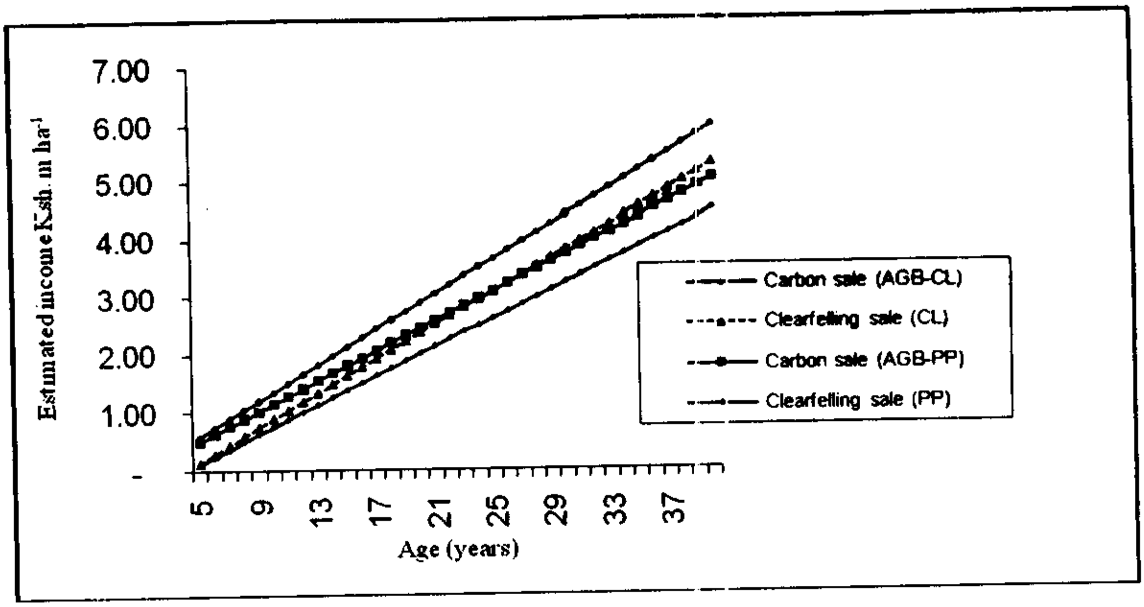

Figure 4.22: Projected income based on M.A.I from sell of carbon (ABG) and clearfelling for *Cupressus lusitanica (CL)* and *Pinus patula (PP)* in Kiambu

Furthermore, at economic rotation age of 30 years in Nyeri North, the tree investor of *Cupressus lusitanica, Pinus patula* and *Eucalyptus saligna* would be expected to realize about 1.8 m, 2.8 m and 2.1 m ha^{-1} from sale of carbon credit, and Kshs. 2.1m, 3.3 m and 2.5 m ha^{-1} from clearfelling, respectively (Figure 4.23). The projections for expected income to be realized from sell of carbon and clearfelling were five to 40 years, even though *Cupressus lusitanica* and *Pinus patula* would be rarely clearfelled at age 5, unless for construction purposes. In addition, the expected income to be realized from *Cupressus lusitanica* and *Pinus patula* at economic rotation of 30 years through sell of carbon credits and clearfelling would be about Kshs 3.2 m, 2.5 m ha^{-1} and Kshs. 3.8 m, 2.9 m ha^{-1}, respectively, at Nyeri South (Figure 4.24).

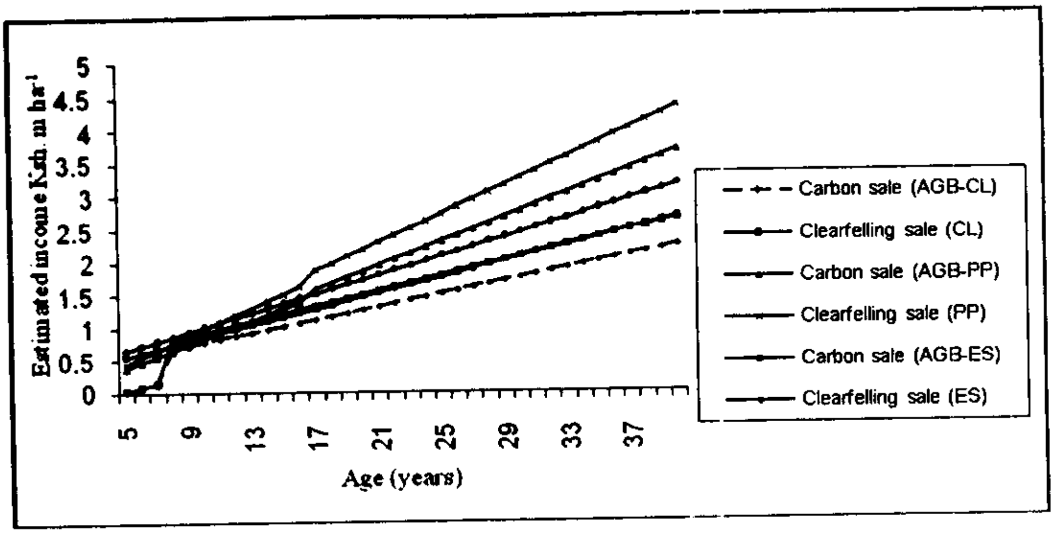

Figure 4.23: Projected income based on M.A.I. from sell of carbon (AGB) and clearfelling of *Cupressus lusitanica* (CL) *Pinus patula*(PP) and *Eucalyptus saligna (ES)* in Nyeri North

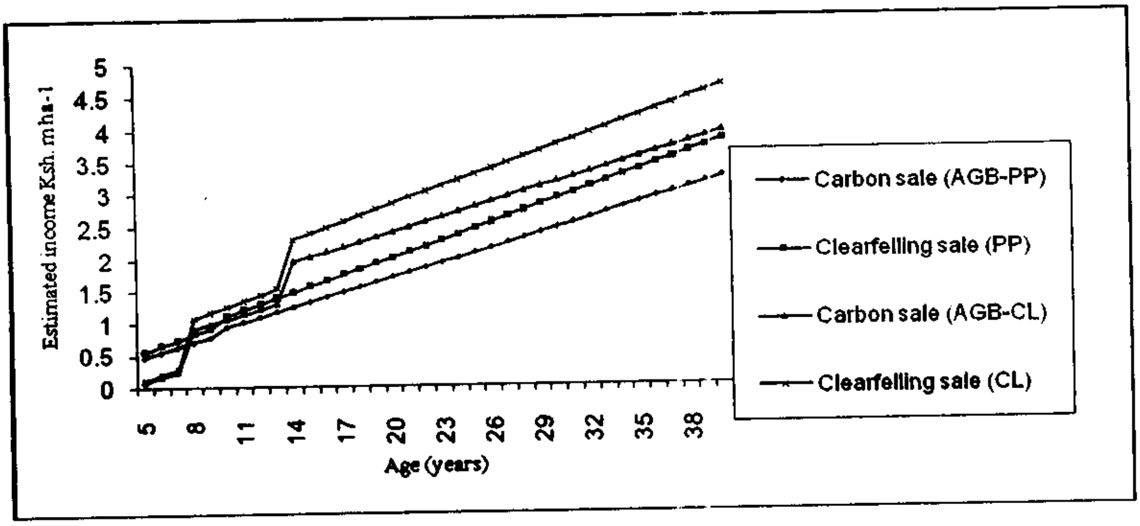

Figure 4.24: Projected income based on M.A.I from sell of carbon (ABG) and clearfelling of *Cupressus luitanica* (CL) and Pinus patula (PP) in Nyeri South

The comparisons between carbon and wood income expected to be realized from *Cupressus lusitanica, Pinus patula, Eucalyptus saligna* and *Juniperus procera* indicated tree investors were more likely to be encouraged to invest on carbon market if soil carbon is included in carbon offsets. This was well evidenced when expected income from carbon sales based on ABG was less than income from clearfelling. Even though there were no significant differences in the income expected to be realized from wood and carbon sell, wood prices would often be revised to reflect the demand of wood and the needs of Kenya Forestry Service as well as those of other tree growers. This would continue widening the gap between income from wood and carbon sales at given economic rotation, resulting to less interest in carbon. This suggested that unstable and fluctuating carbon prices would require some revisions to reflect on the trends of wood income such that tree investors would be persuaded by good returns to invest in carbon market.

To underscore the correct value of carbon credit, it is worth to align it with market value of trees and their ability to sequester carbon. For instance, in this study it was found that in *Juniperus procera* of stand density 150 trees averaged DBH of 50.3 cm at age of 70 years resulted to a volume of about 3.048m^3. In this case, a tree would be clearfelled at a cost of Ksh. 28,930. The estimated above-ground and below-ground carbon sequestered was 4.92 tCO_2 per tree. This implied that a tree of *Juniperus procera* absorbed about 70.3 kg of carbon dioxide every year at a lifetime of 70 years. At a minimum unit cost of carbon credit US $10 and a maximum of US $30 in the current market implies that this would fetch between Ksh. 3,936 and Ksh. 11,808 far below the clearfell price of Ksh. 28,930. Therefore pegging the unit of carbon credit as per tree market value implied that at the age of 70 years, *Juniperus procera* should fetch a minimum value of Ksh. 5,920 (US $ 74) as compared to the present carbon market of US $10. Related studies have shown that carbon prices significantly vary across countries worldwide selling at a minimal of EURO 2.5 to EURO 1069 t/C (Nijnik and Bizikova, 2008; Pohjola and Valsta, 2007; Chladna, 2007).

Nevertheless, a 32 age *Pinus patula* stand of 60 trees per ha at Kiambu had an average DBH of 59 cm. This yielded an average cost of Ksh. 9,837 per tree at clearfelling having absorbed about 5.84 tCO_2 an equivalent of 182 kg of carbon dioxide per year. This implied that the minimum value a tree investor could get from carbon sale at unit cost of US $10 (Ksh.800) would be about Ksh.4672 as compared to Ksh. 9837 implying that the expected minimum cost of a carbon credit should be around US $21 (Ksh. 1685) at this age of tree stand and site. This would not only attract a tree grower to invest for carbon market but also to lengthen the economic age rotation period resulting to effective mitigation of climate change. According to technical guidelines, the economic age rotation of *Pinus patula* for plywood, saw timber and pulpwood is 35, 30 and 18 years, respectively. This further, implied that depending on the economic returns accrued from carbon sell, tree investor might be willing to extend the age rotation period to a maximum of 50 years almost two cycles as stipulated by Kyoto Protocol where trees should be left to stand for a period of 25 years before clearfelling of fast growing species. Chladna (2007) argued that extending rotation period was favourable not only because more wood volume could be sold but also that more carbon credits could be sold as well. Similarly, presence of carbon trading and exponential increase of carbon prices lead extending the optimal rotation period.

In Nyeri North and Nyeri South, *Pinus patula* stands of age 30 and 26, respectively, had 425 and 200 sph in that order whose average DBH was 36 cm. This yielded an average cost of Ksh. 3747 per tree at clearfelling having absorbed about 2.29 and 1.36 tCO_2 an equivalent of 76.3 and 52.3 kg of carbon dioxide per year, respectively. Therefore the minimum cost of carbon credit based on the market value of tree should be US $21 and $34 at Nyeri North and Nyeri South, respectively. Similarly, *Cupressus lusitanica* at age 24 whose stand densities were 532, 525 and 235 at Kiambu, Nyeri North and Nyeri South, respectively, absorbed about 1.57, 0.622 and 1.54 tCO2 in the same order implying each tree absorbed about 65.5, 25 and 164.1 kg of carbon dioxide annually. In order to attract carbon market, the minimum unit cost per carbon credit should be at US $ 27. This would also lengthen the economic rotation period of pulpwood at 15-20 years and saw timber at 30 years to a maximum of 40 years. This suggested that chances might be higher for tree investor to forgo pulpwood and invest for timber thus increasing carbon storage potential in timber products for longer period of time. However, Lippke and Garcia (2008) reported that the key to an effective carbon credit system is recognizing the role of forest products have in the greater economy.

There were high variability on the CO_2e for *Eucalyptus saligna* at 12, 14 and 33 years of age at Kiambu, Nyeri South and Nyeri North respectively, with corresponding stand density of 150, 390 and 150 trees per ha. The mean DBH was 38, 36.5 and 42 cm in the same order resulting to average cost of 3535, 3386 and Ksh. 3938 at clearfelling. At these respective ages, about 194.3, 164 and 78.4 kg of carbon dioxide would be absorbed annually. Therefore, the introduction of carbon credit should be sold at a minimum of US $ 19 to motivate tree investors on shifting to carbon market under different economic rotations. For example, eucalypts are known to grow for fuelwood (6-8 years) with four economic rotations, pulpwood/fibreboard (8 years) with three economic rotations, timber (20 years) with two economic rotations and plywood at age of 30 with possibly two economic rotations. This could be extended up to 100 years depending on the returns that the tree investor would be fetching from the carbon sales thus enhancing carbon sinks for mitigation of climate change.

Balteiro and Rodriguez, 2006 have shown that when carbon credits were included in determining the optimal rotations of eucalyptus plantations and prices increased from EURO

10 to 50, there were long optimal coppicing rotations. Also it was reported for any carbon price, the cycle length decreases when pulpwood prices rose and for fixing the woodprice, the cycle length increased for variations in carbon price Lippke and Garcia (2008) reported that carbon values were likely to rise substantially overtime in order to reduce emissions, the inclusion of all markets in a capital and trade would substantially alter both the production and use of wood to reduce emissions. Overall, the unit cost of carbon credit at US$ 10 to US $30 was underpriced when trees are used as a basis of the cost. This implied other factors like species, wood prices, site and age need consideration while pricing cost of carbon credit. Studies have shown carbon storage potential of a given tree species depends on maximum biomass, site quality, time required to reach the maximum, modifying forest management and investments such as the species, fertilization and site preparation after harvest (Seely et al., 2002; Hassan & Ngwenya, 2006).

4.5. Modelling Determinants of Lifetime Value of the Farmer Willing to Retain Trees

In this output the objective was to identify determinants of the lifetime value of the farmer(s) willing to retain trees on farm. The determinants were grouped into household characteristics, farm factors, tree management and marketability. These were first subjected to descriptive statistics and non-parametric tests before modelling. Correlations among combination of determinants were conducted before fitting the models on determining the likelihood of the farmer retaining trees. Discussions of significant determinants were provided after inferential analysis.

4.5.1. Association and Comparisons of Study Sites Influencing Farmer's Tree Retention

The data were collected from Lari, Kikuyu, Nyeri South and Nyeri North districts to determine group of farmers likely to retain trees on farm. Sites were significantly associated with the three way (χ^2 = 13.49, d.f = 6; p=0.036) and two-way levels (χ^2 = 7.685, d.f = 3; p=0.05) of likelihood of the farmer willing to retain trees on farm. Nyeri North followed by Lari had high proportion of farmers who were most likely to retain trees on farm as compared to those from Kikuyu and Nyeri South. Consequently, using the non-parametric tests, the results based on mean ranks showed there were significant differences among the study sites (Kruskall Wallis H test on 3 way: χ^2 = 9.60, d.f = 3; p=0.022 and 2 way: χ^2 = 7.648, d.f = 3; p=0.054) and the likelihood of farmers willing to retain trees on farm. However, there were no significant differences (p>0.05) on likelihood of tree retention between Kikuyu and Nyeri South (Table 4.18).

Table 4.18: Association of sites and comparisons on likelihood of the farmer's tree retention on farm

	%, frequency (n) and mean rank on 3 way classification of dependent variable (CDV)								% , n and mean rank on 2 way CDV					
	Not likely		Less likely		Most likely		Mean rank		Not likely		Likely		Mean rank	
Sites	%	n	%	n	%	n	μ	n	%	n	%	n	μ	n
Lari	19	9	35	17	46	22	104	48	46	22	54	26	100	48
Kikuyu	38	13	21	7	41	14	90	34	59	20	41	14	95	34
Nyeri South	32	15	27	13	40	19	93	47	60	28	40	19	95	47
Nyeri North	15	12	23	18	62	49	118	79	38	30	62	49	117	79

4.5.2. Household Determinants Associated with Farmer's Tree Retention on Farm

The results showed when the three-way classification of the dependent variable was used, there were significant associations (Three wayχ^2 = 7.631, d.f = 2; p=0.022) between gender of the household head and farmers' tree retention on farm. Male-headed households were most likely to retain trees on farm as compared to female-headed households. This was consistent with the results of non-parametric test, which showed significant differences (Mann Whitney U on 3 way: Z = -2.20, p=0.028 and 2 way: Z =-1.54, p=0.028). However, no significant association (χ^2 = 2.391, d.f = 1; p=0.122) were found on two-way classification of the dependent variable (Table 4.19).

Subsequently, on two way level of classification of dependent variable, main occupation was significantly associated (χ^2 = 3.570, d.f = 1; p=0.059) with farmers' willingness to retain trees on farm. Those that were in formal full time employment had high proportion as compared to full time farmers. On the other hand, three way classification of dependent variable, the results showed no significant association (χ^2 = 3.596, d.f = 2; p=0.166) between main occupation and farmers' likelihood of retaining trees on farm. However, there were significant differences (Mann Whitney U on 3 way: Z = -1.83, p=0.067 and 2 way: Z =-1.89, p=0.059) between main occupation and farmers' willingness to retain trees on farm (Table 4.19).

