ESTIMATION OF ENERGY OF EUCALYPTUS PLANTATIONS FOR FUELWOOD SUPPLY TO TEA FACTORIES IN NANDI COUNTY (KENYA)

BY

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DECLARATION

DECLARATION BY THE CANDIDATE

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DEDICATION

I dedicate this work to my beloved wife Sarah Ochieng and my dear children Kin, Collitedra, Dorcas, Ann and Uvialia for diligent love and compassion they showed me during that difficult period whilst I was compiling this report.

ABSTRACT

Trees and woodlots in plantation establishments are prominent features for wood biomass. In Kenya fuelwood remains the major supplier of energy, making its contribution to total energy supply crucial. However, there is paucity of information and lack of research initiatives on the how fuelwood help in meeting household and industrial energy demands in Kenya. This study determined the biomass energy supply to Nandi Tea Factories from plantations of eucalyptus situated at Eastern Produce Kenya (EPK). Specifically, the study determined: the standing volume of eucalypts plantations of different ages at EPK, variation in proximate and calorific values as a function of age, and developed tree biomass and volume models above ground biomass equation. Four trees were randomly selected from each age group for destructive sampling to enable biomass and proximate value determination. The mean height ranged from 8 to 40 m, dbh from 7 to 25 cm while the standing volume ranged from 15.86 to 736.88 m^3 ha^{-1}. The results revealed significant differences among age (P = 0.0001), calorific value (P = 0.0001), volatile matter (P = 0.0001), ash content (P = 0.0001), fixed carbon (P = 0.0001), desorption (P = 0.0001) and absorption (P = 0.0001). The mean ash content ranged from 0.49 to 0.97%, volatile content was 70.1 to 70.67%, desorption ranged between 0.03 to 0.09%, absorption content ranged from 0.02 to 0.09%, fixed carbon was 10.64 to 10.09% and calorific value w ranged from 18.53 to 19.57 Mj/kg. Ash varied negatively with age The mean ash content, desorption and absorption of *E. grandis* plantation decreased with increasing age of the trees while the volatile content, fixed carbon and calorific values increased with increasing age of the trees. Tree volume was best described by the function Tree biomass increased with volume of the forest plantation as fitted using regression. The tree biomass and volume were positively correlated with a regression coefficient (R^2) of 0.9736. There was a sigmoid relationship between the standing volume and tree age. The recommended harvesting age should be 10 years as determined by the energy content of the trees and further research is needed to know the contribution of the soil organic components and plantation management practices in Eucalyptus plantations as they impact on the amount of biomass and hence the energy content.

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LIST OF ABREVIATIONS

ANOVA	Analysis of Variance
ASTM	America Society for Testing Material
BEF	Biomass expansion factor)
CAI	Current Annual Increment
Dbh	Diameter at breast height
EIA	International Energy Agency
EMC	Equilibrium moisture content
EPK	Eastern produce of Kenya
FAO	Food and Agriculture Organization
Ht	Height
KFS	Kenya Forest Services
KTDA	Kenya Tea Development Agency
LAI	Leaf Area Index
MAI	Mean Annual Increment
MC	Moisture Content
MOE	Ministry of Energy
SAS/STAT	Statistical Analysis System
UNECA	United Nation Economic Commission for Africa

OPERATIONAL DEFINITION OF TERMS

Allometry: Is relationship between the size of organism and size of any of its parts.

Biomass: Is the wood products obtained from tree parts including branches, twigs, tops, and unmerchantable stems

Calorific value: Amount of heat generated by complete combustion of a given mass of fuel [in Megajoules per kilogram (MJ/kg)]

Energy: Refers to the quantitative of property that must be transferred to an object in order to perform work on.

Equations: Statement of equality containing one or more variables

Fuelwood: Consists of unprocessed biomass used to fuel fires, usually for cooking and warmth.

Model: It involves the construction of physical, conceptual or mathematical simulation of real world.

Plantation: Forest management system where trees of similar species, characteristics and age are planted with an intention of optimizing production from unit land area.

Proximate value: It is one of the chemical properties of the heating value constituting of volatile matter, ash content, fixed carbon and moisture content.

Tree volume: Average volume of wood that could be harvested from any one acre of a forested tract.

Woodfuel: Refers to all woody biomass used in some way to provide energy.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Globally, energy demand continues to rise due to increase in population and the need to use more energy for domestic and industrial purposes (Berardi, 2017; Callaway *et al*., 2018). Accordingly, forecast based on the International Energy Agency (EIA) and other sources, estimate that energy demand is expected to rise by approximately 50-55% by the year 2040 (Conti *et al*., 2017; Wiselogel *et al*., 2018). Despite varied energy sources, biomass energy including biodegradable parts of agricultural products, biological residues, wastes from biological sources, such as plant and animal substances continue to supply raw materials for the creation of energy (Balat, 2009; Guo *et al*., 2017; Jacobson and Delucchi, 2018).

Without a doubt, biomass constitutes the third largest energy source after fuel energy derived from coal and oil (Bapat *et al*., 2017). These sources of energy are increasingly becoming more fashionable as apt substitute for fossilized fuels as the wordl move towards consumption of clean energy (Ben-Iwo *et al*., 2016; Suzuki *et al*., 2017). There are numerous biomass sources of energy but the more important one are wood (woody biomass), agricultural sources, solid wastes, biogas and alcohol fuel (Heinimö and Junginger, 2009; Lima *et al*., 2014; Detroy, 2018). Among these forms, wood provides the largest proportion of biomass for energy (Zanchi *et al*., 2012; Zomer *et al*., 2017), accounting for 74% of biomass energy consumption globally (Scarlat *et al*., 2015; Hoogwijk *et al*., 2017).

Woody biomass consumption as an energy source is approximately 80-90% in most African countries. Comprehensively, these are reported as: Burundi (93%), Rwanda (92%) Central African Republic (91%), Mozambique (89%), Burkina Faso (86%), Benin (85%), Madagascar and Niger (83%) (UNECA, 2016; Zomer *et al*., 2017). The woody biomass is used mainly in the form of burning of firewood and charcoal for household cooking needs and other domestic energy driven chores (Balat, 2009; Cornwell *et al*., 2009; Dasappa, 2011). Although there is increasing differences in the woodfuel consumption between rural and urban regions, rural dwellers still exclusively use woodfuel owing to cultural preferences, availability, economic factors and perceived lack of alternative energy sources as well as widespread poverty (Sola *et al*., 2016; Mekonnen *et al*., 2017; Menduma and Njenga, 2018; Mulhollem, 2018).

In Kenya, woody biomass contribution to the total energy need is currently estimated at 68% of the biomass energy (Torres-Rojas *et al*., 2011; Heltberg, 2012; Wanjala *et al*., 2015) and provides for more than 90% of rural household energy needs (Gathui and Mugo, 2010; Githiomi *et al*., 2012). It has been previously reported that Kenya uses 45.3 million tonnes of biomass for wood fuel (Kituyi *et al*., 2001; Waweru, 2014), mainly in the form of charcoal and firewood. Natural forests still supply most of these sources of wood fuel in Kenya (Githiomi and Oduor, 2012; Mbuthi, 2009; Bett *et al*., 2015). Apart from the rural households, agro-based industries in Kenya have shifted away from electricity that is becoming more expensive and unreliable to the use of woodfuel biomass (Osiolo, 2009). For in the tea zones industries use over 90% of wood energy in their systems. Wood biomass in the past for these industries are obtained from trees (Kebede *et al*., 2010). However, collection of wood from the forest was found not sustainable. Besides, gathering fuelwood from the forests is an illegal activity, and thus forbidden by laws and regulations of the Kenya Forest Services (KFS) (GOK, 2016). Efforts have therefore been heightened to search for more supplies of wood as energy sources away from the gazetted and non-gazetted forests. This has seen more focus on obtaining wood energy from on farm establishments.

Tree plantations establishment in Kenya is equivalent to 0.28% of Kenya's land area or about 220,000 ha. (Kagombe and Gitonga, 2005; Farwig *et al*., 2008; Imo, 2009), which imposes a high demand. Nandi County reported a demand of 528,861 tonnes of woody biomass per year in 2000 against a supply of 328,707 (i.e. 68.89% deficit), (http://nandi.go.ke/forestry-agro-forestry/). These estimates are based on trees planted on farms at the households' level and those planted by industries for their internal biomass requirements. Nevertheless, the inventory, assessment and hence the share of trees planted on farms for households' use is still not clear and the amount of wood collected for fuel is still under speculation. Notwithstanding these challenges, the share of individual wood biomass from plantation establishments by the industries are known based on occasional measurement of tree area coverage and density (Omoro *et al*., 2010; Githiomi and Kariuki, 2010; Machua *et al*., 2011). The quantity of woody energy biomass provided by these plantation establishments to the industries in Kenya has not been estimated. Therefore, information on the biomass energy from such establishments are still not clearly documented.

Eastern Produce of Kenya Ltd. (EPK) in Nandi County is one of the tea producing industries that uses energy from wood. The company has planted trees for energy production covering a total area estimated at 2400 ha (Sitienei, 2016), but the energy production from the establishment is yet to be estimated. The mean annual fuelwood usage stands at 53,970 m^3 based on the recent estimates by the company. The plantation is under short-rotation and the main species are *Eucalyptus grandis*, *Cupressus lusitanica* and *Pinus patula*. *Eucalyptus grandis* covers almost 90% of the area planted and thus is currently the main source of wood biomass energy source for the tea industry owned by the company (Paterson *et al*., 1998). Some of the characteristics that make eucalypts ideal fuelwood producing species include the following; fast growth, adaptation to a variety of sites, coppicing ability, good biomass quality and high biomass productivity, (Almeida *et al*., 2010; Viana *et al*., 2010; Leslie *et al*., 2012). Eucalypts contain high lignin content, higher than most hardwood species; rendering it ideal for bioenergy production (Kumar *et al*., 2010). It's the annual production rates range from 20 to 70 m^3 ha^{-1}. There is however lack of information from the agro-industries industries on the amount of biomass energy they get from the *Eucalyptus* forest plantation establishment despite the relevance of such information on the development of sustainable biomass energy.

1.2 Statement of the problem

Trees are important component of woody biomass and therefore have potential to generate fuel energy, particularly in plantation establishments; it is true for Eastern Produce of Kenya Ltd (EPK) in Nandi County. Thus their quantification for estimating energy production potential is sound for planning purposes. Few studies have been done on wood yield prediction in most of the private plantation establishments in Kenya especially for EPK. Attempts have been made to apply traditional forestry measurement techniques to trees in farms, a situation which has led to adoption of wood yield data which is not based on research work. Moreover, information on tree volumes in plantation forests in Kenya is scanty making it more difficult to predict tree biomass using volume, and hence a limitation in the estimation of energy from the plantation. For example, at EPK Company, it is still not clear how variation in the age of plantation forests is likely to affect the energy production from such establishments. Unfortunately, there are few studies that have been conducted in Kenyan private plantations to establish how variation in the age of the forest affect the biomass of the woody species and therefore it is not possible to estimate how such variation would affect energy supply from such forests. Finally it is clear extensive research has been done to develop and use the biomass and volume models to understand the changes in tree biomass. However, extension of such equation to predict the energy yields from the private forest plantations has rarely been done in many agro-ecological zones particularly in Kenya. EPK Ltd Company has been using the tree volume models from Schumacher and Hall model developed in 1984.

1.3 Justification of the study

Since most agro-based industries use wood-fired steam boilers to generate energy, outcome from the present study will without doubt address the problem of unsustainability of fuelwood supply to Nandi tea factory and other agro-industries in Kenya through information relevant for efficient and effective energy production from wood biomass. Accurate estimation of tree volume is important to enable reliable estimates of tree biomass and hence it can be used to predict energy yield from the establishment.

In Kenye, there is need for biomass and volume models that will help in planning purposes generally and management of plantation establishment for specific firms as well as to portion forest areas for harvesting besides to calculate the loss of timber loss for reimbursement for destructions at some point in for instance, infrastructures construction. Models computing biomass and volumes that give vital information on forest resources management can as well be for firewood quantification.