Further, on two-way classification of dependent variable that there was a significant association and difference (χ^2 = 8.020, d.f = 3; p=0.046: Kruskall Wallis H test: χ^2 = 7.979, d.f = 3; p=0.046) between education levels of the respondents and farmers' likelihood of retaining trees on farm. However, no significant associations and differences (χ^2 = 9.046, d.f = 6; p=0.171: Kruskall Wallis H test: χ^2 = 6.036, d.f = 3; p=0.110) were observed between education level and farmers willingness to retain trees on farm on three-way classification of dependent variable. Those who had attained post secondary and primary education had high proportion as compared to those who had no academic qualification (Table 4.19). On the other hand, marital status was not significantly associated (χ^2 = 2.451, d.f = 2; p=0.281;

Mann Whitney U on 3 way: Z = -1.26, p=0.206 and 2 way: Z =-0.88, p=0.377) and different in influencing farmers' lifetime value to retain trees on farm.

Table 4.19: Association of household determinants and likelihood of farmer's tree retention on farm

Household determinants		%, n and mean rank on 3 way CDV								%, n and mean rank on 2 way of CDV					
		Not likely		Less likely		Most likely		Mean rank		Not likely		Likely		Mean rank	
Variables	Categories	%	n	%	n	%	n	µ	n	%	n	%	n	µ	n
Gender	Male	19	30	28	45	53	86	104	161	47	75	53	86	103	161
	Female	39	25	21	8	40	15	83	199	61	23	40	15	89	38
Main occupation	Full time farmer	25	44	28	48	47	82	98	174	53	92	47	82	98	174
	Formal job	15	4	19	5	68	18	119	14	33	9	68	18	118	27
Education level	None	30	7	35	8	35	8	83	23	65	15	35	8	83	23
	Primary	22	17	24	19	54	43	102	79	46	36	54	43	103	79
	Secondary	22	15	32	22	46	32	96	69	54	37	46	32	95	69
	Post secondary	18	5	11	3	71	20	117	28	29	8	71	20	120	28
Marital status	Married	22	41	26	49	52	97	103	187	48	90	52	97	102	187
	Not married	40	6	20	3	40	6	85	15	61	9	40	6	90	15

4.5.3. Farm Determinants Associated with Farmer's Tree Retention on Farm

The results showed 59% owned their land through inheritance from their parents, 31% had purchased and 10% were given by the community/government. There were no significant associations and differences (3 CDV: χ^2 = 4.609, d.f = 4; p=0.333; 2 CDV: χ^2 = 0.554, d.f = 2; p=0.758; Kruskall Wallis H test: χ^2 = 0.117, d.f = 2; p=0.943) between type of land ownership and farmers' tree retention on farm (Table 4.20).

Table 4.20: Association between type of land ownership and likelihood of farmers retaining trees on farm

	% and frequency on 3 way CDV								% and frequency on 2 way CDV					
Type of Land ownership	Not likely		Less likely		Most likely		Margin total		Not likely		Likely		Margin total	
	%	n	%	n	%	n	%	n	%	n	%	n	%	n
Inherited from parents	21	25	30	36	49	59	100	120	51	61	49	59	100	120
Bought	28	17	17	10	55	33	100	60	45	27	55	33	100	60
Given by community and government	30	6	20	4	50	10	100	20	50	10	50	10	100	20

There was a significant difference ($F_{2, 201}$= 5.930; p=0.003) on size of land among the farmers 'not likely', 'less likely' and 'most likely' farmers to retain trees on farm. The farmers who were 'most likely' to retain trees on farm had relatively high mean land size (Table 4.21). Further comparison among the farmers 'not likely', 'less likely' and 'most likely' to retain trees on farm showed that there were significant differences (p=0.011) between those who were 'most likely' and those 'not likely' as well as less likely (p=0.025) retain trees on farm. However, no significant differences between farmers 'not likely' and 'less likely' (p=1.000) to retain trees on farm were observed.

Table 4.21: Statistical measures on land sizes (acres) among the three different likelihood levels of tree retention

Level of tree retention	N	Mean	Std. Deviation	Std. Error	95% CI for Mean Lower Bound	95% CI for Mean Upper Bound	Minimum	Maximum
Not likely	47	2.6	1.91	0.28	2.07	3.19	0.25	7
Less likely	54	3.9	2.85	0.39	3.07	4.63	0.25	15
Most likely	103	11.8	24.91	2.45	6.97	16.71	2.00	177
Total	204	7.6	18.3	1.28	5.08	10.12		

Tree species planted on farm were mainly exotic with very few indigenous ones. The exotic tree species were Eucalyptus, *Cupressus lusitanica* and *Grivellea robusta*. The highest number of indigenous tree species was *Olea africana*. Of exotic tree species, the eucalyptus were easily managed and of fast growth followed by *Cupressus lusitanica* and *Grivellea robusta* which was also observed to be easily intercropped with other agricultural crops (Table 4.22).

Table 4.22: Tree species commonly planted on farm and management in Lari, Kikuyu, Nyeri South And Nyeri North districts

	Frequency and percentage		Frequency and percentage on easy management and fast growth	
Trees planted on farm	n	%	n	%
Eucalyptus spp.	163	21	93	36.8
Cupressus lusitanica	156	20.1	67	26.5
Grivellea robusta	125	16	64	25.3
Olea africana	59	7.8	2	0.8
Pinus patula	50	6.5	17	6.7
Juniperus procera	30	3.9	4	1.6
Prunus africana	45	5.8	3	1.2
Cordial africana	10	1.3	1	0.4
A.meansii	31	4.0	1	0.4
Croton megalocorpus	15	1.9	1	0.8
Others	91	19	-	-
Total	775	100.0	253	100

The cross-tabulation between the uses of trees planted on farm and the likelihood of retention, showed no significant differences (Kruskall Wallis H test: $\chi^2 = 1.243$, d.f = 2; p=0.537) among the three-and two-way CDV. However, there was consistent high proportion of farmers who were 'most likely' to retain trees on farm based on three major uses, namely, wood fuel production, timber and aesthetic (Table 4.23).

Table 4.23: Association between users of tree planted on farm and likelihood of retention

	Percentage and frequency on 3 way CDV								Percentage and frequency on 2 way CDV					
	Not likely		Less likely		Most likely		Margin total		Not likely		Likely		Margin total	
Uses of trees planted	%	n	%	n	%	n	%	n	%	n	%	n	%	n
Production of woodfuel	24	22	33	30	43	39	100	91	57	52	43	39	100	91
Production timber	21	13	26	16	53	32	100	61	47	29	53	32	100	61
Aesthetic value	26	6	17	4	57	13	100	23	43	10	57	13	100	23

However, in circumstances where farmers were motivated to plant trees for environmental conservation and for improving sources of livelihood, there were significant differences and association (Mann Whitney U: Z = -2.114, p=0.034 and χ^2 = 10.453, d.f = 2; p=0.005) among those who were 'not likely', 'less likely' and 'most likely' to retain trees on farm. The latter group tended to increase chances of retaining trees on farm as compared to not likely and less likely (Table 4.24). Even though some farmers were motivated to plants trees, land size was singled out as the most (55%) significant barrier to continuous tree planting (Table 4.25).

Table 4.24: Motivation of tree planting and classification for tree retention.

	Not likely		Less likely		Most likely		Margin total	
Motivational reasons for tree planting	%	n	%	n	%	n	%	n
Environmental conservation	24	22	33	30	43	39	100	91
Sources of livelihood	21	13	26	16	53	32	100	61

Table 4.25: Barriers on continuous tree planting in Lari, Kikuyu, Nyeri South and Nyeri North districts

Hindrances/barriers from continuous tree planting	Frequency (n)	% frequency
Limited land size and ownership	169	39
Inadequate quality seedling and species of interest	44	10
Inadequate labour for tree farming	12	3
Inadequate funds for tree farming	14	3
Occurrences of drought	21	5
Needed land for mainly agricultural activities	41	10
Low level of awareness on forestry returns among farmers	55	13
No immediate returns	31	7
Dislike of forestry	12	3
Side effects of tree growing with crops (reduced soil fertility, high water uptake).	4	1
No interest	25	6
Total	428	100.0

4.5.4. Tree management and Marketability Determinants Associated with Farmers' Tree Retention on Farm

The results showed 84% of the farmers interviewed lacked any technical skills in tree management as compared to 16% who had acquired such skills. These included nursery establishment, thinning, pollarding, short rotation coppice, fertilizer application, tree harvesting, forest economics and management of tree competition with agricultural crops among others. However, there was a significant association (χ^2 = 3.748, d.f = 1; p=0.053) on skills acquisition and farmer's likelihood of tree retention on farm. Majority (66%) of those who had got the technical skills were most likely to retain trees on farm as compared to those who had not obtained the same skills. This was again significantly associated (χ^2 =

3.698, d.f = 1; p=0.054) with their decision in growing trees based on the technical skills acquired (Table 4.26).

Labour involved on tree management was not found to be intense and costly by the majority (74%) as compared to 26% who stated that it was intense and labour costly. This was significantly highly associated (χ^2 = 7.567, d.f = 2; p=0.023) with farmer's tree retention on farm. Further, 94% of the respondents had not received forest extension services as compared to 6%. This was not significantly associated (χ^2 = 3.824, d.f = 2; p=0.148) with farmer's tree retention on farm, although 78% of those who had received extension services, were most likely to retain trees on farm as well as those who had not received (48%) extension services.

Seeking for authority from Kenya Forest Service to harvest trees was significantly associated (3 way CDV; χ^2 = 5.883, d.f = 2; p=0.053; 2 way CDV; χ^2 = 4.123, d.f = 1; p=0.042) with the likelihood of farmer retaining trees on farm (Table 4.27). Overall, 69% of the respondents sought for permit to harvest trees as compared to 41% who did not. Consequently, there was a significant association (χ^2 = 7.318, d.f = 2; p=0.026) between respondents who found such regulations necessary on tree farming and likelihood of retaining trees on farm.

No significant associations (χ^2 = 4.315, d.f = 2; p=0.116) were obtained between existence of village forest association and level of likelihood of farmer retaining trees on farm. Thirty five percent of the respondents stated that there were village forest associations in comparison with 65% of none. Similarly, no significant association (χ^2 = 0.479, d.f = 2; p=0.787) was observed between membership enrolment of which 20% were members while 80% were not members and had likelihood of tree retention on farm. Also no significant association (χ^2 = 3.203, d.f = 2; p=0.202) was found between market availability of tree products and likelihood of the farmer's tree retention on farm. Seventy seven percent had ready market of their tree produce as compared to 23% who did not. Large proportion of respondents who had ready markets tended to be 'more likely' to retain trees on their farms (Table 4.26).

There was no strong significant association between marketing problems and farmer's likelihood (χ^2 = 4.630, d.f = 2; p=0.099) of tree retention on farm (Table 4.26). Seventy nine percent did not experience any marketing problems of their tree produce as compared to 21% who had experienced such problems. The main buyers identified for their trees produce were mainly wood and timber retailers (38%), schools (18%), saw millers (19%) and tea factories (12%) and the rest (14%) restaurants, KPLC, NGOs and Telkom Kenya.

Table 4.26: Tree management and marketability determinants influencing farmer's tree retention on farm

Determinants and category levels		% and frequency on 3 way categorization of likelihood								% and frequency on 2 way categorization of likelihood					
		Not likely		Less likely		Most likely		Margin total		Not likely		Likely		Margin total	
		%	n	%	n	%	n	%	n	%	n	%	n	%	n
Technical skills	yes	14	4	21	6	66	19	100	29	34	10	66	19	100	29
	no	26	43	28	45	46	75	100	163	54	88	46	75	100	163
Use of skills	yes	14	4	7	2	79	22	100	28	21	6	79	22	100	28
	no	26	8	19	6	55	17	100	31	45	14	55	17	100	31
Labour & cost	yes	9	4	28	12	63	27	100	43	37	16	63	27	100	43
	no	30	38	24	31	46	58	100	127	54	69	46	58	100	127
Extension services	yes	0	0	22	2	79	7	100	9	22	2	78	7	100	9
	no	25	45	27	50	48	88	100	183	52	95	48	88	100	183
Harvesting permission	yes	18	17	26	25	57	55	100	97	43	42	57	55	100	97
	no	32	23	27	19	41	29	100	71	59	42	41	29	100	71
Harvesting regulation & tree farming	yes	16	12	29	22	55	42	100	76	45	34	55	42	100	76
	no	35	26	20	15	45	34	100	75	55	41	45	34	100	75
Village forest associations	yes	16	9	35	20	49	28	100	57	51	29	49	28	100	57
	no	27	30	22	25	51	57	100	112	49	55	51	57	100	112
Membership	yes	23	8	31	11	46	16	100	35	54	19	46	16	100	35
	no	25	37	26	38	49	73	100	148	51	75	49	73	100	148
Ready market	yes	21	23	25	27	54	59	100	109	46	50	54	59	100	109
	no	36	12	21	7	42	14	100	33	58	19	42	14	100	33
Marketing problems	yes	10	3	29	9	61	19	100	31	39	12	61	19	100	31
	no	28	33	25	29	47	55	100	117	53	62	47	55	100	117

4.5.5. Correlations among Tree Retention Determinants

There was a positive significant correlation ($p<0.05$) between gender of the household head and marital status as well as with major occupation. There was negative significant correlation ($p<0.05$) between marital status and number of members in the household and age of the household respondent. The latter was also negatively and significantly ($p<0.05$) correlated with level of education. The results also showed a positive significant correlation ($p<0.05$) between major occupation and monthly income as well as education level (Table 4.27).

Table 4.27: Correlationss among various demographic variables of tree retention

Demographic variables	Gender of household head	Marital status	Major occupation	No. members household	Monthly income	Age (yrs)	Education
Gender of household head	1.000	0.247 p=0.001	-0.125 p=0.064	-0.038 p=0.324	-0.048 p=0.281	0.063 p=0.224	-0.098 p=0.118
Marital status		1.000	-0.032 p=0.351	-0.165 p=0.022	-0.041 p=0.310	-0.227 p=0.003	0.070 p=0.197
Major occupation			1.000	-0.108 p=0.094	0.240 p=0.002	-0.029 p=0.361	0.374 p=0.000
No. members household				1.000	0.035 p=0.335	0.063 p=0.449	-0.169 p=0.019
Monthly income					1.000	0.011 p=0.449	0.179 p=0.014
Age in years						1.000	-0.452 p=0.000
Education							1.000

There was a positive significant correlation ($p<0.05$) between technical skills farmers gained in tree management and use of such skills in influencing them in tree growing and harvesting. The skills were equally highly correlated ($p<0.05$) with harvesting regulation, which farmers found to be necessary and useful in motivating their decision for tree farming. Similarly, the technical skills obtained on tree farming by farmers were significantly correlated ($p<0.05$) with extension services received on tree management. This was consistent with the use of skills gained in tree farming. Seeking permission from Kenya Forestry Service to harvest trees was significantly correlated ($p<0.05$) with level of acceptance on such regulations. This was found to be necessary and useful in motivating the farmers to participate in tree farming (Table 4.28). The extension services were also positively and significantly correlated (ρ= 0.189, p=0.015) with motivation to plant trees for environmental conservation and source of livelihood.

Table 4.28: Correlation matrix among the farm determinants of tree retention

	Technical skills	Use of skills	Labour and cost	Extension services	Harvesting permission	Harvesting regulation and tree farming
Technical skills	1.000	0.819 p=0.00	-0.024 p=0.434	0.275 p=0.025	0.152 p=0.144	0.483 p=0.000
Use of skills		1.00	0.013 p=0.463	0.204 p=0.075	0.145 p=0.155	0.372 p=0.004
Labour and cost			1.000	-0.081 p=0.286	-0.063 p=0.331	-0.188 p=0.093
Extension services				1.000	0.130 p=0.182	0.231 p=0.051
Harvesting permission					1.000	0.244 p=0.042
Harvesting regulation and tree farming						1.000

There was also a significant positive correlation (ρ= 0.570; p=0.000) between existence of village forest village association and membership of the farmers. Similarly, there was significant correlation (ρ= 0.491; p=0.002) between village forest membership and ready market of forest products. Additionally, there was a significant positive correlation (ρ= 0.175, p=0.001) between land size and monthly income as well as land size and age (ρ= 0.18, p=0.013) but not age and monthly income (ρ= 0.011, p=0.888). In addition, there was a significant correlation (ρ= 0.213, p=0.000) between land size and the number of trees planted on farm. There was also positive significant correlation (ρ= 0.217, p=0.008) between acquisition of technical skills and marketability of tree produce.

4.5.6. Modelling of Tree Retention Determinants using Binary and Multinomial Logistic Regression models

Both binary and multinomial logistic regression models following stepwise method of fitting variables showed study site, monthly income, land size, extension services, labour and cost involved in tree management and harvesting permission from KFS as significant determinants influencing the likelihood of the farmer willing to retain trees on farm. Logistic regression model showed major occupation, education level, acquisition of technical skills and their effect, significantly influenced the lifetime value of the farmer to retain trees on farm. Similarly, multinomial logistic regression model showed that gender of the household head, age, reasons motivating farmers to plant trees, harvesting regulation and existence of village forest association, were significant factors affecting the farmers' tree retention on farm. Overall, binary and multinomial logistic regression models correctly identified 10 and 12 determinants likely to influence farmers' lifetime value of retaining trees on farm, respectively (Table 4.29).

Table 4.29: Likelihood Ratio tests and model classification of tree retention determinants using binary and multinomial logistic regression

	Intercept		-2 log likelihood		Chi-square ratio test		d.f		p-value		% model classification	
Determinants	Logt	Mult	Logt	Mult	Logt	Mult	Logt	Mult	Logt	Mult	Logt	Mult
Site	0.00	32.0	281	45.1	7.75	13.1	3	6	0.05	0.04	59	50
Gender HH	0.03	17.8	273	24.8	2.4	6.9	1	2	0.12	0.03	55	51
Occupation	-0.01	16.9	275	20.6	3.63	3.67	1	2	0.06	0.16	55	50
Age	0.07	86.4	262	238	0.01	152	1	126	0.93	0.06	52	67
Education	0.07	30.4	267	40.0	8.22	9.56	3	6	0.04	0.14	58	52
Marital status	0.04	16.4	279	18.7	0.79	2.26	1	2	0.38	0.32	53	51
NMH	0.09	89	275	85	0.51	1.52	1	2	0.47	0.47	53	52
Income	0.13	64.2	220	168	13	104	1	80	0.00	0.00	60	53
Land tenure	0.04	29.4	276	43.9	0.55	14.5	2	10	0.76	0.15	52	51
Land size	0.02	72.4	231	130	52	57.9	1	6	0.00	0.00	68	68
Tree use	-0.08	24.1	240	27.3	2.12	3.18	2	4	0.35	0.53	55	48
Motivation	0.10	17.5	225	27.5	1.63	10.0	1	2	0.20	0.01	56	52
Technical skills	-0.04	17.0	262	21.1	3.79	4.08	1	2	0.05	0.13	56	49
Skill effect	0.69	12.6	71.8	16.6	3.78	3.94	1	2	0.05	0.14	66	66
Labour & cost	0.00	17.1	232	25.8	3.80	8.67	1	2	0.05	0.01	57	50
Extension services	-0.02	13	263	18.8	3.19	5.72	1	2	0.07	0.06	53	50
Harvest permission	0.00	18.1	229	23.9	4.14	5.87	1	2	0.04	0.05	58	50
Harvesting regulation	0.01	17.5	208	25	1.49	7.45	1	2	0.22	0.02	55	50
Forest associations	0.01	17.8	234	22.1	0.05	4.35	1	2	0.83	0.11	51	50
Membership	-0.06	17.6	253	18.1	0.15	0.47	1	2	0.70	0.79	51	49
Ready market	0.06	16.8	195	19.8	1.39	3.03	1	2	0.24	0.22	55	51
Marketing problems	0.00	16.4	203	21.7	2.01	5.36	1	2	0.16	0.07	55	50

* Logt = Logistic regression values; Mult = Multinomial logistic regression values; HH = Household head; NMH= number of members in the household

On the other hand, both models showed that marital status, number of members in the household, type of land ownership, uses of trees planted on farmers' field, membership of village forest association, and availability of ready market for selling forest produce, did not significantly ($p>0.05$) influence the likelihood of the farmer to retain trees on farm. In addition to these non-significant determinants, binary logistic regression showed gender of the household head, age, motivation of tree planting, harvesting regulations, existence of village forest association, and marketing problems, did not significantly influence the farmers' tree retention on farm. The binary logistic regression model had a better classification of overall percentage prediction of likely and not likely groups farmers/respondents as compared to multinomial logistic regression model in detecting the likelihood of tree retention on farm.

The techniques of classifying dependent variables into two- and three-way of likelihood of the farmer willing to retain trees on farm correctly identified a number of determinants. This underscored the significance of using such methods in carrying data analysis. The discrepancy that was observed between the two classifications of the dependent variable associated and regressed against the determinants could be explained by random occurrence of small sample sizes in three-way classification as compared to two-way classification and the power of the statistical test based on uncorrelated variables. For example, three-way categorization of dependent variable failed to detect education level and main occupation of the farmer as possible determinants of tree retention. This may be attributed to small sample size of random respondents distributed across the three category levels as compared to two-way. This was well demonstrated when the non-parametric tests were carried out of which the p-value for main occupation notably decreased from 0.166 on checking for significant associations to 0.067 on inferential tests, showing an increasing source of evidence that main occupation was a significant factor associated with tree retention among the group of farmers. Consequently, the p-value of education level considerably decreased from 0.171 to 0.111, showing further an inherent evidence of education level on influencing farmers to plant and retain trees on farm.

Further, the binary logistic regression analysis showed the odds of farmers from Nyeri North likely to retain trees on farm as compared to those from Nyeri South, Kikuyu and Lari were 60, 60 and 50% higher, respectively (Table 4.30). Similarly, multinomial logistic regression model showed farmers from Nyeri North had significantly high logits of most likely to retain trees on farm as compared to those from Kikuyu and Nyeri South. However, there were no significant differences ($p>0.05$) on the chances of farmers from Nyeri North retaining trees on farm as compared to those from Lari. Morevover, there were no significant differences ($p>0.05$) on the logits of the farmers who were 'not likely' to retain trees on farm from Nyeri North as compared to those who were 'less likely' from Nyeri South and Lari. However, there were significant differences ($p<0.05$) on the logits of those who were less likely to retain trees on farm from Nyeri North as compared to those from Kikuyu who were 'not likely' (Table 4.30).

Table 4.30: Binary logistic regression model using stepwise method on fitting determinants of farmer's tree retention on farm

Explanatory variables	β	S.e (β).	Odds ratio	p-value	Reference variable
Site: Lari	-0.66	0.37	0.5	0.076	Nyeri North
Kikuyu	-0.85	0.42	0.4	0.043	Nyeri North
Nyeri South	-0.88	0.38	0.4	0.020	Nyeri North
Gender	0.56	0.37	1.8	0.125	Female
Household members	0.04	0.05	1.8	0.477	Unity
Monthly income	0.00	0.00	1	0.004	Unity
Land size	0.36	0.07	1.4	0.000	Unity
Marital status	0.48	0.55	1.6	0.380	Not married
Major occupation	-0.81	0.44	0.5	0.064	Full time farmer
Education: None	-1.55	0.61	0.2	0.011	Post secondary
Primary	-0.74	0.48	0.5	0.120	Post secondary
Secondary	-1.06	0.48	0.3	0.028	Post secondary
Age (years)	0.001	0.01	1.0	0.927	Unity
Tree use: Fuelwood	-0.55	0.47	0.6	0.243	Aesthetic
Wood timber	-0.16	0.49	0.8	0.533	Aesthetic
Tree Motivation: conserve environment	0.420	0.330	1.5	0.203	Source of livelihood
Technical skills	0.802	0.421	2.2	0.057	No
Effect of skills	1.105	0.585	3.0	0.059	No
Labour and cost	0.697	0.362	2.0	0.054	No
Extension services	1.329	0.815	3.8	0.103	No
Harvesting permission	0.640	0.317	1.9	0.043	No
Harvesting regulation	0.399	0.327	1.5	0.223	No
Forest associations	-0.071	0.325	0.9	0.828	No
Membership	-0.145	0.377	0.9	0.701	No
Ready market	0.471	0.401	1.6	0.241	No
Marketing problems	0.579	0.413	1.8	0.160	No

The significant differences observed among the study sites may be explained by the location of their agro-ecological zones and their predominant farming activities. Nyeri

North, which was represented by Kabaru and Naromoru had relatively large tracks of land, which might explain high level of tree retention on farm. Their proximity to the slopes of Mt. Kenya and the surrounding forest plantations might have induced them to tree planting culture for varied reasons. In addition, Kenya Forestry Service regulation on harvesting forest products and their commercialization may as well explain the higher likelihood of farmers in this region engaging more in tree farming. Similar reasons may be attributed to Lari region, which is mainly surrounded by major forest plantations, namely, Kinale, Uplands and Kerita. Also this may be attributed to availability of seedlings and neighbor to neighbor learning.

On the other hand, the low levels of likelihood of farmers to retain trees on farm from Nyeri South, which lies on easterly edge of Aberdares range, may be attributed to small land holdings with concentration of high population. The nature of their farming activities which was mainly dairy, tea growing and subsistence crops delineated them from active participation in tree farming as much of the land was needed for pasture and food crops. As observed during data collection, majority of the farmers from this region viewed tree growing as a long term investment with no immediate cash to offset household needs, hence lowly prioritized. In cases where farmers had trees on their farms, the site was less productive and sometimes with steep slope which was not suitable for agricultural farming. Similar argument was advanced by Moser et al. (2009) who reported farmer-owned woodlands generally occurred along rivers and streams or in an island of pockets the so called "back forty'' which were too hilly or too rocky for food crops.

Consequently, the low level of likelihood of farmers to retain trees on farm in Kikuyu area, which consisted of Muguga, Karai, Thogoto, Gikambura, Kerwa and Nderi may be attributed to scarcity of land, dairy farming and horticultural activities. This concurs with Arbuckle et al. (2009) who reported landowners who had higher percentage of land in crops were considerably less likely to express interest in agroforestry suggesting that food crops and trees were incompartible. Overall the land use management system of the residents in Kikuyu may be attributed to low levels of tree retention. For instance, farmers in the drier area of Kikuyu, mainly Karai and Gikambura engaged more in tree planting due to less land productivity and less rainfall for agricultural crops as compared to those who were towards Thogoto, Muguga, Nderi and Kerwa areas. In general, research has shown that location factors are also key determinants influencing variations on the likelihood of managing natural resources including trees on farm and engagement in forest management (Volker and Waibel, 2010).

Farmers with higher monthly income had high chance of retaining trees on farm with increase in income having a unit increase in tree retention. Further, the computed predicted probabilities on monthly income of the farmers showed as monthly income increased, there was corresponding increase of probability of the farmers retaining trees on farm (Figure 4.25). This was more evident with farmers who had an income over Ksh. 100,0000 a month as the model predicted 100% of their likelihood of retaining trees on farm. In addition, farmers who were on full time formal employment had high logit (about 50% high) likely to retain trees on farm as compared to full time farmers. Also, farmers who had attained post-secondary education had about 80, 50 and 70% chances higher of retaining trees on farm as compared to those who had no formal education, primary and secondary education, respectively.

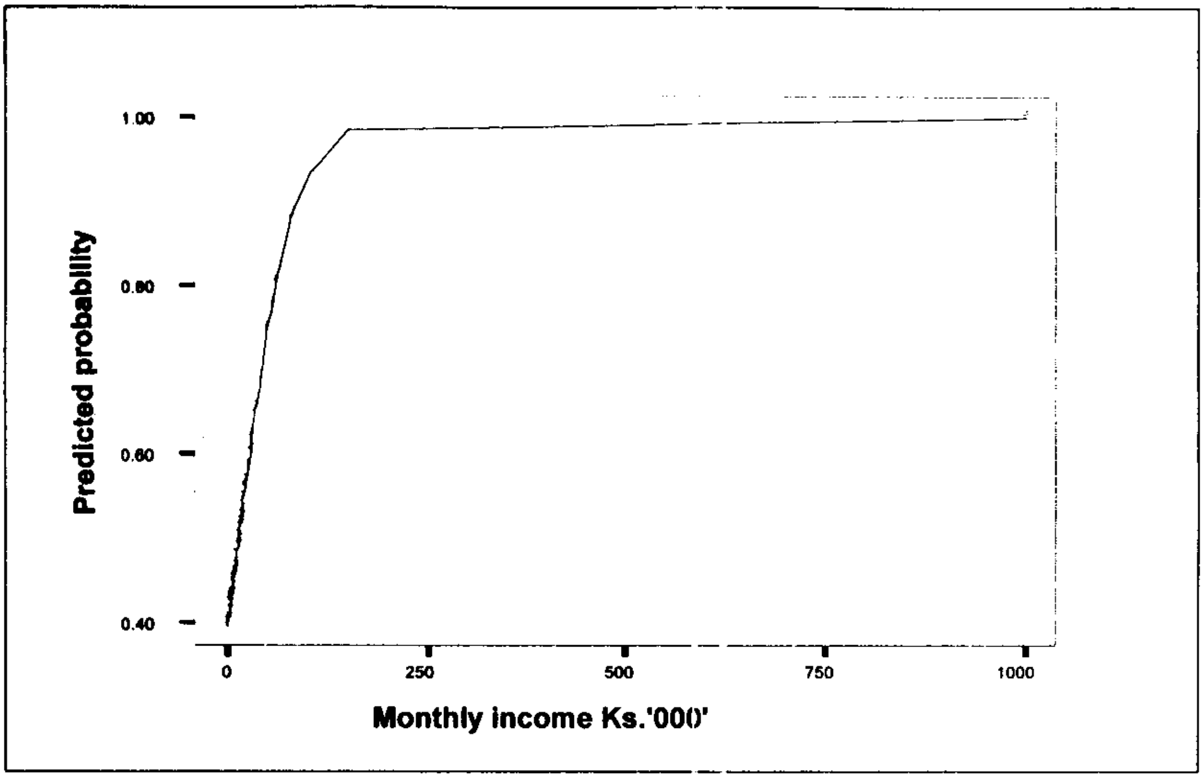

Figure 4.25: Monthly income and predicted probability of tree retention on farm

The significant contribution of likelihood of tree retention due to monthly income, which was highly correlated with major occupation and education level may be explained by the amount of time, exposure to environmental conservation, returns from forest, knowledge on importance of trees, access of funds for meeting households needs, and interest in tree farming, among other sources of energy. The findings of this study where full time farmers were 'less likely' to retain trees on farm as compared to full-time formal employment corroborates well with other studies where older part-time or non-traditional farmers were 'less likely' to be interested in forest farming (Valdivia and Poulos, 2009). Furthermore, there were chances that those who were on full-time employment were not necessarily depending on their land for bulk of their livelihoods hence may give environmental, aesthetic and recreational factors more weight than financial ones when making land use decisions (Arbuckle et al., 2009), resulting in high likelihood of tree retention on farm.

Similarly, studies have shown that those who had off-time employment opportunities, access to credit and total household income may be associated with reduced tree felling on farm leading to high probability of tree retention (Lingani et al., 2009). In addition, farmers who derive significant income from their trees and viewed their forests as source to be tapped periodically for income would engage in practices that would maintain or enhance income regenerating opportunities. Also private forest owners are normally more concerned with gaining more income from their tree produce (Moser et al., 2009; Janse & Ottitsch 2005). Educated farmers (post-secondary) were 'less likely' to fell trees on their farms as compared to their counterparts with little or no academic qualification. This may be explained by knowledge, skills and change of attitude that individuals gain towards conserving the environment by planting more trees and participation in other strategic management conservation methods for future sustainability and improvement of livelihood. This finding was in line with other prior evidence that knowledge of agroforestry was significantly correlated with level of education where college graduates tended to be more interested in agroforestry than their counterparts with less academic qualifications. Every additional year of education decreased the probability that the household exploited forest/tree products and less conversion of woodlands to arable land (Odoemena et al., 2010; Volker & Waibel, 2010; Arbuckle et al., 2009; Dolisca et al., 2007; Pahari et al., 2000).

On the other hand, unit increase of land resulted to about 1.4 times higher, chances of farmers' lifetime value of retaining trees on farm. Further, the computed predicted probabilities on land size of the farmers showed that as land size increased there was corresponding increase of probability of the farmers retaining trees on farm (Figure 4.26). This was further evidenced by a positive correlation between land size and the number of trees planted on farm. Conversely, reduction of land size limited the likelihood of tree retention. This implied that farmers were to invest on trees if and only if land size was sufficient in meeting various household needs including agricultural produce.

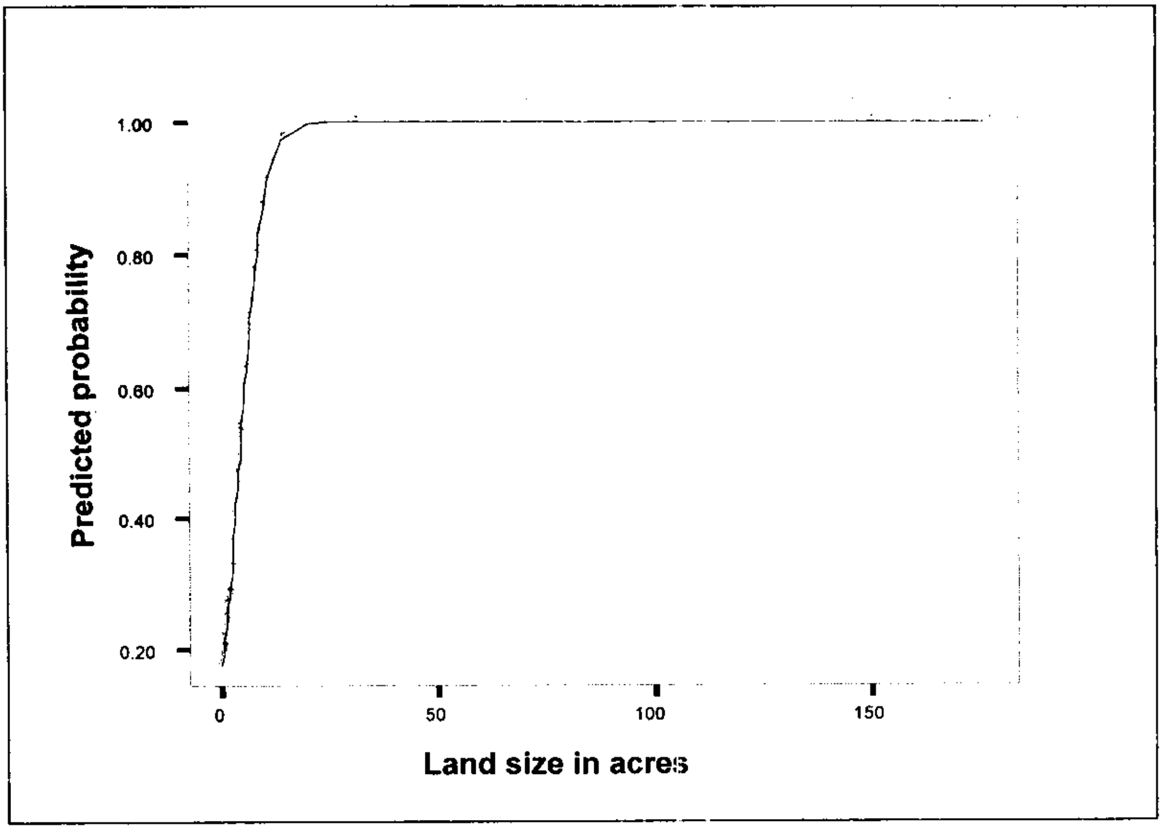

Figure 4.26: Land size and predicted probability of tree retention on farm

Majority of the farmers singled out scarcity of land as major limiting factor/barrier on continous tree planting. Land size and ownership have been found to be among the most critical determinants that would enable forestry farming to thrive well in Africa and other many countries across the world. Essentially, there is always a competition between agricultural, dairy/livestock farming and growing of trees on farm. Cases of small land sizes, farmers prioritize the former and carry out boundary planting or plant less competitive trees with food crops, whereas farmers with large tracks of land, allocate some portions for trees or large scale plantations. However, type of land ownership in this study was not found significant factor of tree retention because farmers suryed had purchased land or inherited from parents or allocated by government. This implied both categories of farmers had an element of permanence land tenure, which has been found a significant factor of tree retention.