1.4 Objectives of the study

1.4.1 Main objective

The main objective of the study was to estimate the energy of eucalyptus plantations for fuelwood supply to tea factories in Nandi County (Kenya)

1.4.2. Specific objectives

1. To determine standing volume using height and diameter of existing eucalyptus plantations of various ages at EPK.
2. To determine variation in proximate and calorific value with age of eucalyptus in EPK plantations.
3. To develop tree biomass model for eucalyptus in EPK plantations.

1.5 Research hypotheses

$H_{01:}$ There is no significant difference in the standing volume with age of eucalyptus plantations at EPK.

H_{02}: There are no significant differences in proximate and calorific value with age eucalyptus trees in EPK plantations.

H_{03}: The tree biomass will not vary linearly with the volume of the eucalyptus in EPK plantations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Energy consumption and biomass energy supply

The role of energy in the economic development cannot be overemphasized. Growth in the economy is largely energy driven both in the developing and developed countries (Van Benthem and Romani, 2009; Kowsari and Zerriffi, 2011). Energy is used to satisfy basic human needs for cooking, lighting and heating at the individual and household levels, and further create employment and generate income at national and global fronts (Wolfram *et al*., 2012). This renders energy supply and consumption an important realm in research. However, in several developing countries several aspects of energy consumption and demand tend to be largely speculative (Legros *et al*., 2009). The most important area of research in energy currently where to obtain different energy sources. There are numerous energy supply sources ranging from electricity, biofuels, fossil fuels and biomass energy.

In many developing economies where energy is needed more than ever to sustain increasing economic growth in those countries, electricity remains elusive from most of the rural populations and is quite costly form of energy (Taliotis *et al*., 2016). Meanwhile the fossil fuels cannot be used in large scale energy need of the rural community due to exorbitant value while coal is limited to particular countries where mining coal deposits is requires more complex machinery than can be afforded by the poor rural folks (International Energy Outlook, 2016). The technology of generating biofuels energy eludes the rural communities and is currently only applicable as energy sources in more industrialized nations (Singh *et al*., 2011; Molino *et al*., 2016). Energy resulting from biomass supply most of the energy needs of the rural communities (Tumuluru *et al*., 2011; Cheng, 2017) and has therefore been a consistent topic for most research.

Biomass is the wood products obtained from tree parts including branches, twigs, tops, and unmerchantable stems (Evans and Finkral, 2009). Energy as derivative of biomass remain the most essential source of renewable energy nourishing approximately two billion people translating to 9% of global total energy supply for cooking and/or heating (Field *et al*., 2018). People in the developing countries are highly reliant on biomass energy (Barnes and Floor, 2018). Energy consumption is strongly related to levels of economic activity in a country, the more energy that is consumed by an economy the more vigorous that economic indices improve (Caputo *et al*., 2015). However, for most economies especially developing economies, only the conventional types of energy (petroleum, electricity) are considered when evaluating the energy need of the county (Owusu and Asumadu-Sarkodie, 2016).

According to FAO (2006), the total wood biomass utilized globally was estimated at 3 billion m^3 with the proportion of fuelwood being 40% on average, but remarkably diverse based on regional apportionment. In Africa it estimated at 85-90%, in North and Central America it is 13-18%. Woodfuel provides at least 72% of energy in 34 low-middle income countries and 90% in 13 low income countries (Karekezi and Kithyoma, 2013). Woody biomass are often derived from natural forests, woodlots, plantations, trees on farms, wetlands, bushland and residues of agricultural crops (Field *et al*., 2008).

Recent estimates of biomass energy in Kenya's is approximately 68 to 74% (Kiplagat *et al*., 2011; Torres-Rojas *et al*., 2011) which is remarkably less than 80-87% recorded slightly over 20 to 30 years ago (Hosier, 1984; Senelwa and Hall, 1993). Between the year 2004 to 2008, when more data was available, Kenya used 28.5 to 36.7 million metric tonnes of biomass which, 71 to 74% was derived from wood (IEA, 2007; Kiplagat *et al*., 2011).

In several low income countries, the rural communities rely on woodfuel as their only source for cooking (Barnes *et al*., 2016). Indeed, in the year 2000, average yearly firewood expenditure in rural areas was 3794 while in the urban areas it was 2701 kg per household, with an estimated per capita use evaluated at 750 in the rural areas and 690 kg for the urban counterpart. These statistics only reflected the situation at the beginning of the millennium but were estimated to progressively increase at 2.7% per annum against a supply that stagnated at less than 1% per year (MoE, 2002). Without any doubt, biomass energy will linger as the main source of energy in the foreseeable future, albeit other sources of energy are beginning to make major inroads as sources of energy.

Agricultural residues, bushlands, closed forests, farmlands, plantations and woodlands constitute the main wood biomass energy supply in Kenya (Martinot *et al*., 2012). Compiled data by Kiplagat *et al*. (2011) and those by Mugo and Gathui (2010) closed forests have an area of 1,247,400 ha. (~2.2% of Kenya's landmass) supplying 1.3 m^3/ha/year (total yield of ~1.3 million m^3), which represent about 45% of the biomass energy resources, which are only accessible to 5% of users. Meanwhile woodlands cover an area of 2,092,000 ha and produce 0.64 m^3/ha/year (yield ~1.3 million m^3)

while bush-land cover 24,629,400 ha. and yield an average of 0.44 0.64 m^3/ha/year (total yield ~10.84 million m^3). Wooded grassland occupies over 10,000 ha but supplies the less biomass (0.25 m^3/ha/year equivalents to ~2.6 million m^3 of biomass). Biomass derived from farmlands (covering 10,000,000 ha.) average ~1.4 m^3/ha/year (total = 14.40 million m^3) are relied upon by most Kenyans as the main source of biomass. There is large potential of forest plantation which currently covers only 91,000 ha. and supply on average 19.9 m^3/ha/year equivalent to 2.7 million m^3 (Kiplagat *et al*. (2011).

Plantation establishment thus appear to supply most biomass which is eighteen fold over unit biomass supply from closed forests and over 30 times over biomass supplied by woodland. However, the land under plantation establishment is currently very low and thus biomass supply is currently still low in the country. Also, the rate of tree planting in Kenya cannot sustain sustainable biomass supply to meet the increasing demand (Mugo and Gathui, 2010) resulting in a deficit of 57.2%. Moreover, most of the biomass from plantation establishments are reported to be consumed in the ago-industries such as in the tea and sugar industries, in the brick making industry, and in the mining industries (Dasappa, 2011).

The biomass energy balances per county in Kenya indicate that majority of the residents use wood biomass and therefore the biomass deficit might have been higher than estimated. Nandi County has two unique forest ecosystems, the South Nandi Forest and North Nandi Forest (http://nandi.go.ke/forestry-agro-forestry/). The later is the largest covering an area of 20,300 ha while the former envelops a total of 16,000 ha. (These are the sources of forested supplies for the County. Such supplies however are restricted and not readily available to the community. Households then have to continue relying on wood fuel supply from on farm production. Approximately 85-95% of the population in Nandi County are rural based and extensively rely on wood fuel as the major source of energy.

2.2 Tree volumes estimations and equations

Tree volume refers to the size of individual tree, also denoting the average wood biomass that could be harvested from any one unit of a forested land such as per hectare or per acre of land (Mascaro *et al*., 2011; McRoberts and Westfall, 2014). Thereare three methods that can be used to represent wood volume including: standing volume of wood or the merchantable volume; log volumes often supplied to mills; and product volume representing the portion of wood sold in markets (timber, plywood and veneer sheets) (Tonolli *et al*., 2011). The intrinsic value of wood volume is to represent the quantity or amount of usable wood in individual log, tree or group of trees during assessment tree economic value (Roy *et al*., 2017). Volume measurement is important to document variations that occur in trees over time (Mugasha *et al*., 2016; Riitters *et al*., 2016).

Since tree volume vary greatly (Sharma *et al*., 2016), age (Genet *et al*., 2009; Donaldson *et al*., 2014) and can be affected by many environmental variables (Schwarz *et al*., 2003; Poorter *et al*., 2012), routine tree volume measurement of individual or plantations are important for forestry inventory, commercial harvest and subsequent management (Hall and Bailey, 2011; Popescu *et al*., 2017). It is however, the methods used to determine tree volumes that should be the point of emphasis on forest management.

Employing models has aided in determining volumes of trees since the beginning of the 20th century and therefore a lot of data and equations are available to estimate volumes of trees (Demaerschalk, 1972; Williams and Schreuder, 2000; Sharma *et al*., 2002; Muukkonen, 2007; Yu *et al*., 2011). Confusion often arise in the choice or use of the models owing to the differences in approaches for estimation of wood volume (Perez, 2008; Henry *et al*., 2011; Burkhart and Tomé, 2012), which can be a challenge for forest managers and practitioners who wish to establish dependable methodologies for estimating wood volume. However, during the choice of any individual or group model, the model choice should applicable need to be free from bias and should strive to be as ensure high degree of accuracy.

A large number of studies and hence large data on tree volume in the developed countries exist from where one can select and compare several models to estimate tree volumes (Sharma *et al*., 2002; Zhang *et al*., 2002; Muukkonen, 2007; Case and Hall, 2008; Fonweban *et al*., 2012). Earlier studies predicted volume using based on the diameter where the breast height of the tree occur (dbh) (Corral-Rivas 2007; Case and Hall, 2008; Hjelm, 2015). After dbh is predicted, volume is obtained from local volume projected tables, charts and regression equations. The models assumed that wood is a uniform diameter throughout (Cao *et al*., 1980). Due to large variation in the wood diameter at different sections of the tree, such models were found to be unsuitable for many species of trees (Yao *et al*., 2012; McRoberts and Westfall, 2014) and couldn’t easily be interpreted even using the available tables and charts and were thus abandoned. Later a large number of studies were conducted which availed large amount of data. These studies estimated the volume of various species of tree and considered variation in several parameters. It was deduced from these studies that additional parameters for estimating volume of the tree are needed. Most of the studies therefore include diameter at point of wood cylinder, crown height, basal area, dbh and height (H) (Brown, 1997; Chen *et al*., 2007; McRoberts and Westfall, 2014). As a result, there have been advances in the development of models for predicting volumes.

For a long time, the equations developed by Näslund (1947), which estimated the volume for several species of trees using the independent variables dbh and height has been frequently used. More than 4000 sample trees were used to make the equations, and have been utilized regularly. These equations have been modified but the basic parameter has remained largely the same and is currently used in predicting volume of several species of tree outside the areas that they were developed. In addition to dbh measures and parameters of height (H or H^2), Eriksson also used crown parameters (height and length) during formulation of models. In addition, upper height diameter, bark thickness, breast height as well as above ground crown height were incorporated into the base of the formula to provide a robust model that formed the basis of taper models (Johansson and Karacic, 2011; Hjelm, 2015). At plantation level, a number of measurements of tree heights and DBH are appropriate for the taper and volume formulae.

Single-tree models, require data on measures allotment, mainly diameters of single trees in the plantation or a section stratagem such as tree height parameters (Johansson and Karacic, 2011). Meanwhile whole-stand models, require fewer details that are capable of simulating growth and yield approximations (McRoberts and Westfall, 2014). Some variables in the single stand models can be obtained quickly, simply and more precisely, while others like single tree height and stand dominant height dimensions take a lot of time and frequently inaccurate. During surveys and inventories of forests, measurements of diameters at breast height are always obtained from all trees, although measurements of heights are acquiring only for a few sample of trees whose diameters were observed (Sharma and Parton, 2007).

Most accurate single stand models using dbh and H which can be derived from easy to obtain tree measurements or inventory data and are thus more common (Maltamo *et al*., 2014). The correlation of tree diameters and the corresponding heights may differ amongst plantations due to the management practices and site conditions (Calama and Montero, 2004). Thus, supplementary predictive measures may be needed to generate single stand equations or models (Sharma and Parton, 2007). In the development of these forms of models, a number of approaches have been useful. Sharma and Parton (2007) found out that yet after incorporating extra stand characteristics in the models like tree basal area, diameter, height, and age as supplementary illustrative parameters. There are usually random difference between diameter and height relationships amid stands and plots.