Siregar et al. (2007) reported that land was a significant factor in influencing a community's decision to plant trees on large scale. Their study showed farmers with small-scale land holdings opted for agricultural, rather than forestplantations, as they needed immediate cash flow hence shorter rotations of crops cultivated. Similarly, Nguyen et al. (2010) reported land privatization on afforestation positively impacted on the number of trees planted by the households. This was further evidenced in this study with positive correlation between land size and monthly income among various households. Therefore, it is easy to understand that for the farmer holding a small amount of land without other sources of income, it is difficult to choose trees over annual crops. In addition, Zhang and Owiredu (2007) reported the amount of land that the households own impacts positively on the household's decision to establish plantations. In this case, for 1% increase in land under outright ownership, there was a 7.6% probability that farmers will establish forest plantations.

Furthermore, the logits of the male-headed households 'most likely' and 'less likely' to retain trees on farm were about 2.9 and 2.8 times significantly higher as compared to female-headed households who were 'not likely'. The significant contribution of male-headed household in likelihood of tree retention as compared to female headed households may be explained by cultural setting of the community members of the study sites where women might have limited access in land tenure, participation in community groups as a result of household duties, free access to fruit trees, among others, resulting to less interest in tree farming. Similar differentials have been found in other related studies (Adebayo et al., 2010; Nuggehalli and Prokoy, 2009; Lingani et al., 2009; Maskey et al., 2006). According to Nuggehalli and Prokoy (2009), social cultural norms and traditions define and shape behaviours of men and women, which present obstacles to participation in resource management effort.

Men are considered to be responsible for village development and governance, reducing women to their personal and household attributes, which continue to constrain them. In their study, they also reported that women did not contribute to decision-making regarding forestry activities. Lingani et al. (2009) reported women are often constrained in accessing and controlling land and forest resources due to construction of gender identities within households. In contrast, Maskey et al. (2006) reported women's participation in community forest management was enhanced by roles of various institutions, which changed the assumption that men were more actively involved in forest management than women.

Farmers who had gained technical skills, which influenced them into tree growing, had about 2.2 times chances higher of retaining trees on farm than those who had not acquired similar skills. Moreover, farmers who did not view labour involved in tree management as intense and costly, their chances of retaining trees on farm were about two times higher as compared to those who viewed tree farming as labour intensive and costly. In multinomial regression model, those who viewed less labour and cost in managing trees were about 4.4 and 2.6 times 'most likely' to retain trees on farm as compared to those who were 'not likely'. This was consistent with comparison on less and 'not likely' to retain trees on farm.

The acquisition of technical skills improved techniques of the farmers on silvicultural tree management and created awareness on the role of trees on farm and for environmental conservation. This resulted to high tree retention. In addition, the positive correlation between technical skills and extension services as well as marketability implied that the farmers had not only obtained knowledge on tree management but also their levels of marketability and the positive contribution of extension services even though majority of the farmers had not received adequate extension services. The limited difficulties experienced in marketing the tree produce continued to affect positively farmers' tree retention especially for those who had planted them as a source of income for improved livelihood.

Access to and use of extension services has a positive impact on silvicultural investment by farmers who had established plantations. Forest owners who had attended forestry extension activities were 2.6 times 'more likely' to have decided to thin their stands than those that had not (Zhang and Owiredu, 2007; Dhubhain et al., 2010). This was also reported by Rodriguez-Vicente and Marey-Perez (2009b) who affirmed that land allocation between forestry and other uses was dependent on market factors such as expected rates of return to alternative types of land use, among other factors. For instance, harvesting age was considered optimal depending on the current and expected market conditions for all potential forest products. In this way, the owner could decide whether or not to harvest timber commercially on the basis of market perspectives.

The significant correlation between extension services and motivation to plant trees mainly for environmental conservation, source of livelihood and aesthetic value enhanced the ability of the farmers to retain trees on farm. This concurs with Arbuckle et al. (2009) who reported strong positive relationship between extension services and interest in agroforestry, especially on conservational issues. This was further buttressed by group of farmers who were interested in tree farming for recreational and aesthetic purposes. This was more evidenced on the group of farmers who did not necessarily depend on their land for the bulk of their livelihoods and were 'likely' to give more weight on environmental, aesthetic and recreational factors when making decision on the use of land. Moser et al. (2009), reported landowners who claimed to be interested in aesthetic or enjoying the woods generally had higher volumes per hectare than those who owned woods because they were part of their farm. Also they reported farmers with an aim of generating income from the tree product had higher volumes per hectare than those who harvested for salvage purposes.

Similarly, in multinomial logistic regression model, farmers who were motivated to plant trees for environmental conservation as compared to those for source of livelihood were about 3.5 to 4 times 'most likely' to retain trees on farm as compared to those who were 'not likely'. Also those who did not experience any marketing problems of tree produce had about 3.8 times higher chances of 'most likely' to retain trees on farm as compared to those who were 'not likely' as a result of experience market problems (Table 4.31).

Table 4.31: Multinomial logistic regression model on fitting determinants of farmer's tree retention on farm

	Most likely/not likely				Less likely/not likely			
Explanatory variable	β	S.e (β).	p-value	Odds ratio	β	S.e (β).	p-value	Odds ratio
Intercept	1.41	0.32			0.41	0.37	0.277	
Site: Lari	-0.51	0.51	0.315	0.6	0.23	0.56	0.678	1.3
Kikuyu	-1.33	0.50	0.008	0.3	-1.03	0.60	0.087	0.4
Nyeri South	-1.17	0.47	0.013	0.3	-0.55	0.53	0.302	0.6
Gender	1.05	0.42	0.013	2.9	1.03	0.50	0.038	2.8
Intercept	0.00	0.37			-0.63	0.44		
Education: None	-1.25	0.72	0.082	0.3	0.64	0.90	0.472	1.9
Primary	-0.46	0.58	0.426	0.6	0.62	0.80	0.439	1.9
Secondary	-0.63	0.59	0.287	0.5	0.89	0.80	0.266	2.4
Intercept	1.39	0.50			-0.511	0.73		
Motivation	1.24	0.44	0.005	3.5	1.40	0.49	0.005	4.0
Intercept	0.37	0.31						
Labour and cost	1.49	0.58	0.010	4.4	1.30	0.63	0.038	3. 7
Intercept	0.42	0.21			-0.20	0.24		
Harvesting permission	0.94	0.39	0.017	2.6	0.58	0.44	0.191	1.8
Intercept	0.23	0.28			-0.19	0.31		
Harvesting regulation	0.98	0.42	0.019	2.7	1.16	0.48	0.017	3.2
Intercept	0.27	0.26			-0.55	0.32		
Marketing problem	1.33	0.66	0.043	3.8	1.23	0.71	0.085	3.4
Intercept	0.51	0.22			-0.13	0.26		
Forest association	0.49	0.445	0.267	1.6	0.98	0.48	0.043	2.7
Intercept	0.64	0.27			-0.18	0.27		

Evaluation of stepwise method based on model classification indicated that two models did not sufficiently predict the likelihood of the farmers to retain trees on farm. Some variables had 100% prediction on 'most likely/likely' and sometimes 97% of not 'likely/less likely' varying to about 32%, thus resulting in overall predicted percentage of model classification not more than 70%. The highest in this case was land with 66% of overall prediction of likelihood of farmers to retain trees on farm. Therefore, due to the correlation effect of some variables as presented earlier, various independent explanatory variables were fitted both in binary using backward wald method and multinomial logistic regression model. However, for the latter model, fitting together various uncorrelated variables, no sufficient significant determinants were found as compared to stepwise fitting of the same variables in multinomial logistic regression model. Only, labour' and village forest association were found as significant determinants on 'less likely/not likely' logits.

In contrast, the binary logistic based on uncorrelated variables fitted together in the model showed that, education, land size, technical skills, and harvesting permission were significantly associated with likelihood of farmers retaining trees on farm. This model further identified village forest association and marketability as other possible determinants of the likelihood of the farmer willing to retain the trees on farm. Farmers who had village forest association had about 2.8 times higher chances to retain trees as compared to those that were not having village forest association. Similarly, age was found to significantly leading to levels of tree retention. Equally, those who did not experience any difficulties in marketing their tree produce were about 70% higher to retain trees on farm as compared to those who experienced marketing problems (Table 4.32). This model correctly predicted 82and 81% of 'not likely' and 'likely' group of respondents, respectively, resulting to 81% of overall predicted percentage. This was quite an improvement from stepwise fitting of variables, hence reliability of the model and coefficient parameters.

Table 4.32: Binary logistic regression model using backward Wald method on fitting determinats of farmer's tree retention

Explanatory variables		β	S.e (β).	d.f	p-value	Odds ratio
Education:	None	-2.006	0.987	1	0.042	0.1
	Primary	-0.178	0.650	1	0.784	0.8
	Secondary	-1.231	0.654	1	0.060	0.3
Gender of household head		-0.813	0.563	1	0.149	0.4
Age		-0.028	0.016	1	0.07	0.97
Land size		0.566	0.107	1	0.000	1.8
Technical skills		1.234	0.576	1	0.032	3.4
Harvest permission		0.985	0.429	1	0.022	2.7
Village forest association		1.037	0.536	1	0.053	2.8
Marketing problems		-1.386	0.614	1	0.024	0.3
Constant		0.343	1.016	1		

In this logistic regression model of selected variables, age of the farmers was found to be a significant determinant influencing the tree retention on farm. Similarly, farmers who sought permission from KFS to harvest their trees had about 2.7 times chances higher of retaining trees on farm as compared to those who did not sought permission (Table 4.32). In addition farmers who had village forest association were about 2.8 chances higher to retain trees on farm as compared to those who did not have.

It was observed that fitting age alone in both logistic and multinomial regression models was not a significant factor influencing the likelihood of the farmer to retain trees on farm. This concurred well with other research where age was found not a significant factor influencing the interest of landowners in agroforestry and farmers' investment on tree growing (Arbuckle et al., 2009; Zhang and Owiredu, 2007). However, in this study when age was fitted together with other determinants namely, education, gender of the household head, landsize, technical skills and harvest permission it was found to be significant in influencing farmers ability to retain trees on farm. These could be groups of farmers whose children were employed and perhaps working away from home, hence resulting to tree farming as it was found to be less labour intensive and likely to help their children and grand children for future use like in construction and other needs. Some of them also were naturally motivated to plant trees for environmental conservation and for aesthetic purposes.

Middle aged and young farmers were also planting trees on their farm with the aim of generating income and household needs like supply of fuelwood, timber, construction poles and demarcation of their lands from the neighbours. This tended to influence the probability of likelihood of tree retention. For instance, a study carried out on farmer participatory evaluation of agroforestry trees in eastern Zambia showed that fuelwood and construction materials were mentioned as the most and second most important by-products among the group of farmers (Kuntashula and Mafongoya, 2005). Nevertheless, some studies have shown that young households contemplated on forest farming as an income activity whereas older people possess superior knowledge about various forest resources, more likely to participate in forestry programs and may utilize more medicinal plants and wild foods resulting to high retention of trees on farm (Valdivia and Poulos, 2009; Lingani et al., 2009; Odoemena et al., 2010; Maskey et al., 2006; Zhang and Owiredu, 2007)

Consequently, the significant contribution of village forest association on the likelihood of tree retention on farm implied that the roles that were undertaken which included; seedling production and supply, tree planting, thinning and pruning, bee keeping, (non-wood products), environmental conservation and marketing, had a positive effect on farm forestry. Even though only 35% of the population sampled had village forest association of which 47% were members as compared to 53% who were not, their existence showed a significant indication on improvement of tree cover. This is in line with other prior evidence where membership of rural institutions did not significantly encourage woodland conversion but were useful instruments for woodland retention. Becoming a member of a farmers' group increased knowledge and farmers' participation in forestry activities (Odoemena et al., 2010; Siregar et al., 2007; Zhang and Owiredu, 2007).

Nevertheless, reinforcement of forest regulation on tree harvesting by Kenya Forestry Service was found acceptable among most of the farmers and significantly influenced the farmers to retain trees on farm and participate in tree growing. This was in contrast with what was commonly expected that seeking permission to harvest trees, which the farmers had planted, would discourage them from continous tree planting. However, the finding revealed that farmers viewed it as a security measure since tree cutting without permission would not only affect the environment but also encourage theft both from farmers' field and government gazzeted forests. In return, this would lengthen the period trees would be on farm and encourage planting. This was further evidenced by Polyakov and Teeter (2005) who examined Ukrainian forest regulatory policy on forest groups and permit classifications that permit or prohibit final felling and found out that such instruments were directed towards maintaining the environment and social functions of specified forests.

CHAPTER FIVE: SUMMARY OF FINDINGS, CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The results and discussions in chapter 4 have pointed out important determinants of forest cover and carbon sequestration for mitigation of climate change and restoration of the environment. The chapter has also provided suitable statistical models in determining the recruitment of seedlings and survival for improving the understanding of their role in forestry. The significance of commonly grown plantation species in carbon sequestration underscored the importance of these trees in payment of ecosystem services resulting to improvement of forest cover in Kenya. The emphasis on statistical modelling of tree retention determinants on farm provided a strong foundation on which farm forestry policies in Kenya would address the purpose of improving forestry cover to 10% as per FAO recommendations. Therefore, in this chapter, conclusions and recommendations are provided to strengthen any future action plans towards the improvement of forest cover and carbon measurements in Kenya.

5.2 Conclusions

This study focused on four objectives. The first one was to to determine the recruitment and survival of commonly grown plantation tree species (*Pinus patula, Eucalyptus saligna, Cupressus lusitanica* and *Juniperus procera*) in contributing to forest cover under different sites. The ARIMA model with one autoregressive parameter, one order of differencing and moving average best fitted the data for seedling recruitment and forecast for five years, 2007 to 2011. No further forecasting was possible due to limited time interval of seedling recruitment data. Time series analysis requires more time intervals at least 50 to correctly model and forecast the trend of seedling recruitment. However, the available and collected data showed some decreased trend of seedling recruitment in Central highlands conservancy.

Exotic seedlings of various trees species were dominantly planted in farmers' field. *Grevillea robusta* followed by *Cupressus lusitanica* were most prefereed by farmers whereas *Markhamia lutea* and *Prunus africana* were commonly planted among indigenous tree species. Also the uptake of eucalyptus hybrid clones underscored a significant role in improving the forest cover in Central highland conservancy. The time series models on forecasting the trend showed that millions of such seedlings would be taken up by farmers and other tree investors resulting in an improvement of forest cover within Central highlands of Kenya. The successful application of time series models in forest data showed further strength of ARIMA models in a wide use of scientific disciplines.

In gazzetted forests *Cupressus lusitanica, Pinus patula* and *Eucalyptus saligna* were the most planted tree species in decreasing order in most parts of Central highland conservancy. *Juniperus procera* was the fifth most commonly planted tree species after *Eucalyptus grandis*. *Cupressus lusitanica* was highly recruited at Lari, Nyeri South and Nyeri North followed by *Pinus patula*. Kiambu had highest mean overall recruitment of seedlings followed by Nyeri North and Nyeri South. This was based on the number of forest stations that varied from site to site explaining the differences on the number of seedling recruitment. Therefore, Kiambu, Nyeri South and Nyeri North played valuable role in improving the forest cover in Central Kenya. The available area also significantly influenced the rate of re-forestation and afforestaion programmes undertaken by Kenya Forest Service for improving forest cover in the country.

Survival rates of commonly grown plantation trees species were influenced by site, DBH, basal area, thinning intensity, age and tree species. *Cupressus lusitanica* and *Pinus patula* had high survival rate among the sites as compared to *Eucalyptus saligna* and *Junipeus procera*. The high survival rate of *Cupressus lusitanica* and *Pinus patula* were attributed to good management practices and uses of the two species as compared to *Eucalyptus saligna*, which had short rotation period. *Junipeus procera* had poor establishment and poor managament in most sites. The low survival rate was also as a result of logging due to high demand and high quality of *Juniperus procera* fencing posts. The long time to maturity was also associated with low establishment of the tree species. Overall, the application of survival models, which are mainly used in medical research, provided good estimates that correctly predict the survival of commonly grown plantation tree species.