In the majority of countries specifically the Sub Saharan Africa, measurements and prediction of tree volume is lagging behind (Henry *et al*., 2010; Henry *et al*., 2011; Fayolle *et al*., 2013). Munishi and Shear (2004) were the only researchers who developed tree volume model useful for the tropical regions especially the rainforest of East Africa using data obtained from Eastern Arc Mountains, Tanzania. Individual total tree volume was regressed against DBH during that process. Although, the practical individual tree volume (v) applied in this model was not pegged on destructive samples, however, they were calculated basal area and height of the trees (h) based on taper equation applying the formula ($v = g \times \frac{h}{3}$). Volume estimated from this equation was later found to be ambiguous and lacked the desired accuracy. In several occasions, a general volume equation $v = g \times h \times f$ is more common for estimating tree volume. The value f varies between trees, where a factor of 0.5 has habitually been used for models for tropical area (Malimbwi *et al*., 1994; Mpanda *et al*., 2011; Kashaigili *et al*., 2013). But the rigour of the moped using such constant estimates has rarely been tested in plantation establishments. Another weakness in relating dbh, h and f, may be due to variability as a result of environmental factors including soil nutrients, disturbance regime, succession, topography position, and tree species related intrinsic factors (Chamshama *et al*., 2004; Feldpausch *et al*., 2012; Mugasha *et al*., 2013). This makes the use of such models problematic.

Tree volume may be estimated by destructive and non-destructive methods (Gibbs *et al*., 2007). Destructive method is very common approach for estimating volume of standing trees. This method involves felling of trees while measuring length and mid diameter of different constituents of harvested trees mainly like tree stem and branches (Malimbwi *et al*., 1994). However, accurate computation of volume at the final harvest will only be dependents on the tree volume equation applied. Non-destructive method of volume estimation involves multiplication of the tree basal area by the tree height and form factor (e.g. Munishi and Shear, 2004) where form factor is obtained from the ratio of tree real volume to volume of geometrical form like cylinder or truncated cone. Volume obtained from this way has the advantage of getting quick results but suffer the problem of accumulated error resulting from the prediction of height. The study on form factor was done by Malimbwi *et al*. (1994) at

Mtibwa and Longuza Forest plantation during development of volume equation. Also, a number of studies have reported standing volume of teak by using nondestructive and destructive methods. For plantation forests, volume studies have been previously done with a focus on merchantable volume (Malimbwi *et al*., 1994). Categorical classification by age class predicted volume with increasing stand age being positively correlated with volume biomass (Butler *et al*., 2005). Overall expectation is that increased volume would lead to increased harvest probability, given that harvests seek to maximize yield.

The use of Current Annual Increment (CAI) and Mean Annual Increment (MAI) curves informs are gaining more recognition in tree model equations (Tompalski *et al*., 2016). The intersection of CAI and MAI curves intersect, inform the managers of efficient volume yields and also considerably ideal rotation age. Calculation of optimal age for harvest also informs managers of the most appropriate age of rotation applicable to the plantation. Unfortunately, in Kenya, there are currently little or no available data on the use of CAI/MAI in the estimation of forest harvest volumes, more particularly for the plantation establishments. In Kenya, the annual production rates of natural forests range from 20 to 70 m^3 ha^{-1}, and a yearly increase of height by 5 m for *E. grandis* (Oballa *et al.*, 2010). The estimate for the eucalyptus standing volume is about 27,000,000 m^3. However, standing volume of various plantation establishments or Eucalyptus within the plantation stands remains unknown.

2.3 Proximate and calorific value of trees and plantations

2.3.1 Proximate values of trees

The biomass energy (MJ/kg), or the heating value of a fuel, quantified by heat produced following complete combustion of a mass of fuel has often been traditionally determined by calculating or calorimetrically by incinerating a sample in muffle furnace (Telmo and Lousada, 2011). Chemical analysis is derived from an ultimate analysis or a proximate analysis of its elementary constituent of C, hydrogen, N, S, ash and moisture whereas proximate analysis evaluate the percentage of fixed carbon, moisture content, volatile organic matter and crude ash. In calorimetry, calorific values are determined (Ragland *et al*., 1991). However, these traditional methods have failed to effectively account for the energy production based on the volume of the trees.

2.3.2 Calorific value

Calorific value (MJ/kg) is heat produced upon total ignition of mass of fuel (Friedl *et al*., 2005). It can help characterize different fuel types (Ragland *et al*., 1991; Erol *et al*., 2010), depending on biomass chemical composition i.e cellulose, extractives, hemicelluloses and lignin. Calorific value depends on physical properties of wood such as size, surface area/unit volume, and porosity as well as thermal properties like specific heat, thermal conductivity and emissivity. Synonymous to heating value, calorific value is can assist in looking for fuel that can generate more energy (Baker, 1983; Maksimuk *et al*., 2017). The calorific value of wood range between 18–22 MJ/kg, but can be influenced by amounts of carbon, lignin and resin content (Baker (1983; Günther *et al*., 2012).

The calorific value of aged trees was more than of lower age trees suggesting that it increases with age, however this must be evaluated for each tree species (Kumar *et al*., 2010). For all species tested, Mianoo and Ulzen-Appian (1996) found that stems had higher calorific value than branches although the difference was not significant. No study is currently available on the calorific value of plantation tree establishment in Kenya, except for *Prosopis juliflora*, in Baringo County (Oduor and Githiomi, 2013).

2.3.3 Moisture content

Moisture content (MC) is the quantity of water in a piece of wood (Curkeet, 2011). It is expressed on either wet or dry basis, depending whether the dry or wet weight of wood is used as the denominator. It can have major effect on various wood properties mainly the net calorific value obtained in the burning process (Gerhards, 2007). Wood for fuel use should have moisture content ranging from about 18- 28%, higher or lower can have significant negative consequences, but Yildiz *et al*. (2016) reported that MC of fuelwood varies widely from 21% to 62% depending on climatic factors, time of harvesting, tree genotypes, parts of the tree harvested as well as storage conditions.

High MC in wood, result to vapourization with energy supply coming from the burning process, resulting in the net reduction of the heating value of the fuel. Meanwhile at low MC volatile matter will be denatured and thus net heating value will be low (Curkeet, 2011). Moisture content is low in stems, gradually increasing towards roots and crown (Erakhrumen, 2009). Also within a tree; the sapwood has higher moisture content than the heartwood, about 30% for heartwood as compared to

50% for sapwood, with the difference being smaller for hardwoods than softwoods (while Baker, 1983).

2.3.4 Ash content

Ash (%) is accounted for by solid waste left after the complete incineration of a fuel. In wood, ash is made up of Ca, K, P, Mg and Si, and in some instanced water molecules (Baker, 1983). In woody biomass, ash content can reach 2.3% with a much higher value likely to reduce its heating value (Oduor and Githiomi 2013). Kumar *et al.* (2010) found that ash content of the tree may be affected by tree age and growing environment.

2.3.4 Volatile matter

Volatile matter are products, exclusive of moisture, released as gas or vapour during combustion (ASTM, 1957; Saint-André *et al*., 2005). The volatile matter for wood ranges from 65% to 92% depending on the species, where the volatile matter yield for bark typically closer to 68-70% (Ragland *et al*., 1991). A study carried out on Eucalyptus hybrids revealed that variation of volatile matter content is minimal with harvesting age, even though the figures were decreasing with increase in age ranging from 82.25% to 79.29% within ages of 2 to 20 years old (Kumar *et al*., 2010). The volatile of trees may vary quantitatively due to mineralization of organic content and differ considerably between parts of the same tree, tree species and growth conditions (Saint-André *et al*., 2005).

2.3.6 Absorption and desorption

Absorption simply refers to the process of gaining moisture from the surrounding air, it is also referred as adsorption while desorption is the process of losing moisture to the surrounding air: when MC of wood reduces below fibre saturation point the water held in the cells will drain from the cell wall material (desorption) while uptake of bound water is adsorption (Berit, 1998), while according to Lamvik (1994), the term adsorption refers to compression of gases on free surface. Wood being hygroscopic material capable of taking on and releasing water to the surrounding environment (Ruiz-Villanueva *et al.*, 2016), may contain higher moisture above fibre saturation point when exposed to water vapour much longer (Droin-Josserand *et al.*, 2015). When exposed to ambient air, wood begins to dry as moisture escape to the surrounding environment.

When wood is placed in an environment with constant or stable temperature and humidity, will ultimately attain that moisture constant that yields zero vapor pressure difference between the wood and surrounding air (Lamvik (1994). Wood often stabilize at 8-14% MC for indoors, and 12- 18% MC for outdoors (Wei *et al.*, 1995).

Absorption and desorption of moisture by wood may be affected by variation in extractives content such as cellulose, hemi-celluloses and lignin (Skaar, 1988), as well as environmental factor such as temperature, relative humidity and wind movement. The rate of moisture absorption and desorption depend on ambient relative humidity and seasoning procedures (Wei *et al.*, 1995).

There is often a problem of desorption, particularly because a moisture content higher than 20% in wood is a precursor for fungal attack which can lead to wood rot and interfere with heating value of wood as well, hence lowering the efficiency of wood as energy provider (Droin-Josserland *et al*., 2015). Popper *et al*., (2008) when conducting absorption and desorption measurement on selected exotic tree species noted that desorption values was higher as compared to absorption values when the relative humidity was below 93% but the trend changed immediately the relative humidity reached 93% and the absorption values emerged higher than desorption values.

According to Ragland *et al*., (1991) chemical properties for heating value include proximate and ultimate analysis. Ultimate analysis provides the percentage weight of wood elements such as carbon in softwood species as 50- 53% and hardwood species as 47- 50%, due to the varying lignin and extractive contents. Curkeet (2011) reported that the average chemical content of dry wood, by weight, is 6.0- 6.5% hydrogen, 38- 42% oxygen, 0.1- 0.2% nitrogen and 0.1- 0.5% sulphur. Results from proximate analysis show 75% to 80% of wood is volatile matter and 20% to 25% fixed carbon (Baker, 1983). By burning a sample in a calorimeter, calorific values are determined (Ragland and Aerts 1991).

Heating value of lignin is greater than for cellulose or hemicelluloses, due to the high in carbon and hydrogen content (Mianoo and Ulzen-Appiah, 1996). Of the fuel elements, hydrogen has the highest heating value making it an excellent source of energy (www.wisegeek.com, 6th May, 2014). The heating value of cellulose and hemicelluloses are about 6,000 Btu/kg, lignin ranged from 7,000 to 7,200 Btu/kg while resinous material from softwood species had 9,700 Btu/kg (Baker, 1983). Softwood normally have higher heating value than hardwood due to higher content of lignin and resinous materials. Nordin (1994) noted that understanding of fuel properties like ash content, calorific value, fixed carbon content, hydrogen and volatile content, is significant for use of one material as fuel.

2.4 Tree biomass models

Developments of biomass and volume models have been widely used in forestry for scientific purposes to achieve higher value of accuracy in measured characteristics (Basuki, *et al*., 2009). The biomass models establish some a difficult to directly measure biomass from easily quantifiable characteristics of the trees such as dbh, height, and/or tree age. The models can be developed from equations exhibiting allometric, simple linear, exponential or hyperbolic functions ($R^2 > 0.8$). According Von Gadow and Brandenkamps (1992), the volume of individual trees is easily estimated from volume equations compiled from detailed accurate measurements of each sections of the tree. Having the height and dbh of a tree, biomass of the tree can be accurately determined.

In natural forests biomass is useful for extrapolation of sustainable utilization of the forest which allows them to be used as robust management tools (Zianis *et al*., 2005). Reliable forest biomass estimates and dynamics of biomass yields have benefited from the knowledge of tree allometry derived from tree volume models. Accurate estimation of biomass also informs the managers of the inherent function of the forest like global geochemical cycling, timber inventories and abstraction, as well as quantification of carbon stock (Henry *et al*., 2010; Vashum and Jayakumar, 2012).

The methods of performing biomass mensuration include remote sensing, GIS and field measurements (Ravindranath and Ostwald, 2008; FAO, 2009).

Calculation biomass of forest inventories are accurate methods where data from the field are used to determine biomass allometric equations (Brown 1997; Clark *et al*., 2001; Chave *et al*., 2005). Allometric regression model is the critical stage for AGB assessment; nonetheless, it is rarely openly examined. Several allometric formulae have been constructed for appliance as of various forest categories and geographical site (Ketterings *et al*., 2001; Zianis *et al*., 2005; Henry *et al*., 2010). The developments of tree allometric models are commonly done following destructive sampling protocols. Site and species specific models are all the time better when extrapolating to stand level biomass or volume.