The second objective of this study was to quantify and analyze carbon sequestered by commonly grown plantation tree species at different ages of growth among environmental sites, for mitigation of climate change. Age, tree species, and environmental sites mainly explained variations on the amount of carbon sequestered. The fast growth of *Eucalyptus saligna* resulted to rapid accumulation of tree biomass, which explained why it had the highest amount of carbon sequestered above- and below-ground (roots) at Nyeri South. Also *Pinus patula* is known to grow relatively faster as compared to *Cupressus lusitanica*. This explained why it followed *Eucalyptus saligna* on the amount of carbon sequestered at Nyeri North while *Cupressus lusitanica* was distance third at Kiambu. The high decomposition rate of litter fall of *Pinus patula* resulted the highest amount of soil carbon in soils followed by *Cupressus lusitanica* with *Eucalyptus saligna* containing least amount of soil carbon. The use of mixed model in the analysis provided reliable estimates and comparisons underscoring the significance of assigning variables as random and fixed effects.

The relationship of growth parameters distinctly showed that DBH was the most significant growth parameter explaining tree biomass and carbon sequestration. Establishing this relationship becomes crucial when estimating the total amount of carbon as sequestered by branches, foliage, roots and litter. Reliable DBH meausurement could as well estimate the age of the tree, which had a significant contribution on differences on the amount of carbon sequestered.

The correlations between soil elements, N, P, K, C and soil pH indicated that measurement of one element would anticipate measure of another element Nitrogen and Carbon correlated indicating that determining their ratio could be used in estimating either of the other. This also indicated that available N has a direct association with % C both above-ground tree biomass and in soils. The intensity of tree planting especially for *Cupressus lusitanica* and *Pinus patula* at Kiambu and AEZ explained different reasons why Kiambu had the highest amount of soil carbon followed by Nyeri South and Nyeri North.

Rich humus, litter fall and depositions probably explains why the upper surface soil depth of 0-20 cm had highest % C. This decreased with an increasing soil depth. However, soil bulk density increased with an increase in soil depth, which had an overall effect of higher total soil carbon. Since soil depth and bulk density were multipliers of quantifying soil carbon per ha, there was an overall increasing trend of soil carbon with depth. It was also noted that carbon stored in soils was higher than carbon in aboveground tree biomass.

The third objective was to evaluate expected income of carbon quantified from commonly grown plantation tree species in comparison with sale of wood as incentives of tree farming in improving forest cover and mitigation of climate change. There were significant amount of carbon dioxide equivalent removed from the atmosphere among commonly grown plantation tree species. The variations were associated with environmental sites, soils, tree species, stand density, tree size and age. This was directly linked to the amount of carbon tree sequestered as concluded in the second objective. The genetic and architectural composition of various tree species explained further the differences on CO_2e for biomass accumulation at trunks, branches, roots and soils. Trees with higher crown and DBH measurements had direct relationship with CO_2e demonstrating the role of trees in mitigating climate change as CO_2 is one of the greatest greenhouse gases.

The carbon market is likely to suffer from getting committed clients who are likely to forego the sale of wood and preserve trees for payment of environmental services. This was because current prices fetched below the expected amount from the sale of wood. However, including soil carbon with above-ground carbon and the provision of better carbon prices, there was a likelihood of high tree investors opting to growing trees for carbon market. If this was not considered, then the carbon prices must be higher as much as US $ 100 per ton of CO_2e. Significant differences on the expected amount of income to be realized from the sale of carbon were due to tree species, age, stand density, site and carbon pricing. Overall, investing in the carbon market would significantly boost the country's economy and improve health of the environment through mitigation of negative effects of climate change.

The fourth objective was to identify and analyze determinants of lifetime value of the farmer willing to retain trees on farm in improving forest cover and carbon sinks. The classification of dependent variable into two and three way, which was associated and regressed with various determinants, provided an indepth analysis of the data from this objective. The use of descriptive statistics especially chi-square identified a number of factors that were associated with the likelihood of the farmer willing to retain trees on the farm. The application of non-parametric tests also enhanced the skills of determining the differences among the variables in relation to the established association. The use of correlations strengthened the modelling techniques as uncorrelated factors provide reliable estimates for determining the certainties of farmer's tree retention on farm. Fitting correlated predictors in the model leads to multicollinearity resulting to inflation of standard errors of estimates and confidence intervals. This produces unreliable estimates, reducing the power of the statistic in correctly predicting the likely outcome of anticipated event.

The use of binary and multinomial logistic regression models led to correct identification of the determinants of the lifetime value of the farmer willing to retain trees on farm for long period of time in improving forest cover and carbon. The determinants were site, gender of the household head, age of the household head, education level, average monthly income, main occupation, size of the land, use of extension services, acquisition of technical skills, labour, use of trees, harvesting regulation, market conditions and existence of forest association. The site differentials were as a result of land sizes, proximity to the forests, locality as well as the wealth and poverty status. Older farmers were more likely to retain trees on farm because of less labour and for future generation as compared to younger ones who venture into tree growing as source of livelihood. It was also evident that those who were formally employed had high likelihood of tree retention because venturing into tree growing was valued as off employment and long-term investment, which required very little labour.

Acquisition of technical skills improved the likelihood of farmers retaining trees on farm because of gaining more knowledge on how to tend trees, regulations to be followed and marketability. This was further evidenced by farmers who had formal education and were more likely to retain trees on farm as compared to those who had none or limited formal education. It was also notable that households that had high monthly income increased chances of retaining trees on farm. This would as well be linked to land size where farmers who were aware on the role of forestry for employment, creation and provision of income were more likely to increase their land size through purchasing for tree investment.

5.3 Recommendations

The following recommendations are drawn from the findings of this study as per the objectives.

5.3.1 Recruitment and Survival of Commonly Grown Plantation Tree Species

Modelling forest cover requires combination of robust tools that would provide reliable estimates based on various components to assist in the projection of likely scenarios in future. An assessment of seedling recruitment in farmers' field and government forest would be vital in improving the understanding of the status of forest cover in Kenya. Therefore,the use of time series models proved to be one of the possible methods that forestry sector would utilize in forecasting the trend of tree cover in Kenya and expected intervention measures. This would also be useful for planning purposes because the availability of seedlings would depend on the accessibility to quality seeds. The demand and supply of seedlings would aid the seed supplies on steady flow of seeds in meeting the afforestation and reforestation programmes.

To effectively utilize the time series techniques, there is a need for the forestry sector especially KFS and owners of tree nurseries to keep record of distributed number of seedlings yearly or quarterly. This is because time series analysis requires a lot of data collected at equal time intervals.

Cupressus lusitanica followed by *Pinus patula* and *Eucalyptus saligna* were the most rectruited seedlings on gazzetted forests. *Grivellea robusta*, *Cupressus lusitanica*, *Markhamia lutea*, *Casuarina equistofolia* and *Prunus africana* were among the most dominant tree species rectruited on farm. Therefore, there is a need for widening the genetic base of planting material that have less competition with plant food crops to encourage farmers intercrop trees with food and cash crops. The wider genetic base would also aid in rehabilitation of degraded areas, which in return would improve the status of forest cover in the country.

High mortality was found for *Juniperus procera* and *Eucalyptus saligna* due to poor establishment and management. As a result, there is a need to enhance the efficient management of gazzetted forest plantations to enhance forest cover in the country.

Also the application of survival models on forest data underscored the power of survival analysis in many disciplines. Thus, there is a need to subject forestry data to advanced methods of analysis other than using traditional methods on percentage summaries of stand density in order to provide reliable estimates for future prediction on survival of commonly grown plantation tree species, among others, in improving forest cover. This further, strengthened methods that could be used in analyzing survival data of tree species.

5.3.2 Carbon Sequestration from Commonly Grown Plantation Tree Species

Eucalyptus saligna had highest amount of carbon sequestered followed by *Pinus patula* and *Cupressus lusitanica* across ages and sites. Therefore, more awareness is needed on the potentials such tree species have for mitigation of climate change through removal of carbon dioxide from the atmosphere.

The relationship that existed among the tree growth parameter requires that estimation of biomass equations both for above-ground and below-ground need to be developed to improve on the accuracy or estimates of carbon quantification. For example, there is a need to have biomass expansion and conversion factors to aid estimation of total tree biomass on the basis of DBH and height measurements.The differentials on the amount of carbon sequestered among tree species, sites, age. stand density and tree measurements requires that when providing estimates of carbon stock under forest systems, these factors need to be taken into account.

5.3.3 Income Returns from Sale of Carbon and Wood

Carbon pricing had a significant effect on influencing tree investor to opt for carbon market instead of wood and other tree products. This required that the prices of carbon to be adjusted on the basis of the market value of the tree to enable tree investors make decision on investment of payment of environmental services. There was also a need to provide information on the best methodologies that tree investors would use while negotiating for carbon market.

Soils stored a significant amount of carbon in commonly grown plantation tree species and there is a need to include soil carbon while accounting for the total amount of carbon sequestered by trees. This needs to be included while paying for carbon.

5.3.4 Tree Retention Determinants

The use of binary and multinomial logistic regression models provided reliable estimates of the determinants of lifetime value of the farmer willing to retain trees on farm. The exploration of the data based on the dependent and independent variables provided useful insight of the data for effective modelling. Thus, this study contributed to the general knowledge on methodologies and recommends that similar approach could be used for related studies.

Land size was a significant factor influencing the farmer's decision to retain trees on farm. In order to enhance forest cover and carbon sinks through farm forestry, there is a need to target such group of farmers because their likelihood of taking up tree investment would be high as compared to those with small land holdings.

Monthly income was a significant determinant that would enable the farmer retain trees on farm. Therefore, individuals with higher earnings need to be targeted while promoting farm forestry to improve forest cover. Further, sensitization to formal employees on taking up forestry activities would be valuable as the results showed that these group of farmers were keen to invest in tree farming.

Technical skills were highly associated with the farmer's ability to retain trees on farm. Therefore provision of more extension services would significantly boost farmers' willingness to retain trees on farm for long period of time.

Tree harvesting regulation was found to significantly influence farmer's lifetime value to retain trees on farm. Strengthening KFS regulation mechanisms would help most of the farmers keen on tree growing.

Availability of market for forest produce influenced the farmer's decision to engage in tree farming. This improved their likelihood of tree retention. Therefore, introducing complimentary marketing services would encourage farmers engage in tree production.

Age was also found to be a determinant affecting the farmer's decision to retain trees on farm. Older farmers had high likelihood of tree retention because they valued trees to be less labour intensive. Young farmers were in tree farming as source of livelihood and, therefore targeting these group of farmers while promoting farm forestry would lead to improvement of forest cover and carbon sinks.

5.3.5 Areas of Further Research

Studies on tree rectruitment using stochastic modelling techniques would lead to further expansion of methodogies suitable in estimating tree recruitment. This would also cover mortality of tree species at different locations and transitional states.

Research on below- and above-ground biomass estimation of major indigenous and exotic tree species would significantly contribute to development of local biomass expansion and conversion factor. This would be useful in estimating tree biomass for carbon quantification and CO_2e for mitigation of climate change.

Market trends on carbon pricing need further research to adequately inform various players on likely incentives farmers would obtain from carbon trading. This would also help in diversifying carbon schemes for the purpose of encouraging developed/industrial countries to cut on carbon emissions.

REFERENCES

Adebayo, A.G., Oyun, M.B. and Kadeba, O. (2010). Access of rural women to forest resources and it's impact on rural household welfare in North Central Nigeria. *Forest Policy and Economics Vol. 12: 439-450*

Alder, D. and Silva, J.N.M. (2000). An empirical cohort model for management of Terra Firme forests in the Brazillian, Amazon. *Forest Ecology management 130, 141-157.*

Alder, D. (1995). Growth modeling for mixed tropical forests. *Tropical Forestry Papers.* Oxford Forestry Institute, University of Oxford, 231p.

Alberti, G., Perrssotti, A. P., Piussi, P., Zerbi, G. (2008). Forest ecoystem carbon accumulation during secondary succession in the Eastern Prealps of Italy. *Forestry, Vol. 81, No.1: 1-11*

Amichev, B., Y., Burger, J., A., Rodrigue, J. A. (2008). Carbon sequestration by forests and soils on the mined land in the Midwestern and Appalachian coalfields of the U.S. *Forest Ecology and Management Vol. 256: 1949-1959*

Anatoli, I.Y., Konstantin, G. A., Igor, A., Aliaksandr, K., Akushevich, L. and Ukraintseva, S.V. (2007). Stochastic model for analysis of longitudinal data on aging and mortality. *Mathematical Biosciences. 208: 538-551.*

Anita, S. (2000). *Analysis and control of Age-Dependent Population Dynamics,* Kluwer Academic publishers, Dordreccht.

Anita, S. (1998). Optimal harvesting for a non-linear age dependent Population Dynamics, *J. Math. Anal.Appl. 226*

Antibus, R. and Linkins III, A.E. (1992). Effects of liming a red pine forest floor on mycorrhizal numbers and mycorrhizal and soil acid phosphatase activities. *Soil Biology and Biochemistry, Vol. 24. No.5:479-487*

Arbuckle Jr. J.G., Valdivia, C., Raedeke, A., Green J. and Rikoon, J. S. (2009). Non-operator landowner interest in agroforestry practices in two Missouri watersheds. *Agroforest Syst. Vol. 75: 73-82.*

Astrup, R., Coates, D.K. and Hall, E. (2008). Recruitment limitation in forests: Lessons from an unprecedented mountain pine beetle epidemic. *Forest Ecology and Management Vol. 256: 1743-1750*

Balteiro, L. D. and Rodriguez, L.C.E. (2006). Optimal rotations on Eucalyptus plantations including carbon sequestration-A comparison of results in Brazil and Spain. *Forest Ecology and Management Vol. 229: 247- 258*

Banfield, G.E., Bhatti, J.S., Jiang, H., Apps, M.J. (2002). Variability in regional scale estimates of carbon stocks in boreal forest ecosystems: results from West- Central Alberta. *Forest Ecology and Management Vol. 169: 15-27*

Barbu, V. and Lannelli, M. (1999). Optimal control of population dynamics, *J. Opt. Theory Appl 102 : 1-14.*

Berkson, J. and Gage, R.P. (1950). Calculation of survival of cancer. *In: Proceedings of the staff meetings of the Mayo clinic, vol. 25, pp. 220-286.*

Bigsby, H. (2009). Carbon banking: Creating flexibility for forest owners. *Forest Ecology and Management Vol. 257: 378-383*

Billen, N., Roder, C., Gaiser., T., Stahr, K. (2009). Carbon sequestration in soils of SW-Germany as affected by agricultural management- callibration of the EPIC model for regional simulations. *Ecological Modelling Vol. 220: 71-80*

Breugel, M. v., Hall, J.S., Craven, D. J., Gregoire, T, G., Park, A.., Dent, D. H., Wishnie, M. H., Mariscal, E. D., J.., Ibarra, D.., Cedeno, N.. and Ashton, M. S. (2010). Early growth and survival of 49 tropical tree species across sites differing in soil fertility and rainfall in Panama. *Forest Ecology and Management in press*

Buchman, R.G., Pederson, S.P., and Walters, N.R. (1983). A tree survival model with application to species of the Great Lakes region. *Canadian Journal of Forest Research. 13: 601-608.*

Buchman, R.G. and Shiftley, S.R. (1983). Essentials for forecasting mortality trends and changes. In: Bell, John F., Atterbury, Toby, eds. *Proceedings of an international conference. Renewable resource inventories for monitoring changes and trends. 1983 August 15-19; Corvallis*, OR. SAF Publ.83.14. Carvallis, OR: Oregon State University, College of forestry: 141-144.

Busoni, G. and Matucci, S. (1997). A problem of optimal harvesting in two stage age dependent population models, *Math. Biosci 143 : 1-33*

Chladna, Z. (2007). Determination of optimal rotation period under stochastic wood and carbon prices. *Forest Policy and Economics Vol. 9: 1031-1045*

Central Bureau of Statistics (2004). Statistical Abstracts, Ministry of Planning and National Development, Government printers.

Chen, X., Zhang, X., Zhang, Y., Booth, T. and He, X. (2009a). Changes in carbon stocks in bamboo stands in China during 100 years. *Forest Ecology and Management Vol. 258: 1489-1496.*

Chen, X., Zhang, X., Zhang, Y., Wan, C. (2009b). Carbon sequestration potential of the stands under the Grain for Green Program in Yunnan Province, China. *Forest Ecology and Management Vol. 258: 199-206.*

Chertov, O.G., Komarov, A.S., Bykhovets, S.S., Kobak, K.I. (2002). Simulated soil organic matter dynamics in forests of the Leningrad administrative area, northwestern Russia. *Forest Ecology and Management Vol. 169: 29-44.*

Collet, D. (1994). *Modeling survival data in medical research.* Chapman and Hall. /CRC, New York, NY, 347 pp.

Cox. D.R. and Oakes, D. (1984). *Analysis of survival data.* Chapman and Hall. London.

Davis, S. C., Hessl, S. C., Scott, C. J., Adams, M., Beth., Thomas, B, R. (2009). Forest carbon sequestration changes in response to timber harvest. *Forest Ecology and Management Vol. 258: 2101-2109*

De Vries, W., S., S., Dobbertin, M., Sterba, H., Laubhann, D., van Oijen, M., Evans, C., Gundersen, P., Kros, J., Wamelink, G.W.W., Reinds, G.J., Sutton, M.A. (2009). The Impact of nitrogen deposition on carbon sequestration by European forests and heathlands. *Forest ecology and Management Vol. 258: 1814-1823*

Dhubhain, A., Ni., Maguire, Karl and Farrelly, Niall. (2010). The harvesting behaviour of Irish private forest owners. *Forest Policy and Economics Vol. 12: 513-517*

Digby, P., Galwey, N. and Lane, P. (1989). Genstat 5 a second course. Oxford University press p. 166-187.

Dolisca, F., McDaniel, J. M., Teeter, L. D. and Jolly, C. M. (2007). Land tenure, population pressure, and deforestation in Haiti: The case of Foret des Pins Reserve. *Journal of Forest Economics Vol. 13(2): 277-289.*

Dowell, R., C., Gibbins, D., Rhoads, J. L., Pallardy, S. G. (2009). Biomass production physiology and soil carbon dynamics in short rotation grown *Populus deltoids* and *P. deltoids* x *P. nigra* hybrids. *Forest Ecology and Management Vol. 257: 134-142*

DRSRS and KFWG (2006). Changes in Forest Cover in Kenya's Five water towers 2003- 2005. *Report covering two-year period of study with support from Royal Netherlands Embassy.*

Eaton, J. M., and Lawrence, D. (2009). Loss of carbon sequestration potential after several decades of shifting cultivation in the Southern Yucatan. *Forest Ecology and Management Vol. 258: 949-958*

Elliot, K.J., Knoepp, J.D. (2005). The effects of regeneration harvest methods on plant diversity and soil characterics in the southern Appalachians. *Forest Ecology and Management Vol. 211: 296-317*

Epila-Otara, J.S. and Ndhokero, J. (2009). Selection and site matching of Eucalyptus clones in Uganda. *Journal of East African Natural Resource Management (JEANARM) Vol. 3 (1, I-iv): 237-248*

Evelyn, O.B. (2009). Utilizing geographical information system (GIS) to determine optimum forest cover fro minimizing runoff in degraded watershed in Jamaica. *J. International Forestry Review Vol. II (3), 375-393*

Fang, J., Oikawa, T., Kato, T., Mo, W. and Wang, Z. (2005). Biomass carbon accumulation by Japan's forests from 1947 to 1995. *Global Biogeochem. Cycles. Vol 19: 1-10.*

Farwig, N., Sajita, N., Bohning-Gaese, K. (2009). High seedling recruitment of indigenous tree species in forest plantationsin Kakamega Forest, western Kenya. *Forest Ecology and Management Vol. 257: 143-150*

FAO. (2003). Forestry Outlook Study for Africa: Sub-regional report West Africa, Rome, p.66

Foster, N.W. and Morrison, I.K. (2002). Carbon sequestration by a jack pine stand following urea application. *Forest Ecology and Management Vol. 169: 45-52*

Fukuda, M., Iehara, T. and Matsumoto, M. (2003). Carbon stock estimates for Sugi and Hinoki forests in Japan. *For. Ecol. Manage. Vol. 184: 1-16.*

Gaboury, S., Boucher, J., Villenuve, C., Lord, D., Gagnon, R. (2009). Estimating the net carbon balance of boreal open woodland afforestation: A case study in Quebec's closed-crown boreal forest. *Forest Ecology and Management Vol. 257: 483-494*

Gachene, C.K.K. and Kimaru, G. (2003). Soil Fertility and Land Productivity - A guide for extension workers in the eastern Africa region. Technical Handbook No.30. Regional Land Management Unit (RELMA)/ Swedish International Development Cooperation Agency (Sida). ISBN: 9966-896-66-X.

Gaiser, Thomas., Abdel-Razek, M., Bakara, H. (2009). Modelling carbon sequestration under zero tillage at the regional scale. II. The influence of crop rotation and soil type. *Ecological Modelling Vol. 220: 3372-3379*

Gene, . I. (2007). The profitability of forest protection versus logging and the role of payments for environmental services (PES) in the Reserva Forestal Golfo Dulce, Costa Rica. *Forest Policy and Economics Vol. 10: 7-13.*

Ginwal, H.S. (2009). Provenance and family variation in growth performance of *Eucalyptus tereticornis* (Sm.) in a provenance cum progeny trial in Midnapore, India. *Forest Ecology and Management Vol. 258: 2529-2534*

Glenday, J.. (2008a). Carbon storage and Carbon emission offset potential in African riverline forest, the lower Tana river forests, Kenya. *Journal of East African Natural History. Vol. 97(2): 207-223.*

Glenday, J. (2008b). Carbon storage and emission offset potential in an East African tropical rainforest. *Forest Ecology and Management Vol. 235: 72-83.*

Glenday, J. (2006). Carbon storage and emission offset potential in an African dry forest, the Arabuko-Sokoke Forest, Kenya. *Environ Monit Assess Vol. 142:85- 95*

Guinto, D, F., House, A, P.N., Hong Xu, Z. and Saffigna, P. G. (1999). Impacts of repeated fuel reduction burning on tree growth, mortality and recruitment in mixed species eucalypt forests of Southeast Queensland, Australia. *Forest Ecology and Management Vol. 115: 13-27*

Guo, Z., Fang, J., Pan, Y. and Birdsey, R. (2010). Inventory- based estimates of forest biomass carbon stocks in China: A comparison of three methods. *Forest Ecology and Management Vol. 259: 1225-1231*

Gurtin, M. and Murphy, L.F. (1981). On the optimal harvesting of age- structured populations: Some simple models, *Math Biosci. 55: 115-136.*

Halofsky, J. and Ripple, W. (2008). Linkage between wolf presence and aspen recruitment in the Gallatin elk winter range of Southwestern Montana, USA. *Foresty, Vol. 81: 195-207*

Hamilton, D.A. and David A., Jr. (1986). A logistic model of mortality in thinned and unthinned mixed conflier stands of northern Idaho. *Forest Science. 32: 989-1000.*

Hamilton Jr. and Edwards, B.M. (1976). Modelling the probability of individual tree mortality. *Research paper INT-185.* USDA forest service, Intermountain forest and Range Experiment station, Ogden, UT, 22 pp

Hanson, F.B.and Ryan, D. (1998). Optimal Harvesting with both population and price dynamics, *Math Biosci. 148: 129-146.*

Hargreaves, K.J., Milne, R., Cannell, M.G.R. (2003). Carbon of afforested peatland in Scotland. *Forestry, Vol. 76: 299-317*

Hassan, R. and Ngwenya, P. (2006). Valuing forest services missing from the national accounts: The contribution of cultivated forests to wealth accumulation in Swaziland. *Forest Policy and Economics Vol. 9: 249-260*

Hett, J.M. (1971). A dynamic analysis of age in sugar maple seedlings. *Ecology. 52: 1071-1074.*

Hill, C., M. (2004). Economic benefits and costs of tree planting for salinity control. A contributed paper presented at the 48th Annual Conference of the Australian Agricultural and Resource Economics Society Melbourne, Victoria 11-13 February 2004

Hoch, L., Pokorny, B. and jong De, W. (2009). How successful is tree growing for smallholders in the Amazon. *International Forestry Review Vol. 11 (3): 299 310.*

Hopmans, P., Bauhus, J., Khanna, P., Weston, C. (2005). Carbon and Nitrogen in forest soils: Potential indicators for sustainable management of eucalypt forests in South-eastern Australia. *Forest Ecology and Management Vol. 220: 75-87*

Hopmans, P., Elms, S. R. (2009). Changes in total carbon and nutrients in soil profiles and accumulation in biomass after a 30-year rotation of Pinus radiata on Polzolized sands: Impacts of intensive harvesting on soil resources. *Forest Ecology and Management Vol. 258: 2183-2193*

Horner, G. J., Baker, P. J., Mac Nally, R., Cunningham, S. C., Thomson, J. R., Hamilton, F. (2010). Forest structure, habitat and carbon benefits from thinning floodplain forests: Managing early stand density makes a difference. *Forest Ecology and Management Vol. 259: 286-293*

Hosmer, D.W. and Lemeshow, S. (1989). *Applied logistic regression*. New York: John Wiley. 307 p.

Hosmer, D.W. and Lemeshow, S. (1980). A goodness of -fit test for the multiple logistic regression model. *Communication in statistics. A10: 1043-1069.*

Hritonenko, N. and Yatsenko, Y. (2006). Optimization of harvesting return from age-structured population, *J. Bioecon. 8 : 167-179.*

Hritonenko, N.and Yatsenko, Y. (2005). Optimization of harvesting age in integral age-dependent model of population dynamics, *J. Math Biosci 7:132-144*

Hu, H., Wang, G. G. (2008). Changes in forest biomass carbon storage in South Carolina Piedmont between 1936 and 2005. *Forest Ecology and Management Vol. 255: 1400-1408*

Husch, B., Beers, T., W. and Kershaw, J.A.Jr. (2003). Forest Mensuration, 4th edition. John Wiley and Sons, Inc. p373.

Ibarra, E. and Hirakuri, S. R. (2007). Institutional conflict and policy effectiveness: The case of the Costa Rican institutional reform. *Forest Policy and Economics Vol. 9: 591-601*

Im, E. H., Admas, D. M. and Latta, G. S. (2007). Potential impacts of carbon taxes on carbon flux in western Oregon private forests. *Forest Policy and Economics Vol. 9: 1006-1017*

International Panel of Climate Change (IPCC), (2001). *Third assessment Report Climate Change 2001*. The scientific basis. Cambrdige Univesity Press, UK

IPCC, (2003). *Good practice Guidance for Land use change and forestry*, chapter 3: land use, land use change and forestry sector Good practice Guidace (Task 1). IGES, 2003.

IPCC, (2006). 2006 IPCC Guidelines for National Greenhouse Gas inventories, chapter 4.

Jacobs, Douglass, F., Selig, Marcus, F., Severeid, Larry, R. (2009). Aboveground carbon biomass of plantations -grown American Chestnut (*Castanea dentata*) in absence of blight. *Forest Ecology and Management Vol. 258: 288-294*

Jaetzold, R., Schmidt, H., Hornetz, B and Shisanya, C. (2006). Farm management Handbook of Kenya; Natural conditions and farm Management information, Part B- Central Kenya, Subpart B2. Central Province, 2nd editionVol. II, Ministry of Agriculture, p. 151-172; 188, 202, 222;345-348; 352-371.

Janse, G. and Ottitsch, A. (2005). Factors influencing the role of Non- wood forest products and services. *Forest Policy and Economics Vol. 7: 309-319*

Jiang, H., Apps, M. J., Peng, C., Zhang, Y., Liu, J. (2002). Modelling the influence of harvesting on Chinese borea forest carbon dynamics. *Forest Ecology and Management Vol. 169: 65-82.*

Johnson, K., Scatena, F. N., Pan, Y. (2010). Short and longterm responses of total soilm orgnic carbon to harvesting in northern hardwood forest. *Forest Ecology and Management Vol. 259: 1262-1267*

Johnson, D.W., Knoepp, J.D., Swank, W.D., Shan, J., Morris, L.A., Van Lear, D.H., Kapeluck, P.R. (2002). Effects of soil management on soil carbon: results of long term resampling studies. *Environmental Pollution Vol. 116: S210- S208*

Kariuki, M. (2008). Modelling the impacts of various thinning intensities on tree growth and survival in a mixed species eucalypt forest in Central Gippsland, Victoria, Australia.

Karlsson, K. and Norell, L., (2005). Modelling survival probability of individual trees in Norway spruce stands under different thinning regimes. *Can. J. Res. 35: 113-121*

Kaumbutho, P.G. and Simalenga, T.E. (eds). (1999). *Conservation tillage with animal traction.* A resource book of the Animal Traction Network for Eastern and Southern Africa (ATNESA). Harare. Zimbabwe. 173p

Kauppi, P. E., Rautiainen, A., Korhonen, K. T., L., Aleski., Liski, Jari., Nojd, P., Tuominen, S., Haakana, M., and Virtanen, T. (2010). Changing stock of biomass carbon in a boreal forest over 93 years. *Forest Ecology and Management Vol. 259: 1239-1244.*

Keane, R.E., Mike, E., Austin, F. C., Huth A., Lexer, M.J., Debra, P.,
Allen, S. and Wyckoff, P. (2001). Tree mortality in Gap models: Application to climate change. *Climate Change 51: 509-540.*

Keane, R.E., Drury, S.A., Karau, E.C., Hessburg, P.F., and Reynolds, K.M., (2010). A method of mapping fire hazard and risks across multiple scales and applications in fire management. *Ecological Modelling 221: 2-18*

Kenya Forestry Society, (2006). Kenya Forestry in the New Millenium and the Challenges Facing a forester under the Forestry Act No 7 of 2005. *Proceedings of the First Scientific Conference on 10th -11th August 2005.* Kenya Forestry Society, Nairobi. Kenya. pp. 92

Kenya National Bureau of Statistics (2010). Republic of Kenya, 2009 Kenya population housing census. P.25

Ketterings, Q. M., Coe, R., Noordwijik, M.., Ambagau, Y. and Palm, Cheryl,A. (2001). Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. *Forest Ecology and Management Vol. 146: 199-209*

Kirongo, B.B. and Muchiri, M.N. (2009). Modelling early growth of Eucalyptus Hybrid clones and Local landraces grown in Kenya. *Journal of East African Natural Resource Management (JEANARM) Vol. 3 (1, I-iv): 257-271.*

Knoepp, J. D., Clinton, B. D. (2009). Riparian zones in southern application headwater catchments: Carbon and nitrogen response to forest harvesting. *Forest Ecology and Management Vol. 258: 2282-2293.*

Knoepp, J.D., Swank, W.T. (1997). Forest management effects on surface soil carbon and nitrogen. *Soil science society of America Journal Vol. 61: 928-935*

Kohl, M., Stumer, W.K.B., and Riedel, T. (2008). Effect of estimation of forest management and decay of dead woody material on the reliability of carbon stock and carbon stock changes-A simulation study. *Forest Ecology and Management Vol. 256: 229-236.*

Konyar K, and Osborn, C.T. (1990). A national level economic analysis of conservation reserve program participation: a discrete choice approach. J. Agric Econ Res. Vol 42(2): 5-12.

Kuntashula, E.and Mafongoya, P. L. (2005). Farmer participatory evaluation of agro-forestry trees in eastern Zambia. *Agricultural systems Vol. 84: 39-53.*

Laclau, J.-P., Bouillet, J.-P., Goncalves, J.L.M., Silva, E.V., Jourdan, C., Cunha, M.C.S., Moreira, M.R., Saint-Andre, L., Maquere, V., Nouvellon, Y. and Ranger, J. (2008). Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil-Growth dynamics and aboveground net primary production. *Forest Ecology and Management Vol. 255: 3905-3917.*

Lingani, P. C., Tigabu, M., Savadogo, P. O., Perchrister., O.J.M. (2009). Determinants of access to forest products in Southern Burkina Faso. *Forest Policy and Economics, Vol. 11 No.7:516-524*

Larsen, J. (2008a). Forest cover shrinking. Earth Policy Reader. http://www.earth-policy.org/indicators/C56/forest_cover_2002 (Accessed on 6/7/2008)

Larsen, J. (2008b). People and planet. Shrinking forests. http://www.peopleandplanet.net/?lid=27110&section=32&topic=26 (Accessed on 8/8/2008)

Lemma, B., Kleja, D.B., Olsson, M., Nilsson, I. (2007). Factors controlling soil organic carbon sequestration under exotic tree plantations. A case study using the CO2Fix model in southwestern Ethiopia. *Forest Ecology and Management Vol. 252: 124-131.*

Leskinen, P., Miina, J., Mehtatalo, L., and Kangas A. (2009). Model correlation in stochastic forest simulators-A case of multilevel multivariate model for seedling establishment. *Ecological Modelling Vol. 220: 545-555*

Liski, J., Palosuo, T., Peltoniemi, M., Sievanen, R. (2005). Carbon and decomposition model Yasso for forest soils. *Ecological Modelling Vol. 189:168- 182.*

Lippke, B and Garcia, P.J. (2008). Will either cap and trade or a carbon emissions tax be effective in monetizing carbon as an ecosystem service. *Forest Ecology and Management Vol. 256: 2160-2165*

Liski, J., Perruchoud, D., Karjalainen, T. (2002). Increasing carbon stocks in the forest soils of Western Europe. *Forest Ecology and Management Vol. 169: 159-175.*

Liu, J., Peng, C., Apps, M., Dang, Q., Banfield, E. and Kurz, W. (2002). Historic carbon budgets of Ontario's forest ecosystems. *Forest Ecology and Management Vol. 169: 103-114*

Lynch, T.B., Gering, R. L., Huebschmann, M.M., and Murphy, P.A. (1999). A survival Model for Shoartleaf Pine Trees Growing in Uneven-aged stands. *Paper presented at the tenth Biennial Southern Silvicultural Research Conference, Shreveport, LA February 16-18th, 1999.*

Mahaptra, K. and Kant, S. (2005). Tropical deforestation: a multinomial logistic model and some country-specific policy prescriptions. *Forestry Policy and Economics Vol. 7: 1-24*

Maselli, F., Chiesi, M., Moriondo, M., Fibbi, L., Bindi, M., and Running, S.W. (2009). Modelling the forest carbon budget of a Mediterranean region through the integration of ground and satellite data. *Ecological Modelling Vol. 220: 330-342*

Marklund, L., Gunner and Schoene, D. (2006). Global Forest Resources Assessment 2005; Global Assessment of Gowing Stock, Biomass and Carbon Stock. Forest Resource Assessment Programme, Working Paper 106/E, Food Agricultural Organization of the United Nations, Forestry Department, Rome.p 20; 51-54.