Several allometric models were formulated for a variety of uses in different forest categories and site conditions. Allometric models have been reported in some studies as to use dbh as the single variable (Nunes *et al*., 2013). For instance, dbh is capable to give details 91.2% and 90.6% of the inconsistency in crown and stem biomass in *Eucalyptus nitens* (González-García *et al*., 2013). Incorporating tree height increases the accuracy of the allometric models. According to Menéndez-Miguélez *et al*., 2014), for each species chosen for biomass estimation could be easily predicted by an independent equation where dbh, and tree height are explanatory variables. Sub sampling has been noted by Dietz and Kuyal (2011) as a very essential stage in the biomass estimation process since the entire biomass of a tree can neither be transported nor dried, thus, it is necessary to cautiously select representative sub samples of appropriate size from each of the biomass components and the presence of a label on each sub sample must be confirmed. In Dietz and Kuyal (2011) experiment, large samples were broken into small sizes and oven dried before biomass measurement by tree components. In computing biomass of the above ground part of the tree, Mugasha *et al*. (2013) stated that mean dry to green weight ratio for each tree section should be computed and summed up. Dietz and Kuyal (2011) noted that below ground biomass is rarely assessed although it consists of about 20% of total tree biomass.

Mugasha *et al*. (2013) also reported that below ground parts of trees were not reckoned as important forest products hence lacked models, particularly because developing such models was very unreliable. The model presented by Mugasha *et al*. (2013) included:

$\text{Biomass} = \beta_0 + \beta_1 dbh + \beta dbh^2$

$\text{Biomass} = \beta_0 dbh^{\beta 1}$

$\text{Biomass} = \beta_0 dbh^{\beta 1} ht^{\beta 2}$

$\text{Biomass} = \exp\ [(\beta_0 + \beta_{1,}\ \text{In}\ (ht \times dbh^2)]$

The extensive review of literature presented in this study shows that a number of studies have estimated tree volumes based on a set of equations some of which still rely on models developed more than 50 years ago from forests. Some of these equations are often modified by incorporating new parameters, resulting in disparity of outcomes compared to the original equations. The reviews indicate that new parameters being incorporated into the model are unique to each region. However, volume equations modeling for many trees in plantation establishments in Kenya are rarely found in literature. As a result, volume equations should continuously be updated and validated for various regions and for different types of forest plantation practices. In Kenya, constant validation of tree volume equation is rare and they continue to rely on models that were developed over decades ago.

In terms of proximate and calorific values, the review content that an understanding of calorific values of plantation establishments in Kenya are infrequently undertaken and therefore this most important energy component of the plantation is rarely known. Finally, in terms of biomass-volume models the review established that there are several applicable biomass-volume models that are available but their applicability in tree plantation establishment in Kenya has remained rather limited and therefore studies are required to determine how they vary with age of plantations.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

The study was conducted in the tea estates that are owned and managed by Eastern Produce Kenya Ltd (EPK). This area was chosen because of it has both tea and eucalypt plantations.

3.1.1 Background, Location and Area

EPK tea estates are located in Nandi County, about 350 km north-west of Nairobi City. It lies within Kakamega- Nandi Forest complex which is one of the last surviving relics of Guinea- Congolean tropical rain forest in Kenya. The area lies between 1,000 to 2,000m above sea level, latitudes 0° and 0° 34″ to the north and longitude 34°44″ and 35°25″ to the east. The area of the EPK estates is 7,942.664 ha, of which 48% is under tea, 42% is under forest (indigenous and fuelwood plantations) and 10% under infrastructure (www.eastenproduce.com, 20th September, 2013). There are five factories and seven estates under the ownership of Eastern Produce Kenya Ltd. EPK also provides extension services to approximately 7,500 smallholders tea farmers (www.eastenproduce.com, 20th September, 2013).

The EPK tea estates are; Kipkoimet, Kibabet, Kapsumbeiwa, Kepchomo, Chemomi, Savani, and Sitoi, along with Chemomi, Savani, Kipkoimet, Kepchomo and Kapsumbeiwa factories. Other estates being managed on behalf of various local clients are; Kaboswa, Kipkeibon, Siret, Kaprachoge and Kibwari, with Kibwari and Siret factories.

3.1.2 Climate

The area experiences an equatorial climate and bimodal rainfall. Long rains commence in March to June and the short rains in October to November. Mean annual rainfall for the area is 1,500 mm. Mean temperatures during the long rainy season is 18 ± 2°C while higher temperatures averaging 23 ± 3°C occur during dry months. The lowest temperatures of 12°C, occur during the cold season of July to August. The mean relative humidity ranges from 60-67%.

3.1.3 Topography and soils

The area exhibits varied physiographic features consisting of undulating landscapes on the Kapsabet Plateau in the west, the forest regions, volcanic landscapes in Tindert Enscarpment, and an undulating landscape towards the Nyando gendtly undulating basin in the Southern edge.

The soil in the area was probably formed during the quaternary period and is mainly made of igneous rocks, volcanic ash mixture and pyroclastic rocks from recent volcanoes. As a result of the recent volcanic activities, the soils are fertile, well drained, moderately deep, dark-reddish brown, loamy to clay with humic top soil (Jaetzold and Schmidt, 1983).

3.1.4 Economic activities

Predominant economic activities in this zone are tea growing and forestry for the estates while for the communities surrounding the estates who are the smallholders, their main other cash crops include sugar cane, coffee, horticultural crops and maize is also grown extensively, playing a dual role as both a cash crop and a food crop. The farmers also keep livestock.

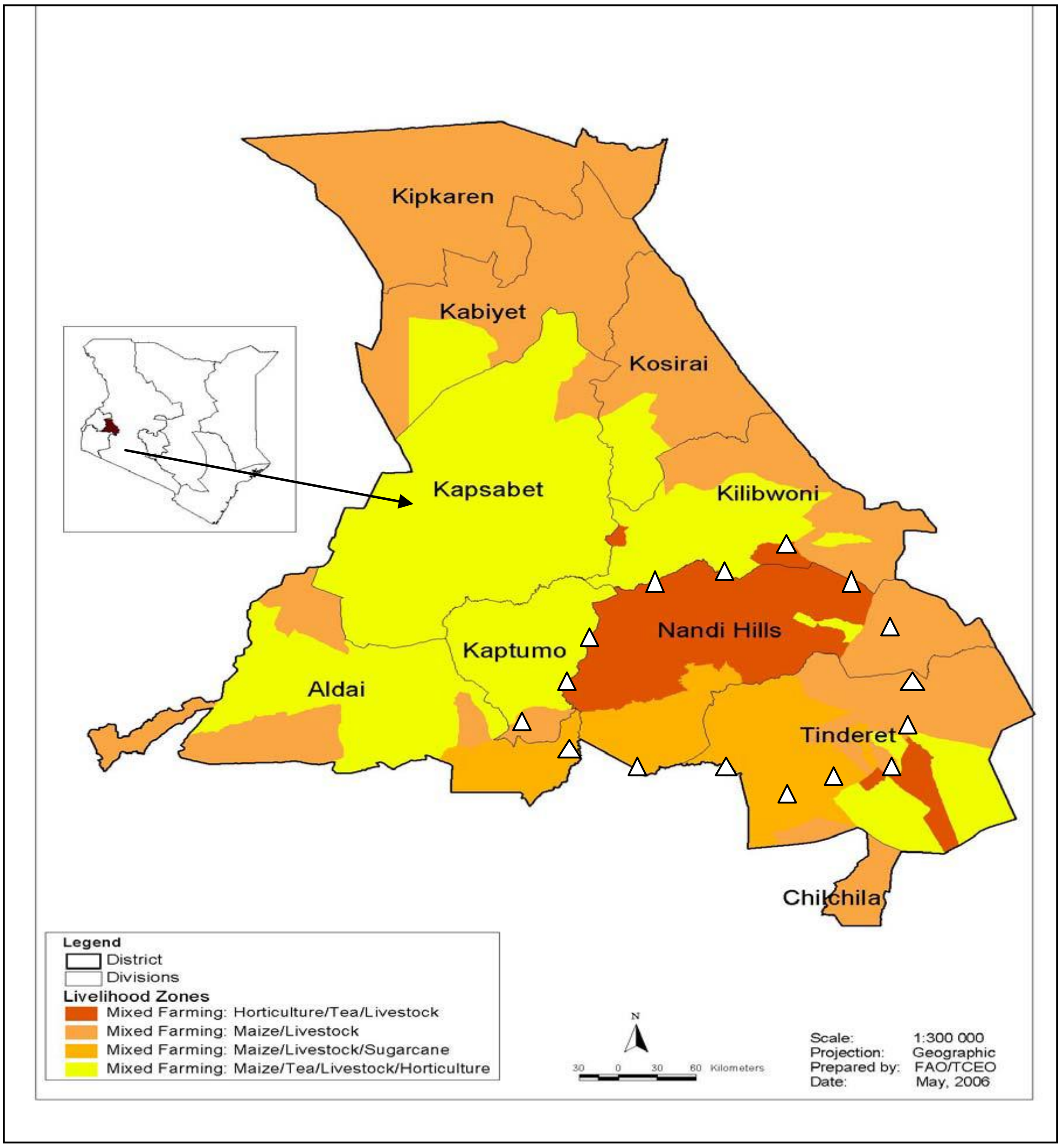

Figure 3.1: Map of Nandi County showing study area marked by this △shape

(Source: Author, 2018)

3.2 Experimental Design

3.2.1 Eucalyptus plantation inventory

Data for number of stems/hectare, dbh and mean plantation height within the EPK estates were obtained from inventory data collected from the field in the year 2015, by company employees. Data was collected from 0.01 ha (5.64 m diameter) plots in all compartments throughout the estates. The number of plots per compartment was determined by the area of the compartment, based on the inventory protocol of EPK Ltd as:

- < 1 ha: 3 plots
- Between 1.01 ha and 2 ha: 5 plots
- Between 2.01 ha and 10 ha: 8 plots
- Between 10.01 ha and 15 ha: 10 plots
- Between 15.01 ha and 20 ha: 15 plots
- Greater than 20 ha: 20 plots

The location of the plots was selected randomly in the office, by marking points on digital maps, reading off the relevant co-ordinates and then utilizing a GPS to locate these points as the plot centres on the ground. In each of the 0.01 ha plots the dbh of every stem was recorded and the height of three trees closest to the centre of the plot (EPK Ltd inventory protocol). Tree height was measured using a Suunto clinometer. Other information for plantations such as date of planting (or last coppice, where relevant), and total hectares were also recorded.

Three volume equations were tested using regression analysis with data (Annex 2(A)) for 56 trees of known dbh, height and volume.

The equations were:

1. $\text{InV} = \beta_0 + \beta_1\text{In(dbh)} + \beta_2\text{In(ht)}$ (Equation 1)

2. $V = \beta_{0\,+}\,\beta_1(1/D)$ (Equation 2)

3. $V = \beta_{0\,+}\,\beta_1(D)$ (Equation 3)

3.2.2 Proximate and calorific value measurement

Eucalyptus of different ages (4, 6, 8, 10, 12, and 14) were used in this test. The trees were raised under similar soil and routine management conditions. For each age group, three trees were randomly selected. The plantations were selected randomly. The locations of the selected 18 trees were also randomized. The selected trees were felled and six wood sample discs, measuring 60 mm in length obtained from stump height (0.15m); dbh (%); 20; 40; 60 and 80 of the total tree height and labeled. A total of 108 discs were transported to the chemistry laboratory at University of Eldoret.

Each disc was further cross-cut into two discs; Disc A, measuring about 30mm was cut from the bottom of each disc for assessment of moisture, ash, volatile matter, adsorption and desorption, and disc B, the remaining portion was used for determination of calorific. Total of 216 discs were used during laboratory tests.

3.2.2.1 Calorific value

The disc B samples, measuring for calorific values, were debarked and then oven-dried to constant weights at a constant temperature of 70°C. The dry samples were sliced and milled to pass through a 40 to 60 mm mesh sieve. Approximately 1.00 g of thoroughly mixed samples were weighed in triplicates in the crucibles using electronic portable balance and placed inside an oxygen bomb calorimeter to quantify the calorific value. Initial and final temperatures were recorded. The bomb calorimeter was standardized and calibration constant recorded (Annex 29).

Calorific Value of sample = $\frac{(T2-T1)*C}{Z}$

Where:

T^2 = Final temperature

T^1= Initial temperature

C= Calibration constant

Z = Weight of the sample

3.2.2.2 Moisture content

The disc A samples were chipped and milled to pass through 250 mm sieve in concomitance to the method D2013 or practice D346. The crucible was first reconditioned by putting it into muffle furnace at 900^{o}C for 2 min, and then cooled in a desiccator for 10 min and weigh to the nearest 0.01 mg. Approximately 1.000 g of the test sample which were at equivalent room temperature were weighed in crucibles in triplicates and then the crucible with the test samples placed in oven at a constant temperature 105^{o}C until a constant weight was obtained (Annex 29).

$$Moisture\ content = \frac{Initial\ weight - Oven\ dry\ weight}{Oven\ dry\ weight} * 100$$

3.2.2.3 Ash content

Approximately 1.000 g of thoroughly mixed samples were drawn from chipped and milled disc A, and weighed in triplicates in the crucible and placed in the muffle furnace at 600^{o}C for four hours. The crucibles were transferred from furnace directly to desiccators using muffle furnace tongs. The samples were cooled in the desiccators for 1 hr and their final weight taken to the nearest 0.1 mg. The samples were placed back into the muffle furnace at 600^{o}C and dried to constant weight. Weights of the empty crucibles were also measured. Final weight of the sample = weight of crucible containing sample - weight of empty crucible (Annex 29).

$$Ash\ content\ (\%) = \frac{M_3 - M_1}{M_2 - M_1} * 100$$

Where: M_1= Mass of empty crucible + lid

M_2= Mass of empty crucible + lid +sample before heating

M_3= Mass of empty crucible + lid+ ash

3.2.2.4 Volatile matter

Approximately 1.00 g of thoroughly mixed samples that were oven-dried at a temperature of 105^{o}C was weighed in the crucible in triplicates and transferred to muffle furnace at 900^{o}C for three hours. The crucibles were directly transferred to the desiccators using muffle furnace tongs for cooling for 30 min and their final weight taken to the nearest 0.1 mg. The samples were placed in the muffle furnace at 900^{o}C to constant weight. Weight of the empty crucible with lid was also measured (Annex 29).

$$Volatile\ matter\ content\ (\%) = \left(\frac{M_2 - M_3}{M_2 - M_1} * 100\right) - MC$$

Where: M_1= Mass of empty crucible and lid

M_2= Mass of empty crucible + lid +sample before heating.

M_3 = Mass of empty crucible + lid +sample after heating.

MC = Moisture content on wet basis

3.2.2.5 Moisture absorption

The weights of empty crucibles were determined. Approximately 2.00 g of thoroughly mixed samples from chipped and milled disc A, were drawn and dried in an oven for 24 h at 105^{o}C, then their weights were measured in crucibles in triplicates. Hydrated copper sulphate was weighed and placed in the desiccators and wire gauze put on top. The open crucible containing weighed samples were placed on the wire gauze. After 24 hr, the crucibles and the samples were measured to the nearest 0.01 g. (Annex 29).

$$Moisture\ absorption\ \% = \frac{M_3 - M_1}{M_2 - M_1} * 100$$

Where: M1= Mass of empty crucible.

M2 = Mass of crucible + samples

M3 = Mass of crucible + samples after 24 hrs in the desiccator.

3.2.2.6 Moisture desorption

The weights of empty crucibles were determined. Approximately 2.00 g of thoroughly mixed samples from chipped and milled disc A, were drawn and dried in an oven for 24 h at 105^{o}C, then their weights were measured in crucibles in triplicates. Anhydrous copper sulphate was weighed and placed in the desiccators and wire gauze put on top. The open crucible containing weighed samples were placed on the wire gauze. After 24 hr, the crucibles and the samples were measured to the nearest 0.01 g.

$$Moisture\ desorption\ \% = \frac{M_3 - M_1}{M_2 - M_1} * 100$$

Where: M_1= Mass of empty crucible.

M_2 = Mass of crucible + samples

M_3 = Mass of crucible + samples after 24 hrs in the desiccator.

3.2.2.7 Fixed carbon

Fixed carbon (FC %) was calculated as :–

FC (%) = 100 - (% Ash content + % Volatile matter content+ % Moisture content) (Annex 2 (C)).   .

3.2.3 Above ground tree biomass and volume model

To obtain the representative tree samples, age distribution was considered. The plantations where the research was conducted were randomly selected. Four trees were selected randomly from each age group and used for destructive sampling. The age distribution ranged from 2 to 15 years, thus, totaling 56 trees.

After felling, diameter was accurately measured every 2 m for stems and big branches with diameters of more than 10 cm (Fig 3.2a). Stump height and mid-diameter were additionally measured. Each section's volume was computed using Smalian's formula.

$$Volume = \frac{(D^2+d^2)3.14*L}{80,000}$$

Where:

D = log bottom diameter

d = log top diameter

L= log length

While the volume of each stump was worked out using Huber's formula;

$$Volume = \frac{(D^2)3.14*L}{40,000}$$

Where;

D = log mid-diameter

L= log length

The total tree volume was the summation of volume of each section plus and the log.

Figure 3.2a: Taking diameter at 2 m interval and 3.2b: Determining Fresh weight (Source : Author, 2014)

The fresh weight of the whole trees were determined immediately in the field after felling using spring weighing balance and recorded (Figure 3.2b). Tree material was portioned into leaves, branches and stem following standard recommendation that take care of moisture content. Sample discs of 30 mm thickness were obtained from the stem; at bottom, middle and top at 10 cm diameter and from the branches and a sample from leaves as well, adding up to five samples per tree. The fresh weight of sample discs were determined *in situ* using spring weigh scales as kitchen scale determined the weight of smaller specimens. The sections were labeled according to: replicates, number, age, plantation, branches, leaves and stem. Triplicate tree samples were stored in sealed plastic bags, and transported to the laboratory for further determination of moisture content. Dry weights was obtained by drying the sample at a temperature of 105°C until a constant mass (Figure 3.3a). After achieving the constant dry weight (Figure 3.3b), the ratio of dry to wet weight was determined (Mbelase, 2012). Field data (Annex 29).

$$Whole\ tree\ dry\ weight = \left[\frac{Average\ dry\ weight\ of\ samples}{Average\ fresh\ weight\ of samples} * (Whole\ tree\ fresh\ weight)\right]$$

Figure 3.3a: Sample disc oven drying and 3.3b: Weighing after drying

(Source : Author, 2014)

3.3 Data analysis

3.3.1 Eucalyptus plantation Inventory

Linear regression was conducted using the volume data calculated from trees of various ages with the help of SAS/STATS (2002) to identify the best fit models for volume against height, diameter and age.

3.3.2 Estimation of CAI and MAI

CAI and MAI curves were plotted and the intersection the two points informed on the theoretical optimal harvest age to maximizes timber yield (Avery, 2002).

3.3.3 Effect of age on proximate and calorific values

The effect of age on proximate and calorific values was analyzed using Analysis of variance (ANOVA) with age as fixed a factor using SAS/STAT (2002) to identify differences in proximate and calorific values at various ages. The data collected from trees of various ages was analyzed using SAS/STATS (2002) to identify the best fit models (Ash content, calorific value, volatile matter, fixed carbon, dry moisture, and desorption and adsorption).

3.3.4 Volume and Biomass Modelling Equations

Modelling of Volume and Biomass was done using SAS/STATS (2002). Log lengths and diameters at both ends of the logs measurements taken allowed modelling of Volume, and fresh weight and dry measurements assisted in modelling of Biomass.

CHAPTER FOUR

RESULTS

4.1 Standing volume of the eucalypt plantations of various ages at EPK

Information on the dbh and height used to derive the volume is shown in Annex 1) and Annex 2).

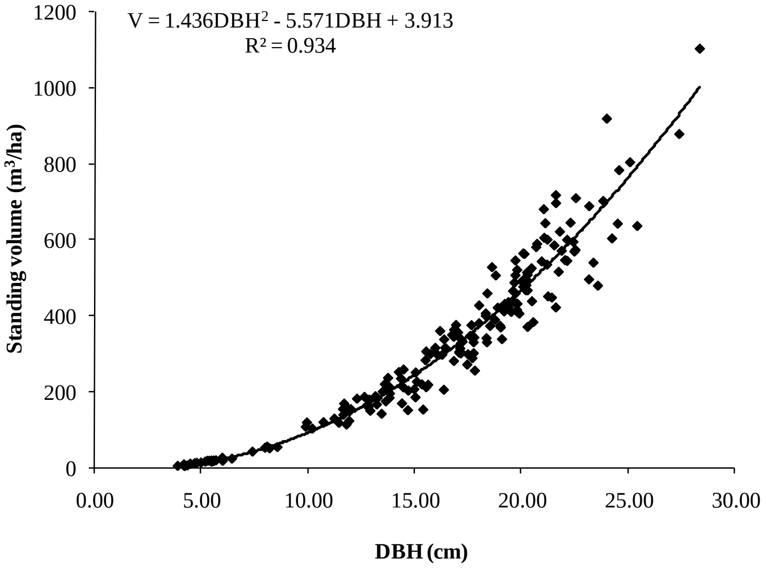

Figure 4.1: Standing volume and dbh of trees at EPK tea factory

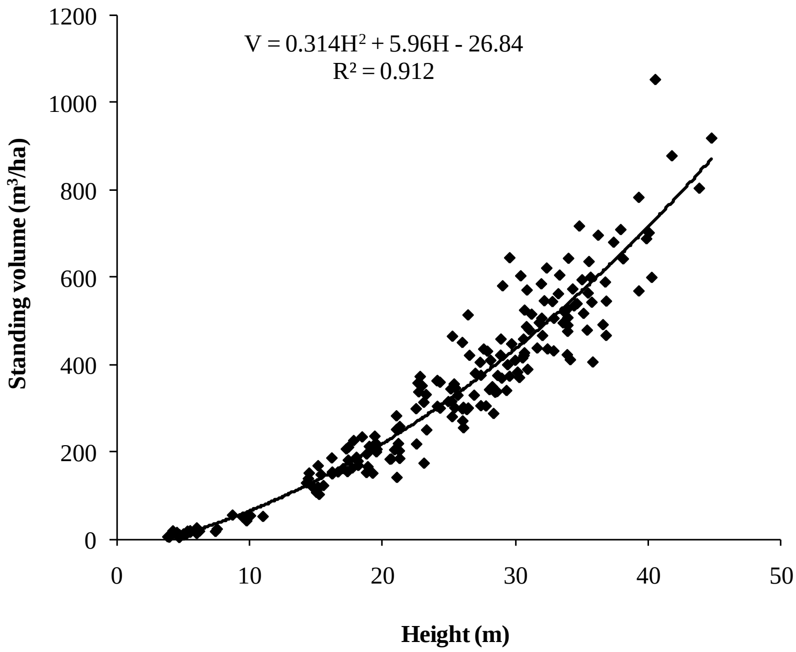

Figure 4.2: Standing volume and height of trees at EPK tea factory

After performing regression analysis (Annex 30), equation 1 had the best model fit (R^2 = 0.9722) compared to equation 2 (R^2 = 0.897) and equation 3 (R^2 = 0.595). As a result the logarithmic model fitted data better than using diameter alone. This can be explained by the fact that scatter plots in Figs 4.1 and 4.2 suggest curvilinear relationships between standing volume and diameter at breast height (D) and tree height (H) as predictor variables. Thus the volume equation:

$Ln V = -9.270 + 2.594In (D) + 0.152 In(H)$ was applied to compute volume for each plot then extrapolated to volume per hectare, volume per plantation, volume per age and total volume for all estates (Annex 28). The estimated volume of EPK estates ranged from 15.86 to 736.88 m^3 ha^{-1}

The regression outputs showing relationships between the trees volume against dbh is provided in Annex 1 while the trees volume against height of the plantation is shown in Annex 2. Based on the tables, there was significant (Pr < .001) positive relationship between volume and dbh as well as trees height.

The relationship between standing volume of the trees and age are shown in Annex1 (C). There was an increase in standing volume with age following a sigmoid pattern of distribution. The regression outputs showing relationships between the standing volume against age is provided in Annex 3.