Mazingira News. (2008). Climate change. April/June, Issue No. 003 p.12

Masera, O.R., Garza-Garligaris, J.F., Kanninen, M., Karjalainen, T., Liski, J., Nabuurs, G.J., Punssinen, A., de Jong, B.H.J., and Mohren, G.M.J. (2003). Modelling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. *Ecological Modelling 164 (2-3), 177-199.*

Maskey, V., Gebremedhin and Dalton, T. J. (2006). Social and Cultural determinants of collective management of community forest in Nepal. *Journal of Forest Economics Vol. 11: 261-274*

Mathu, W. (2007). Forest law enforcement and governance in Kenya. A paper prepared for the East African Community-led regional process in the framework of the Ministerial Declaration, Yaoundé, Cameroon, October 16, 2007 on the Africa Forest Law Enforcement and Governance (AFLEG)

Medina, G., Pokorny, B. and Campbell, B.M. (2009). Community forest management for timber extraction in the Amazon frontier. *International Forestry Review Vol. 11(3): 408-420*

Mette, T., Albrech A., Ammer C., Biber P., Kohnle.U. and Pretzsch H. (2009). Evaluation of the forest growth simulator SILVA on dominant trees in mature mixed Silver fir-Norway spruce in South-West Germany. *Ecological Modelling 220, 1670-1680.*

Miller, S. D., Goulden, M. L., Menton, M. C., Da Rocha, H. R., Freitas, H.C.De., Figueira, A.M. E. and De Sousa, C.A.D. (2004). Biometric and micrometeorological measurements of tropical forest carbon balance. *Ecological applications. Vol. 14(4): 114-126.*

Ministry of Environment and Natural Resources. (1994). Kenya Forestry Master Plan

Miyamoto, Y., Griesbauer, Hardy, P. and Green D. Scott. (2010). Growth responses of three coexisting conifer species to climate change across wide geographic and climate ranges in Yukon and British Columbia. *Forest Ecology and Management Vol. 259: 514-523*

MolDijkstra, J.P., Reinds, G.J., Kros, H., Berg, B., de Vries, W. (2009). Modelling soil carbon sequestration of intensively monitored forest plots in Europe by three different approaches. *Forest Ecology and Management Vol. 258: 1780-1793*

Moser and John, W. (1972). Dynamics of an uneven-aged forest stand. *Forest Science. 18:184-191*

Moser, O. (1965). Untersuchungen uber die Abhangigkeit der natturlichen Verjungung der Fichte Vom Standort. Clb. Ges. *Forstwesen 82, 18-55.*

Moser, W. K., Leatherberry, E. C., Hansen, M. H. and Butler, B. J. (2009). Farmers' objectives towards their woodlands in the upper Midwest of the United States:

implications for woodland volumes and diversity. *Agroforest Syst Vol. 75: 49-60*

Msangi, T.H., Shangali, C.F., Mugasha, W.A., Maguzu, J. and Bomani, F.A. (2009). Early growth of various hybrid clones in different agro-ecosystems in Tanzania: A short communication. *Journal of East African Natural Resource Management (JEANARM) Vol. 3 (1, I-iv): 249-251*

Muenchow, G. (1986). Ecological use of failure time analysis. *Ecology 67, 246-250.*

Mutitu, K.E., Otieno, B.O., Oeba, V.O., Nyeko, P. and Day, R.K. (2007). Spatial distribution of the Blue Gum Chalcid, Leptocybe Invasa on Eucalyptus species in Kenya. *Discovery and Innovation Vol. 19 (AFORNET Special edition No. 4): 369-374*

Nabuurs, G.J.and Mohren, G.M.J. (1995). Modelling analysis of potential carbon sequestration in selected forest types.

Nabuurs, G.J., Thurig, e., Heidema, N., Armolaitis, K., Biber, P., Cienciala, E., Kaufmann, E., Makipaa, R., Nilsen, P., Petritsch, R., Pristova, T., Rock, J., Schelhaas, M.J., Sievanen, R., somogyi, Z., Vallet, P. (2008). Hotspots of the European forests carbon cycle. *Forest Ecology and Management Vol. 256: 194-200.*

Naka, K., Hammett, A.L. and Stuart, W. B. (2000). Constraints and opportunities to forest policy implementation in Albania. *Forest Policy and Economics Vol. 1: 153-163*

Natali, H. and Yuri Y. (2007). The structure of optimal time- and age- dependent harvesting in the Lotka-McKendrik population model. *Mathematical Biosciences 208: 48-62.*

Nathan, R., Safriel, U.N. and Noy-Mier, I. (2001). Field validation and sensitivity analysis of a mechanistic model for tree seed dispersal by wind. *Ecology 82, 374-338.*

Nath, T.K. and Inoue, M. (2009). Forest based settlement project and its impacts on community livelihood in the Chittagong Hill Tracts, Bangladesh. *International Forestry Review Vol. 11 (3): 394-407*

Navar, J. (2009). Allometric equations for tree species and carbon stocks for forests of northwest Mexico. *Forest Ecology and Management Vol. 257: 427- 434.*

NEMA news Magazine, (2007). *Quarterly publication of the National Environment Management Authority, April-June.* Nairobi, Kenya. pp 36.

Nedorezov, L.V., Makorova, T.L., and Makarov, R.N. (2001). A succession model forska_mod for the time course of forests of the boreal zone. *Siberian Journal of Ecology. 5: 529-539.*

Neter, J., Wassermann. W. and Kurter, M.H. (1989). *Applied linear models.* 2nd ed. Homewood, IL Irwin. 667 p.

Nguyen, T.T., Bauer, S. and Uibrig, H. (2010). Land privatization and afforestation incentive of rural fars in the Northern Uplands of Vietnam. *Forest Policy and Economics Vol. 12: 518-526*

Nijnik, M. and Bzikova, L. (2008). Responding to the Kyoto Protocol through forestry: A comparison of opportunities for several countries in Europe. *Forest Policy and Economics Vol. 10: 257-269*

Nilsen, P. and Strand, L.T. (2008). Thinning intensity effects on carbon and nitrogen stores and fluxes in a Norway spruce (Picea abies (L.) Karst) stand after 33 years. *Forest Ecology and Management Vol. 256: 201-208*

Nilsson, S. (2005). Experiences of policy reforms of the forest sector in transition and other countries. *Forest Policy and Economics Vol. 7: 831-847*

Nuggehalli, R. K. and Prokopy, L.S. (2009). Motivating factors and facilitating conditions explaining women's participation in co-management of Sri Lankan forests. *Forest Policy and Economics Vol. 11: 288-293*

Nyeko, P., Mutitu, K.E., Otieno, B., Oeba, V. and Day, R.K. (2007). Farmers' experiences on the Blue Gumm Chalcid, Leptocybe Invasa infestation on Eucalyptus species in East Africa. *Discovery and Innovation Vol. 19 (AFORNET Special edition No. 4): 382-388*

Odhiambo, J.W. and Khogali, A.K. (1986). A transition model for estimating academic survival through cohort analyis. *Int.J. Math. Educ. Sci. Technol., Vol. 17. No. 3:339-346*

Odhiambo, J.W. and Owino, J. (1985). A stochastic model for estimating academic survival in an education system. *Kenya Journal of Science and Technology Series A 6(1): 59-67.*

Odoemena, B., Eboh, E., Okoli, P., Uguwonnah, G., Ihedioha, D., Okoruwa, A. and Odo, F. (2010). Econometric analysis of the micro- level determinants of woodland conversion to arable cropping and Implications to policy in Eastern Nigeria. *African Journal of Agricultural Research Vol.(11): 1168- 1178.*

Oeba, V.O., Muchiri, M.N. and Kariuki, J.G. (2009). Growth performance of Eucalyptus hybrid clones and four common landraces in Kenya. *Journal of East African Natural Resource Management (JEANARM) Vol. 3 (1, I-iv): 219-236*

Okalebo, J.K., Gathua, K.W. and Woomer, Paul, L. (2002). Laboratory methods of soil and plant analysis: A working manual, 2nd edition. Sacred office, Nairobi, Kenya p. 28-29; 42-44 and 78-80.

Onyekwelu, J. C. (2007). Growth, biomass yield and biomass functions for plantation-grown Nauclea diderrichii (de wild) in the humid-tropical rainforest zone of south-western Nigeria. *Bioresource Technology 98, 2679- 2687*

Onyekwelu, J. C. (2004). Above-ground biomass production and biomass production equations for even-aged Gmelina arborea (RXB) plantations in south- western Nigeria. *Biomass and Bioenergy Vol. 26: 39-46.*

Pahari, K., Shunji, M. and Yoshifumi, Y. (2000). Sustainability Analysis for Human Population in Relation with Global Deforestation using Remote Sensing and GIS in International Archives of Photogrammetry and Remote Sensing, *Vol. XXXIII, Part B3, Proceedings of 19th Congress of International Society for Photogrammetry and Remote Sensing, Amsterdam, pp. 800-804*

Pahari, K. and Shunji, M. (1999). Modeling for Prediction of Global Deforestation in ISPRS. *Journal of Photogrammetry and Remote Sensing, Vol. 54(5-6): 317-324.*

Palviainen, M., Finer, L., Laiho, R., Shorohova, E.K., Vanha-Majamaa, I. (2010). Carbon and nitrogen release from decomposing Scots pine, Norway spruce and silver birch stumps. *Forest Ecology and Management Vol. 259: 390-398*

Pattanayak, S.K., Mercer, D.E., Sillas, E.,and Yang, J. (2003). Taking stock of agroforestry adoption studies. *Agroforest Syst. Vol 57: 173-186.*

Paul, K.I., Jacobsen, K., Koul, V., Leppert, P., and Smith, J. (2008). Predicting growth and sequestration of carbon by plantations growing in regions of low-rainfall in southern Australia. *Forest Ecology and Management Vol. 254: 205-216.*

Paul, K.I., Polglase, P.J., Nyakuengama, J.G., and Khana, P.K. (2002). Change in soil carbon following afforestation. *Forest Ecology and Management Vol. 168: 241-257.*

Peichl, M. and Arain, M. A. (2007). Allometry and partitioning of above- and belowground tree biomass in age-sequence of white pine forests. *Forest Ecology and Management Vol. 253: 68-80.*

Pelster, D, E., Kolka, R. K. and Prepas, E. E. (2009). Overstory vegetation influence nitrogen and dissolved organic carbon flux from the atmosphere to the forest floor: Boreal Plain, Canada. *Forest Ecology and Management Vol. 259: 210-219.*

Philip, M. S. (1994). Measuring Trees and Forests. 2nd edition, CAB International, University Press, Cambridge. P54-55.

Porte, A. and Bartelink, H.H. (2002). Modelling mixed forest growth: a review of models for forest mangement. *Ecological Modelling Vol. 150: 141-188.*

Pohjola, J. and Valsta, L. (2007). Carbon credits and management of Scots pine and Norway spruce stands in Finland. *Forest Policy and Economics. Vol. 9: 789-798.*

Polyakov, M. and Teeter, L. (2005).The influence of regulatory forest policy tools on biodiversity measures for forests in Ukraine. *Forest Policy and Economics Vol. 7: 848-856*

Prior, L. D., Murphy, B. P.and Rusell-Smith, J. (2009). Environmental and demographic correlates of tree recruitment and mortality in north Australian savannas. *Forest Ecology and Management Vol. 257: 66-74.*

Pukkala, T., Lahde, E and Laiho, O. (2009). Growth and yield models for uneven-sized forest stands in Finland. *Forest Ecology and Management 258, 207-216.*

Rammig, A., Fahse, L., Bugmann, H. and Bebi, P. (2006). Forest regeneration after disturbance: A modeling study for the Swiss Alps. *Forest Ecology and Management 222, 123-136.*

Rammig, A., and Fahse, L. (2009). Simulating forest succession after blowdown events: The crucial role of space for realistic management. *Ecological Modelling Vol. 220: 3555-3564*

Rautiainen, A., Saikku, L. and Kauppi, P.E. (2010). Carbon gains and recovery from degradation of forest biomass in European Union during 1990-2005. *Forest Ecology and ManagementVol. 259: 1232-1238.*

Reed, K.L. (1980). The effects of risk of fire on the optimal rotation of a forest. *Journal of Environmental Economics and Management 11: 180-190.*

Rennolls, K. and Peace, A. (1986). Flow models of mortality and yield for unthinned forest stands. *Forestry. 59(1): 47-58.*

Republic of Kenya (2005a). Kiambu district Strategic Plan 2005-2010 for implementation of the national population policy for sustainable development. p 3.

Republic of Kenya (2005b). Nyeri district Strategic Plan 2005-2010 for implementation of the national population policy for sustainable development. p 3.

Rodriguez, L. G., Perez, M. R., Yang, X., Fu, M., Geriletu and Wu, D. (2009a). Changing contribution of forests to livelihoods: evidence from Daxi village, Zhejiang Province, China. *International Forestry Review* Vol. 11 (3): 319-330

Rodriguez-Vicente, V. and Marey-Perez, M. F. (2009b). Land-use and land- use patterns in non-industrial private forests: Factors affecting forest management in Northern Spain. *Forest Policy and Economics Vol. 11: 475- 490*

Sasaki, N. and Kim, S. (2009). Biomass carbon sinks in Japanese forests: 1966-2012. *Forestry, Vol. 82, No. 1: 113-123.*

Schulp, C. J.E., Nabuurs, G., Verburg, P. H., de Waal, Rein, W. (2008). Effect of species on carbon stocks in forest floor and mineral soil and implications for soil carbon inventories. *Forest Ecology and Management Vol. 256: 482-490.*

Seely, B., Welham, C., Kimminis, H. (2002). Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. *Forest Ecology and Management Vol. 169: 123-135.*

Seidl, R., Rammer, W., Jager, D., Lexer, J. M (2008). Impact of bark beetle (Ips typographus L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. *Forest Ecology and Management Vol. 256: 209-220*

Sierra, C, A., Del Valle, J. I., Orrego, S. A., Moreno, F. H., Harmon, M. E., Zapata, M., Colorado, G. J., Herra, M, A.,Lara, W., Restrepo, D. E., Berrouet, L. M., Loaiza, L. M.,and Benjumea, J. F. (2007). Total Carbon stocks in a tropical landscape of the Porce region, Colombia. *Forest Ecology and Management Vol. 243: 299- 309.*

Siregar, U, J., Rachmi, A., Massijaya, M.Y., Ishibashi, N. and Ando, K. (2007). Economic analysis of sengon (*Paraserianthes falcataria*) community forest plantation, a fast growing species in East Java, Indonesia. *Forest Policy and Economics Vol. 9: 822-929*

Spencer, M. (2008). Past states of continuous-time Markov Models for ecological communities. *Mathematical Biosciences 211: 299-313*

Sprugel, D. G., Rascher.K. G., Gersonde, R., Dovciak, M., Lutz, J. A., and Halpern, C. B. (2009). Spatially Explicit modeling of overstorey manipulations in young forests: Effects on stand structure and light. *Ecological Modelling Vol. 220: 3565-3575*

Stevens, A., Wesmael, B.V. (2008). Soil organic carbon stock in the Belgian Ardennes as affected by afforestation and deforestation from 1868 to 2005. *Forest Ecology and Management Vol. 256: 1527-1539*

Stern, N. (2006). The economics of climate change. The Stern review. Cambridge University press, New York. P 372

Stilma, E.S.C., Keesman, K.J. and Werf W.V. (2009) Recruitment and attrition of associated plants under a shading crop canopy: Model selection and calibration. *Ecological Modelling Vol. 220: 1113-1125.*

Stoffberg, G.H., van Rooyen, M.W., van der Linde, M.J., Groeneveld, H.T. (2010). Carbon sequestration estimates of indigenous street trees in the City of Tshwane, South Africa. *Urban Forestry and Urban Greening Vol. 9: 9-14*

Stoffberg, G.H., van Rooyen, M.W., van der Linde, M.J., Groeneveld, H.T. (2008). Predicting the growth in tree height and crown size of three street tree species in the city of Tshwane, South Africa. *Urban Forestry and Urban Greening Vol. 7: 259-264*

Swanson, M. E. (2009). Modelling the effects of alternative management strategies on forest carbon in the Nothofagus forests of Tierra del Fuego, Chile. *Forest Ecology and Management Vol. 257: 1740-1750*

Sweet, C. (2010). "UPDATE: Global Carbon Trading Up In 2009, Though Prices Lower". *The Wall Street Journal http://online.wsj.com/article/BT-CO-20100106-712782.html*

Teagasc Agriculture and Food Development Authority (TAFDA). (2007). Forestry Development Unit, A road map for the Farm Forestry Sector to 2015. *A technical report p. 3-13*

Teck, R. and Hilt.D.E. (1990). Individual- Tree Probability of Survival model for the Nothereastern United States. *Research Paper NE-642.*

Turner, M.G., Gardner, R.H. and O'Neill, R.V. (2001). *Introduction to models.* In: Turner, M.G., Gardner, R.H., O'Neill, R.V. (Eds.), Landscape Ecology. Springer-Verlag, New York, pp. 47-69.