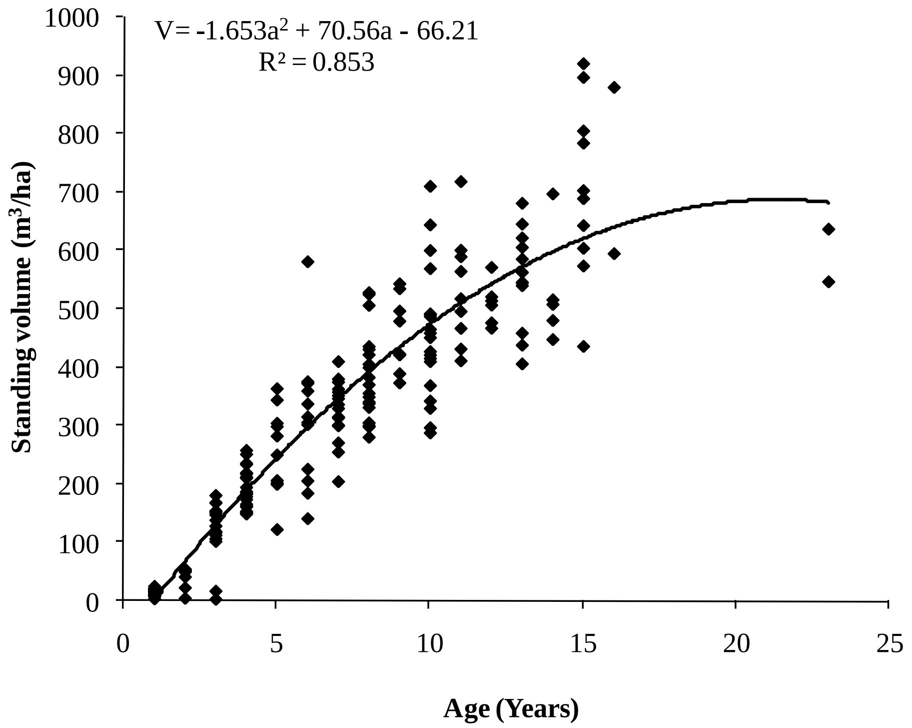

Figure 4.3: Relationship between standing volume of the trees and age

Graph of CAI and MAI at the EPK Nandi

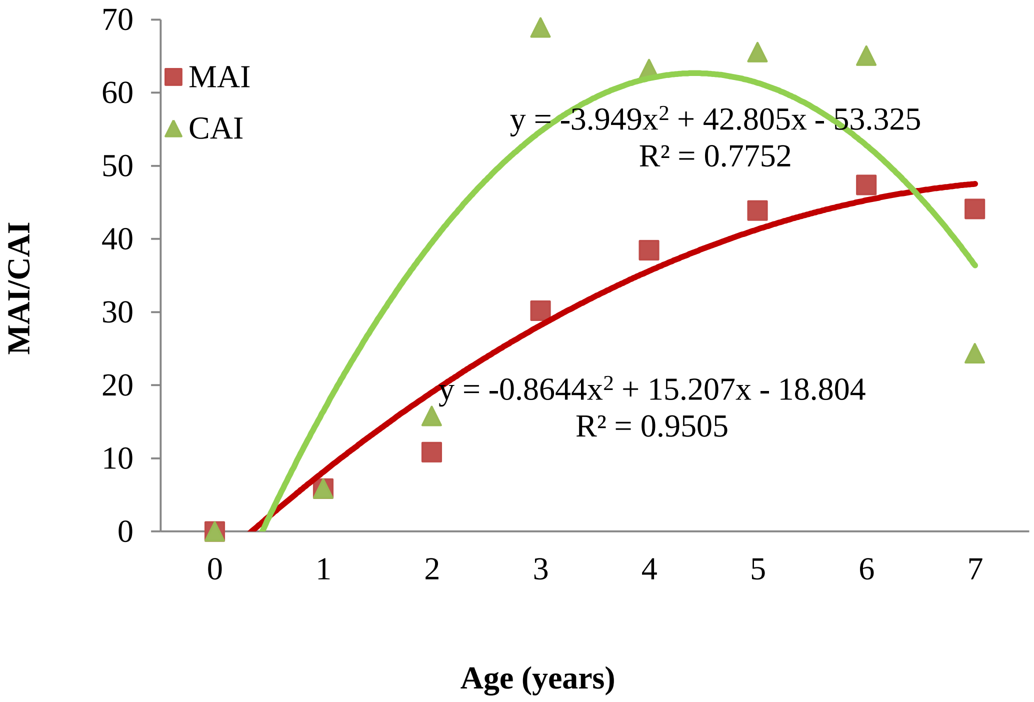

Figure 4.4: Relationship between CAI and MAI at the EPK Nandi

Based on the above graph, the optimal volume to harvest the tree range between 5 to 10 years, the exact age of harvesting is determined by the interaction between the CAI and MAI. The result in the figure indicate that the most appropriate harvesting volume is where there is a convergence between CAI and MAI which is at age 8.5 years where the volume from the area harvested will be optimized.

4.2 Variation in proximate and calorific value as a function of age of the eucalypt trees in EPK plantations

4.2.1 Ash content of the woody biomass

The mean ash content of the forest of various ages together with separation of the means based on Tukey's HSD test is shown in Figure 4.4.

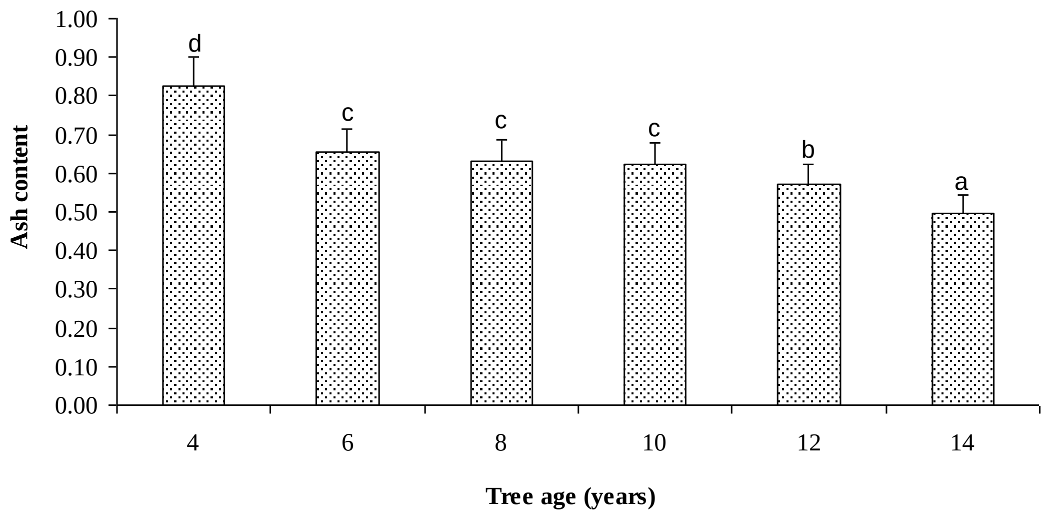

Figure 4.5: Mean (± SD) and Tukey's separation of the ash content of the *E. grandis* at various ages.

The mean of the ash content in the plantation establishments was different based on age. ANOVA table showing differences in the ash content of the *E. grandis* within the plantation establishments is shown in Annex 4 which indicates that indeed the differences in ash content were statistically significant in the plantation of different ages. The highest percentage of the ash content within the plantation occurred at age 4, this was followed by the ash content of plantation aged 6, 8 and 10 years while plantation aged 14 years had the least percentage of ash content compared to other ages during the study.

Since there were significant differences in the ash content with age, Tukey HSD was computed as shown in Annex1 (E). The minimum significant differences confirm indeed that ash content differed with age of the trees in the forest.

The linear relationships between ash content and age of the *Eucalyptus grandis* at EPK plantation establishments was plotted in a scatterplot as provided in Figure 4.6.

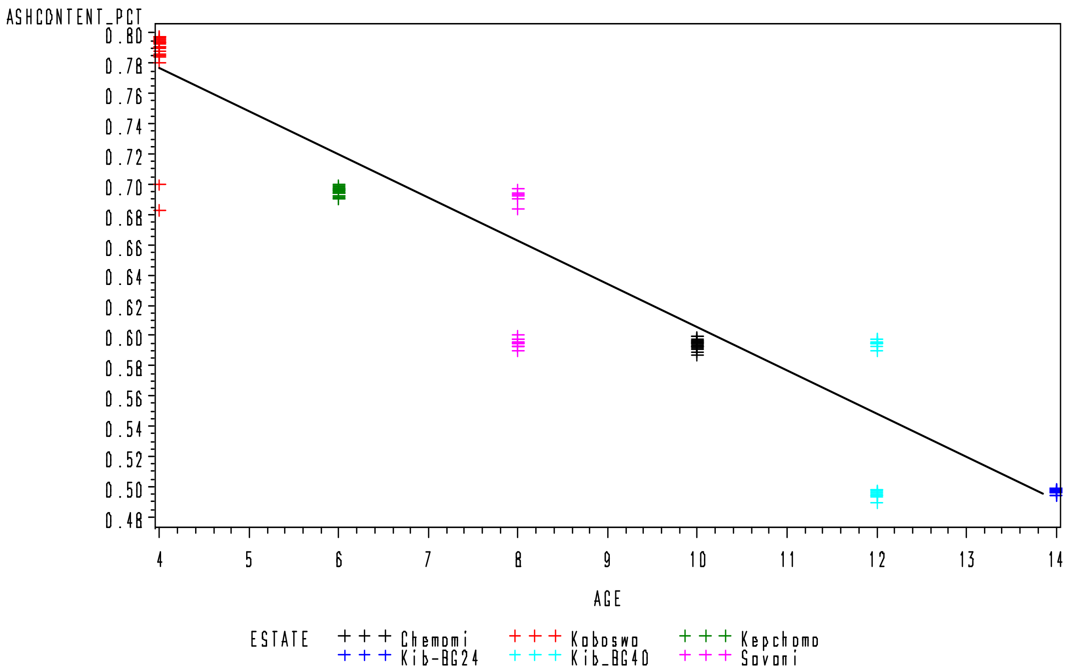

Figure 4.6: Scatterplot of *E. grandis* ash content PCT by age at the EPK.

Based on the observed scatter diagram, ash content of the forest decreased with age of the forest from year 4 to years 14 of the period.

To clearly define relationship between ash content and age of the trees stands, linear regression was conducted and the results are as shown in Annex 6. There was a strong linear relationship between the ash content and the age of the forest with a regression coefficient of 0.9209, which had a slope that is significantly greater than 0 (*Pr* > F < 0001) based on the ANOVA analysis of the regression trends

4.2.2 Volatile content

The mean concentrations of volatile content of the forest of various ages are illustrated in Figure 4.7.

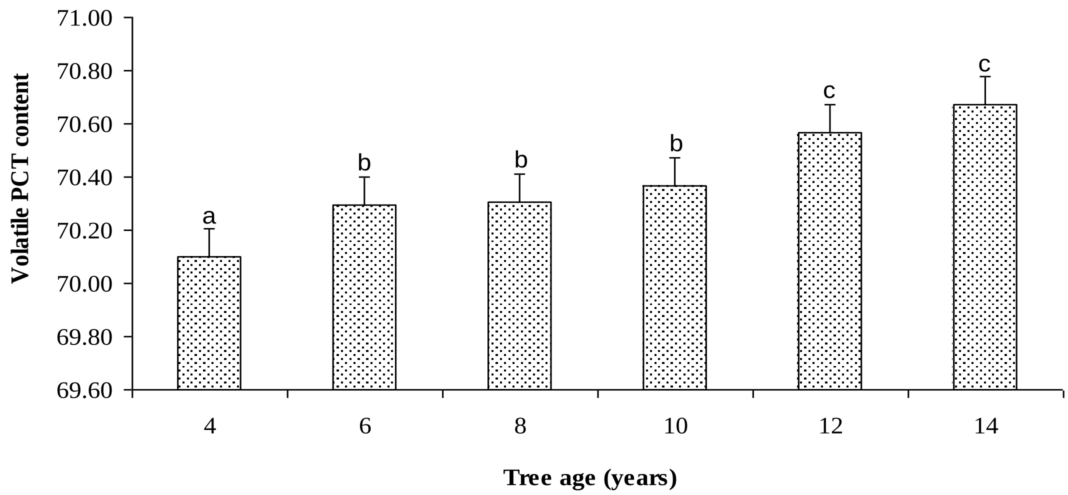

Figure 4.7: Mean (± SD) and Tukey's separation of the volatile PCT content of *E. grandis* at various ages.