Valdivia C. and Poulos C. (2009). Factors affecting farm operators' interest in incorporating riparian buffers and forest farming practices in northeast and southeast Missouri. *Agroforest Syst. Vol. 75: 61-71*

Valkonen, S., Isango, J., Mabvurira, D., Muchiri, M. N. and Saramaki. (2000). A review of growth and yield models for plantation forests in Eastern And Southern Africa. Technical notes 114: 1-59

Vanclay, J.K. (1989). A growth model for North Queensland rainforests. *For. Ecol. Manage. 27, 245-271.*

Vallet, P., Meredieu, C., Seynave, I., Belouard, T., Dhote, J.F. (2009). Species substitution for carbon storage: Sessile oak versus Corsican pine in France as a case study. *Forest ecology and Management Vol. 257: 1314-1323.*

Vesterdal, L., Ritter, E., Gundersen, P. (2002). Change in soil organic carbon following afforestation of former arable land. *Forest Ecology and Management Vol. 169: 137-147*

Vesterdal, L., Schmidt, I, K., Callesen, I., Nilsson, L.O., Gundersen, P. (2008). Carbon and Nitrogen in forest floor and mineral soil under six common European tree species. *Forest Ecology and Management Vol. 255: 35-48*

Volker, M. and Waibel, H. (2010). Do rural households extract more forest products in times of crisis? Evidence from the mountainous uplands of Vietnam. *Forest Policy and Economics Vol.12: 407-414*

Wamelink, G.W.W., Dobben, H.F. and Berendse, F.(2009a). Vegetation succession as affected by decreasing nitrogen deposition, soil characteristics and site management. A modeling approach. *Forest Ecology and Management Vol. 258: 1762-1773*

Wamelink, G.W.W., Wieggers, H.J.J., Reinds, Kros, J., G.J., Mol-Dijkstra, J.P., van Oijen, M., de Vries, W., Berendse, F. (2009b). Effect of nitrogen desposition reduction on biodiversity and carbon sequestration. *Forest Ecology and Management Vol. 258: 1774-1779*

Wamalwa, L., Chagala, E., Oeba, V., and Oballa, P. O. (2007). Adpatability of four-year old Eucalyptus species and clones in Kenya. *Discovery and Innovation Vol. 19 (AFORNET Special edition No. 4): 369-374*

Wamelink, G.W.W., van Dobben, H.F., Mol-Dijkstra, J.P., Schouwenberg, E.P.A.G., Kros, J., de Vries, W. (2009). Modelling impacts of changes in carbon dioxide concentration, climate and nitrogen deposition on carbon sequestration by European forests and forest soils. *Forest Ecology and Management Vol. 258: 1794-1805*

Wang, J.R., Zhong, A.L., Simard, S.W., Kimmins, J.P. (1996). Above ground biomass and nutrient accumulation in an age sequence of paper birch (Betula papyrifera) in the interior Cedar Hemlock zone, British Columbia. *Forest Ecology and Management Vol. 83: 27-38*

Waring, R.H. (1987). Characteristics of trees predisposed to die. *Bioscience. 37: 569-574.*

Watt, M. S., Palmer, D. J., Dungey, H.and Kimberley, M. O. (2009). Predicting the spatial distribution of *Cupressus lusitanica* productivity in New Zealand. *Forest Ecology and Management Vol. 258: 217-223.*

Waterworth, R.M. and Richards,G.P. (2008). Implementing Australian forest management practices into a full carbon accounting model. *Forest Ecology and Management Vol. 255: 2434-2443*

Weishampel, P., Kolka, R., and King, J.Y. (2009). Carbon pools and productivity in a 1-km2 heterogeneous forest and peatland mosaic in minnesota, USA. *Forest Ecology and Management Vol 257: 747-754.*

Weiss, G. (2000). Evaluation of policy instruments for protective forest managament in Austria. *Forest Policy and Economics Vol. 1: 243-255*

Williams, M., Ryan, C.M., Rees, R.M., Sambane, E., Fernando, J. and Grace, J. (2008). Carbon sequestration and biodiversity of re-growing miombo woodlands in Mozambique. *Forest Ecology and Management Vol. 254: 145- 155.*

World Bank (2010). *State and Trends of the Carbon Market 2010.* http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/ENVIRONMENT/EXTCARBONFINANCE/0contentMDK:22592488~pagePK:64168445~piPK:64168309~theSitePK:4125853,00.html

Woodall, C.W., Grambsch, P.L., Thomas, W. (2005). Applying survival analysis to a large-scale forest inventory for assessment of tree mortality in Minnesota. *Ecological modeling 189:199-208*

Woodall, C.W., Heath, L.S., and Smith, J.E. (2008). National Inventories of down and dead woody material forest carbon stocks in the United States: Challenges and opportunities. Forest Ecology and Management Vol. 256: 221-228.

Workman, S.W., Bannister, M.E., and Nair, P.K.R. (2003). Agroforestry potential in the southern United States: perceptions of landowners and extension professionals. *Agroforest Syst. Vol 59: 73-83*

Yemshanov, D. and Perera, A. H. (2002). A spatially explicit stochastic model to simulate boreal forest cover transitions: general structure and properties. *Ecological Modelling Vol. 150: 189-209.*

Zhang, C.F., Meng, F.-R., Bhatti, J.S., Trofymow, J.A., Arp,Paul, A. (2008). Modeling forest litter decomposition and N mineralization in litterbags, placed across Canada: A 5-model comparison. *Ecological Modelling Vol. 219:342-360*

Zhang, G., Boom, C., Zhang, G., Liu, X., Du, Q and Peng, S. (2009). Simulating dynamics of managed monsoon evergreen broad- leaved forests in South China. *Ecological Modelling Vol. 220: 2218-2230*

Zhang, D. and Owiredu, E.A. (2007). Land tenure, market and the establishment of forest plantations in Ghana. *Forest Policy and Economics* *Vol. 9: 602-610*

Appendix 1: Farmers' Questionnaire

Identification of determinants of lifetime value of the farmer willing to retain trees on farm.

Introduction:
In Kenya, the closed canopy forest cover is considered to be too low (less than 2%) as compared to 9% and 21% for the rest of Africa and the rest of the world, respectively. This is considered to pose a serious challenge not only to climate change and safe/clean environment but also to the country's economy which mainly depends on agricultural production and whose population relies on forest products and services for many basic requirements. The culture of tree cutting/felling shows that nearly half of the forests are at risk across the world, posing a serious challenge of global warming. Reforestation is one of the main ways of mitigating the climate change. This calls for the need to increase the forest cover and hence natural carbon sinks. Kenya through the new Forest Act, 2005, envisions achieving this through various forestry programmes where farm forestry is seen as the main viable option. Therefore, major objective of this survey is to identify the possible determinants that are likely to enable a farmer retain trees on farm for longer period of time. Your responses and willingness to participate in this study is highly acknowledged and will treated as confidential.

I. Background Information

Questionnaire No.__________ Enumerator's Name__________________ Date_______

District__________________ Division________________ Location______________

Sub-location______________ Village________________

Farm/household location: GPS____________________altitude__________________

II: Details of the Respondent *(Interview it last).*

1. Sex: *1. male 2. female*: ______________
2. Gender of the household head: *1. male 2. female* ______
3. Main occupation: *1. Farmer 2. Civil servant 3. Scientist 4. Teacher 5.Any other specify*____________.
4. Year born:____________
5. Level of education: *1. None 2. Primary 3. Secondary 4. College. 5. University* _________
6. Marital status: *1. Married 2. Single 3. Widowed 4. Divorced 5. Separated* __________
7. Number of members in the household:______________

8. Monthly income in Ksh.____________________

III Land ownership and land use

9. Type of landownership: *1. Inherited from parents 2. Bought 3. Given by community 4. Leased 5. Inherited+bought 6 Inherited+bought+leased 7. Any other, specify*________________
10. In the type of the landownership selected in Q9, what is the total size of your land?____________acres.
11. In reference to Q9. State when you were allocated land. Specify the years accordingly.

Year	Size	Year	Size

12. Provide the details of your land use, size allocated for each use and type of crops grown.

Land use	**Size in acres**	**Type of crop planted**
Food crops		
Cash crop		
Fallow		
Bushland		
Woodlot		
Plantation of trees		
Pasture		
Other specify		

IV Trees on Farm & Purpose

13. List all the tree species you have on farm both planted and natural

Tree species Local name	**Tree species Scientific name**	**No. of trees**	**1st year of planting**	**Size in acres**	**Establishment** (planted/natural regeneration)	**Uses** *(1.woodfuel 2. shade 3. timber 4. live fence 5. Aesthetic 6. medicinal 7. poles&pots 8. windbreak 9. fruit 10. others)*

1. Eucalyptus spp., 2. Grivillea robusta 3. Senna siamea 4. Terminalia brownii, 5. Pinus patula, 6. Cupressa lusitanica 7. Cordial abyssinica 8. Markhamia lutea, 9. Juniperus procera 10. others specify---

14. Have you planted trees for the last twelve months? *1. yes 2. no* ***(if no go to Q20)***

15. If **yes** in **Q14**, list the priority species, number, area planted and source of your seedlings in the last five years.

Tree species Local name	**Tree species Scientific name**	**Year of planting**	**No. of trees**	**Size in acres**	**Source of seedlings**
		2009			
		2008			
		2007			
		2006			
		2005			
		2004			

1. Eucalyptus spp, 2. Grivillea robusta 3. Senna siamea 4. Terminalia browni, 5. Pinus patula, 6. Cupressa lusitanica 7. Cordial abyssinica 8. Markhamia lute 9. Juniperus procera 10. others specify---

16 What motivates you to plant trees? Tick as appropriate *(1. Conserve the environmen, 2. Source of livelihood (provides income, firewood, fencing poles, posts, construction etc) in my household 3. Controls erosion & flood 4.Supply of clean oxygen 5. Wanted to venture to carbon market 6.To enable me venture into beekeeping 7. For ecotourism &recreation 8. Source of medicinal products 9. Joined outgrowers scheme in the area (NTZDC, KPLC, Telkom Kenya, KTDA) 10. Any other specify.____)*

16. Rank the three most important reasons for you growing trees.

Reason	**Rank**	**Prioritized tree species for the reason ranked**
1. Provision of woodfuel/construction posts, rafters, timber, poles for my household		
2. Source of income		
3. Preserve and conserve the environment		
4. Any other specify		

18. Do you keep records of your tree farming? *1. Yes 2. No*

19. If **Yes in Q18**, state the kind of records you keep *(enumerator to be shown samples and copy the key variables of the records)*

20. What hinders you from continuous planting of trees? Tick appropriately. *(1. land size 2. no interest 3. lack of quality seedling 4. lack of labour 5. lack of species of interest 6. lack of money 7. Any other specify______________________)*

21. In your own opinion, what are the general barriers to involvement in farm forestry? *1. Potential value of unplanted land 2. lack of land 3. No immediate returns 4. Forestry is a permanent solution 5. Need all my land for agriculture 6. Dislike of forestry 7. Low level of awareness forestry returns among farmers*
*8. Any other specify*____

22. Given an extra land in a rural area, what will be your priorities of using the land? *1. Plant trees 2. Grow cash crops (tea, coffee etc) 3. Pasture 4. Horticulture*
*5. Any other specify*____________________

23. Give your overall plans on how you want use your land for the next five years.

____
____
____
____
____

V. Tree management

24. Have you ever got any additional technical skills on tree farming? *1. Yes 2. No*

25. If **Yes in Q22**, what skills? *1. Nursery establishment 2. Thinning 3. Pruning 4. Pollarding 5. Short rotation coppice (specialized for of forestry involving high yielding trees at close spacing & harvesting at regular intervals) 6. Fertlizer application 7. Tree Harvesting 8. Forest economics 9. Weeding 10. .competition between trees and agricultural crops* 11. Any other, specify________

26. Have these skills acquired in any way influenced your decision in tree growing and harvesting *1. Yes 2. No*

27. **In an event of a problem in your household that requires financial solution, will you prioritize selling your trees?** *1. Yes 2. No*

28. **If No Q27,** why?

____
____
____
____

29. Is the labour involved in tree management intense and costly? *1. Yes 2. No*

30. If, **Yes in Q29,** will this discourage you from continuous planting of trees? *1.Yes 2. No*

31. Which tree species gives you easy management. *1. Eucalyptus spp., 2. Grivillea robusta 3. Senna siamea 4. Terminalia brownie, 5. Pinus patula, 6. Cupressa lusitanica 7. Cordial abyssinica 8. Markhamia lutea, 9. Juniperus procera 10. others specify---*

32. Do you get regular visits from forest extension officers guiding you on tree management? 1. *Yes 2. No.*

33. Do you seek permission from the Kenya Forestry Service to harvest your trees? 1. *Yes 2. No*

34. Do you find such regulation necessary and useful in motivating your decision for tree farming? *1. Yes 2. No*

35. Do you have village forest association? *1. Yes 2. No*

36. If Yes **in Q35,** what are their major roles in tree farming?

____
____
____
____
____
____
____

VI. Social Function of Farm Forestry

37.To what extent are you aware of following roles that farm forestry will play if well implemented.

Roles	***1. Very aware 2.Aware 3. Moderately aware 4.Not aware***
1. Provision of local employment for the youth and aged	
2. Improvement of rural economy	
3. Recreation and ecotourism	
4. Good body health (reduction of air pollution) hence reduction of health expenses	
5. Educational resource for schools and community members	
6. Social sustainability through increased emphasis on amenity and landscape	
7. Stabilization in rural populations and help to build confidence, strength and sprit among communities.	

38. To what extent do you agree with following pathways in reference to Sustainable farm Forest Management (SFM)?

Future of social function of farm forestry	***1. Strongly agree 2. Agree 3. Disagree 4. Strongly disagree***
1. Promotion of SFM through national policy	
2. Implementation of SFM through appropriate forest legislation	
3. Public campaign promoting SFM with particular emphasis on rural communities	
4. Group certification of farm forests	
5. Promotion of practical advantages of certification & SFM through ✓ Targeting younger owners	
✓ Organizing extension field days	
✓ Empower people to become self-active in forest	
✓ Operations in the early stages of the forest cycle	
✓ Target members of farming and/or forestry groups.	

39. Are you a member of any farmer organization that has tree-planting activities? *1. Yes 2. No*

40. If **yes Q39**, which organization and what are their main activities?

Enumerator estimate amount of firewood used equivalence if buying and multiply with number of days in year etc, do for the others used and state the amount.

42. Please provide the costs incurred in tree farming for the last three years.

Forest costs	2008	2007	2006
	Ksh.	Ksh.	Ksh
1. Purchase of Seedlings			
2. Labour-weeding			
3. Thinning			
4. Pruning			
5. Transport			
6. Planting			
7. Cutting			
8. Sawing			
9. Chemicals			
10. Cultivation			
11. Advisory services			
12. Any other specify			

43. Have you employed workforce in your farm to tend your tree farming activities? *1. Yes 2. No*

44. If **Yes**, in **Q43** specify the activity, number of casual labourers and wages.

Forest activity	No. casual labourers	Wage per month	Remarks
1. Nursery			
2. Forest guarding			
3. Silvicultural management			
4. Any other specify			

45. Do you have ready market for your forest products? 1. *Yes 2. No.*

46. Who are the potential buyers of your forestry products including seedlings? *1. KPLC 2. Telkom Kenya 3. Tea factories 4. Schools 5. Hotels & restaurants 6. NGOs participating in promotion farm forestry 7. Any other specify*____________________________

Organization	Name of the organization	Three Main activities
Forest association		1. 2. 3.
Women group		1. 2. 3.
Co-operative Society		1. 2. 3.
Youth Group		1. 2. 3.
Others specify		1. 2. 3.

VII: Economic Benefits of Trees on farm

41. Please provide your on farm returns for the last three years of the following forest products

Forest products/benefits	2008	2007	2006
	Ksh.	Ksh.	Ksh
1.Firewood (sales)			
2.Firewood (consumed)			
3. Rafters sales			
4. Rafters (used)			
5. Posts (sales)			
6. Posts (used in fencing/constructions)			
7. Poles (sales)			
8. Poles (used for construction)			
9. Timber (sales)			
10. Timber (used for household needs)			
11. Sales from honey (if beekeeping –farm forest			
12. Seedlings-sales			
13. Seedlings-planted from own nursery			
14. Charcoal sales			
15. Charcoal used			
16. Medicinal-sales			
17. Medicinal-used			

47. Do you experience any problems of marketing your forest products including seedlings?
1.Yes 2. No

48.If **Yes, Q47**, what are the problems and what need to be done in alleviating the problems?

Problem	**What need to be done to alleviate the problem**
1.	
2.	
3.	
4.	
5.	
6.	

49. State the extent at which you agree with following statements.
For the forest cover to be attainable through farm forestry, the following should hold in marketing the forest products.

Statement	*1. Strongly agree 2.Agree 3. Disagree 4. Strongly disagree*
1.Introduction of complementary marketing services to encourage farmers to engage in tree production.	
2.Identification of the markets for farm forestry products to match the range of products that farmer might produce.	
3. Assessment of the likely financial profitability to smallholders through analysis of the value market place and costs of producing goods & placing them in the market.	
4.Restricting the role of intermediaries as much as possible to ensure that smallerholders benefits to the fullest extent possible & is not encouraged in negative practices.	
5. Price stabilization measures for farm forest products	

50. Enumerator's notes

___

___

___