ANOVA table showing differences in the volatile PCT content of *E. grandis* based on ages of the trees within the plantation establishments is shown in Annex 7. The result of the table indicates that indeed, the volatile content of the tree plantation establishments varied significantly with age. The means were separated based on Tukey's HSD test with parameters shown in Annex 8. The figure indicates that the mean volatile PCT content in the tree plantation establishments increased with age.

Correlation between volatile PCT with age of the forest in EPK is shown in Figure 4.9. The volatile PCT increased with age of the forest from age 4 to 14 years period.

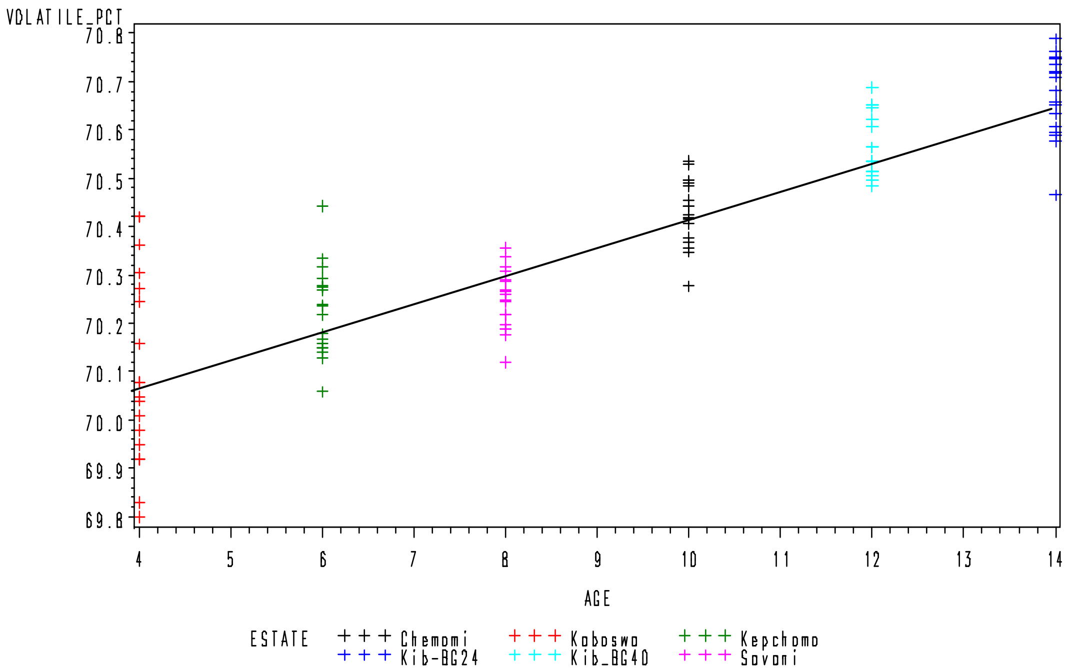

Figure 4.8: Plot of *Eucalyptus grandis* volatile PCT by age at the EPK Tea Estates

Relationship between the volatile PCT and age of the trees in the forest was found to be significant Annex 9 with a strong positive relationship between the volatile PCT and the age of the forest with a regression coefficient of 0.8265, which had a slope that is significantly greater than 0 (P < 0001).

4.2.3 Desorption PCT of the woody biomass

The desorption PCT content of the forest in relation to forest age is illustrated in Figure 4.9.

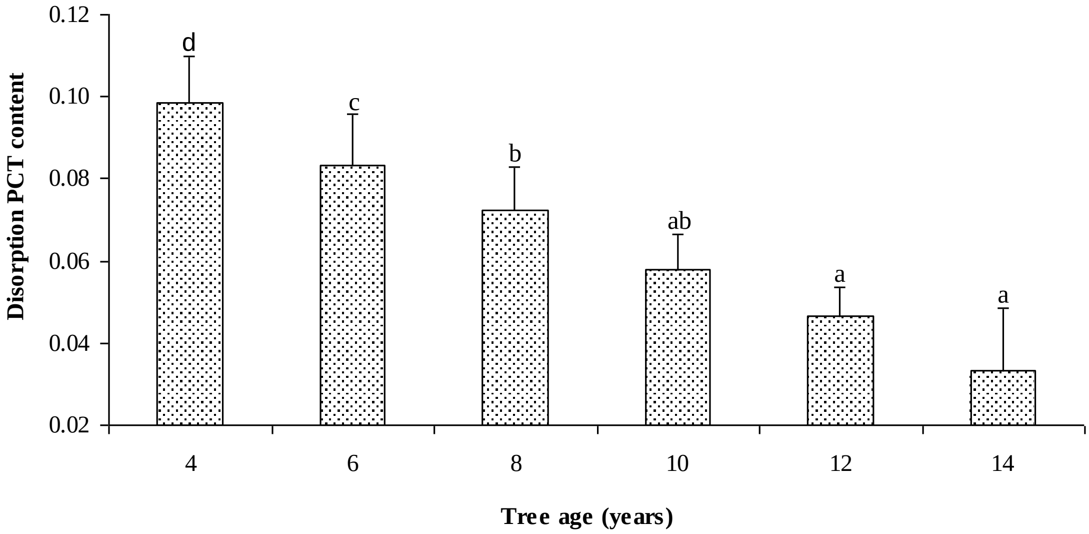

Figure 4.9: Mean (± SD) and Tukey's separation of desorption content of *E. grandis* at various ages within the plantations at EPK

Differences in the mean desorption among different ages was computed using ANOVA (Annex 10). The result of the ANOVA table showed that desorption content of the *E. grandis* differed significantly among the years of the plantation establishments. Subsequent to the significantly different means, desorption content of the plantation was compared based on Tukey's Studentized separation of means (Annex 11). The lower value of the error mean square and the minimum significant differences within the table, confirm that indeed there was significant differences between desorption among different ages of the forest plantation. Based on the Tukey's separation of means, the desorption at age 4 years was the highest, followed by those of age 6 years, and then age 8, while age 12 years and 14 years had the lowest desorption content but were not significantly different between each other.

Since there was a decreasing trend between desorption and age of the tree, relationship between desorption against age was determined. The desorption PCT of the woody biomass showed negative relationship with the age of the forest (Figure 4.12).

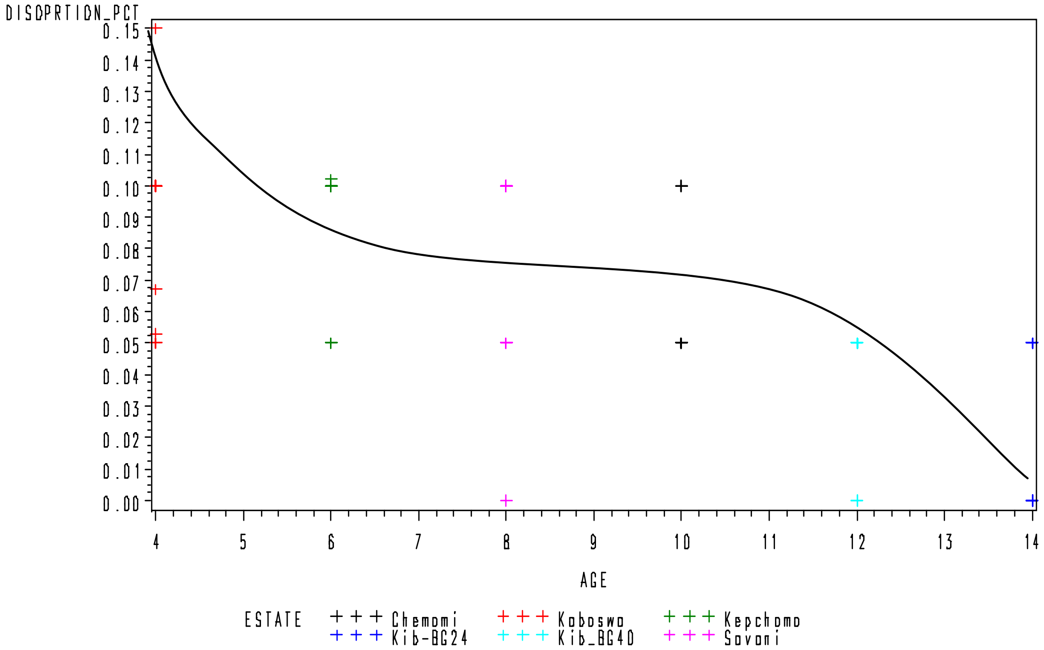

Figure 4.10: Plot of *E. grandis* desorption PCT by age at the EPK Tea Estates

The linear relationship between desorption and age of the trees in the forest was evaluated and the result presented in Annex 12. There was a moderate negative linear relationship between desorption and the age of the forest with a regression coefficient of 0.5083. The slope of the regression was significantly greater than 0 (*Pr* > F < 0001) based on ANOVA of the regression trends.

4.2.4 Absorption PCT content

The absorption PCT content of the forest of various ages is illustrated in Figure 4.11.

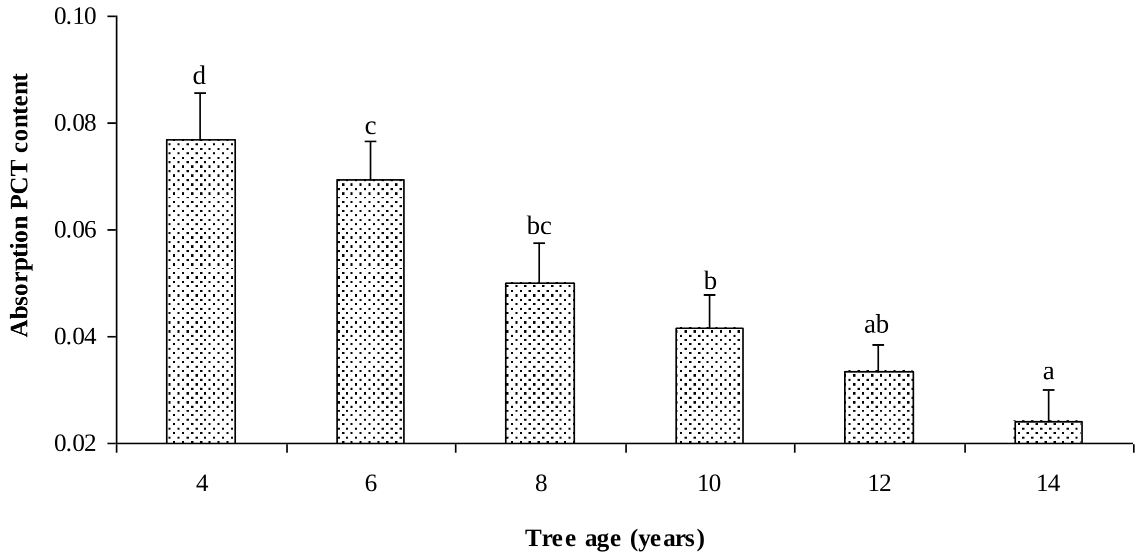

Figure 4.11: Mean (± SD) and Tukey's separation of the absorption content of *E. grandis* at various ages.

Differences in the absorption content of the forest with age based on analysis of variance are shown in Annex 13. The table, depict a significant difference in absorption with time. Since the ANOVA results confirmed that there was a significant difference, the means were separated based on Tukey's HSD test (Annex 14).

Since there were significant differences in the absorption with age, Tukey's HSD was computed as shown in Annex 15. The minimum significant differences confirm indeed that the ash content differed with age of the trees in the forest.

Absorption PCT of the woody biomass against age of the tree was plotted as a scatterplot is shown (Figure 4.12). Based on the set of observations from the figure, absorption had a negative relationship with the age of the forest.

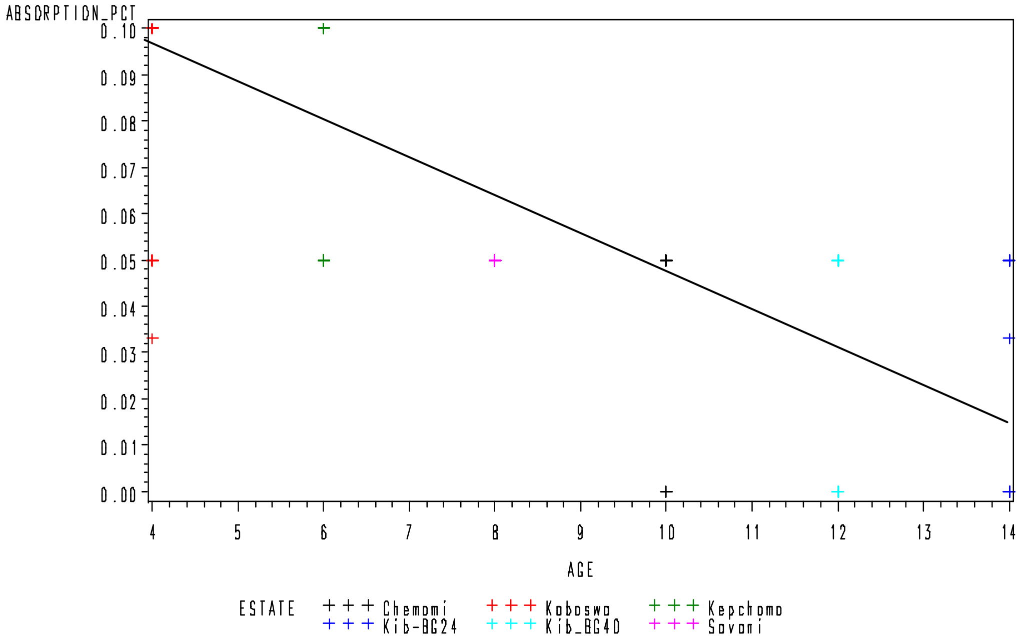

Figure 4.12: Plot of *Eucalyptus grandis* absorption PCT by age at the EPK

The linear relationship between the absorption and age of the trees in the forest was evaluated and the result presented in Annex 16. There was a moderate negative linear relationship between the absorption and the age of the forest with a regression coefficient of 0.5263, which had a slope that is significantly greater than 0 (*Pr* > F < 0001) based on the ANOVA analysis of the regression analysis.

4.2.5 Fixed carbon content

The mean fixed carbons of the forest of various ages are illustrated in Figure 4.13. ANOVA table showing differences in the fixed carbon of the *E. grandis* in the plantation establishments is shown in Annex 17. The differences in fixed carbon content were statistically significant in the plantation of different ages. The means were separated based on Tukey's HSD test (Annex 18). The figure indicates that the mean fixed carbon content in the tree plantation establishments increased with age.

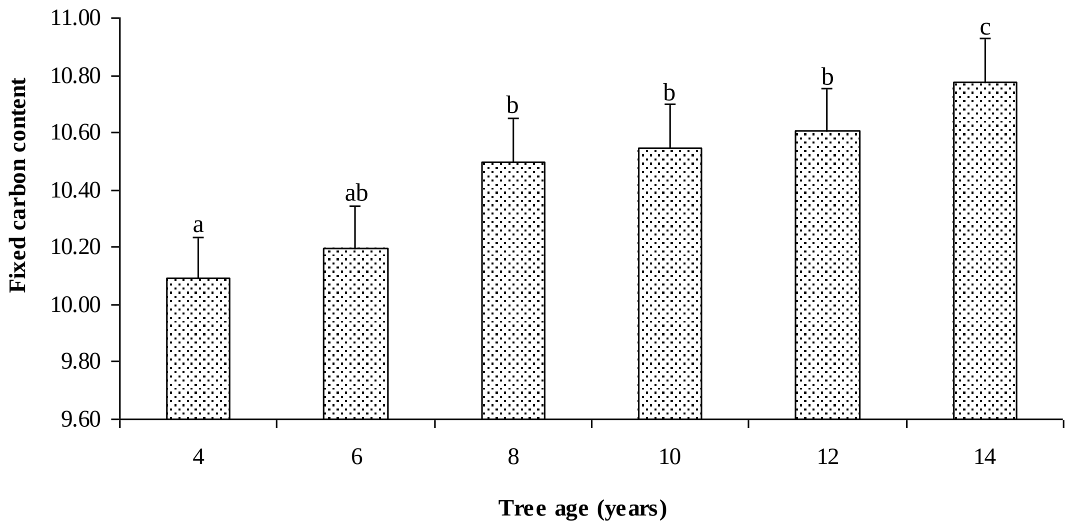

Figure 4.13: Mean (± SD) and Tukey's separation of the fixed carbon content of *E. grandis* at various ages.

Fixed carbon also significant positive trend with age of the forest (Figure 4.14)

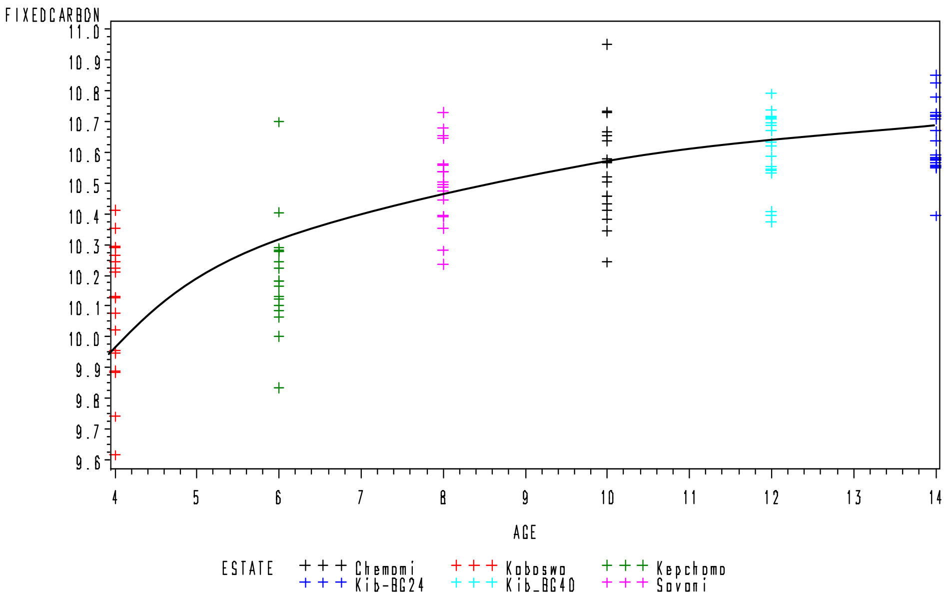

Figure 4.14: Plot of *Eucalyptus grandis* fixed carbon by age at the EPK

The linear relationship between fixed carbon and age of the trees in the forest was evaluated and the result presented in Annex 19. There was a moderate positive linear relationship between fixed carbon and the age of the forest with a regression coefficient of 0.7591, which had a slope that is significantly greater than 0 (*Pr* > F < 0001) based on the ANOVA analysis of the regression trends.

4.2.6 Mean calorific value

Mean calorific value at varying ages is illustrated in Figure 4.15. ANOVA table showing differences in the mean calorific value of the *E. grandis* within the plantation establishments is provided in Annex 20. The analysis of the table indicates that indeed the differences in mean calorific value of the trees within the forest were statistically significant in the plantation of different ages. Based on the fact that the means were statistically different, separation was done using Tukey's HSD test (Annex 21). The mean calorific in the tree plantation showed significant differences with age of the forest plantations.

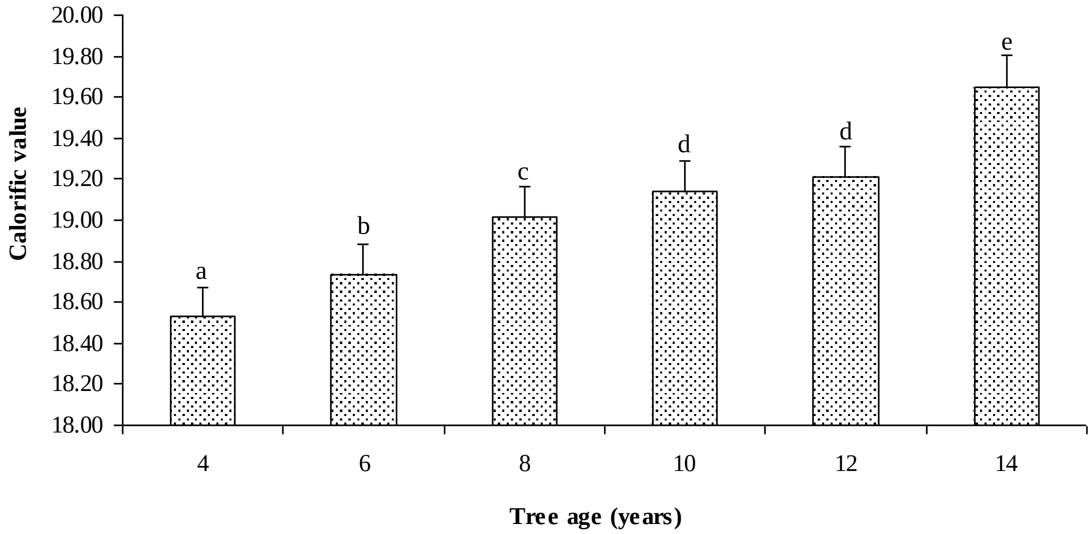

Figure 4.15: Mean (± SD) and Tukey's separation of the calorific value content of *E. grandis* at various ages.

Calorific of the woody biomass against age of the tree was plotted as a scatterplot as shown in Figure 4.16. Based on the set of observations from the figure, calorific value had a positive relationship with the age of the forest.

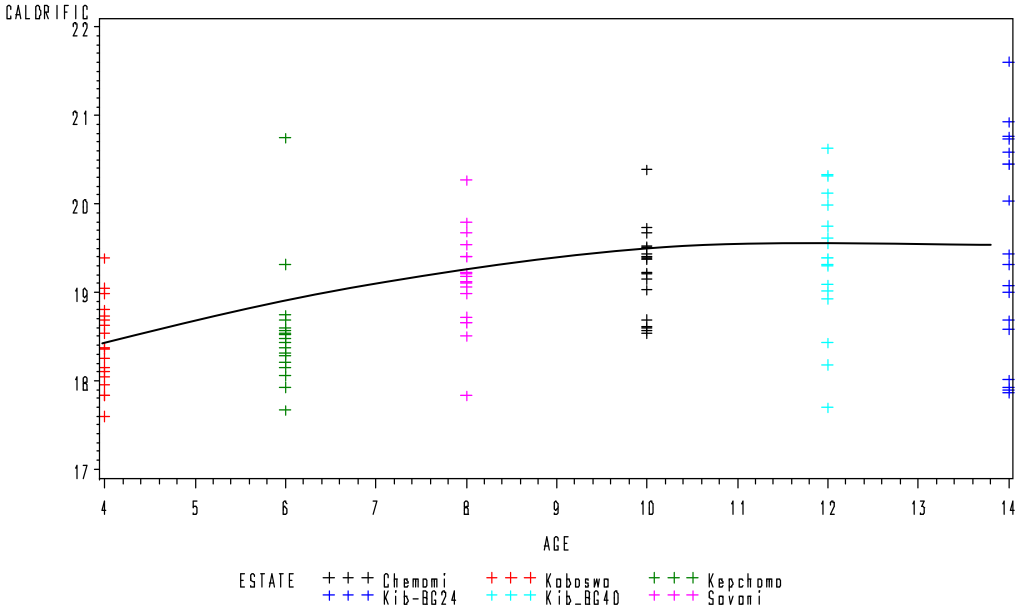

Figure 4.16: Scatterplot of *E. grandis* calorific value by age at the EPK Tea Estates

The linear relationship between the calorific value and age of the trees in the forest was evaluated and the result presented in Annex 22. There was a moderate positive linear relationship between the calorific value and the age of the forest with a regression coefficient of 0.5263 with a slope that is significantly greater than 0 (*Pr* > F < 0001).

4.3 Tree biomass and volume model for eucalypts in EPK plantations

Scatter plot showing the increase in tree biomass as a function over age over 15 years is shown in Figure 4.17. The result indicates that tree biomass increased with age within the seven estates where the study was conducted.

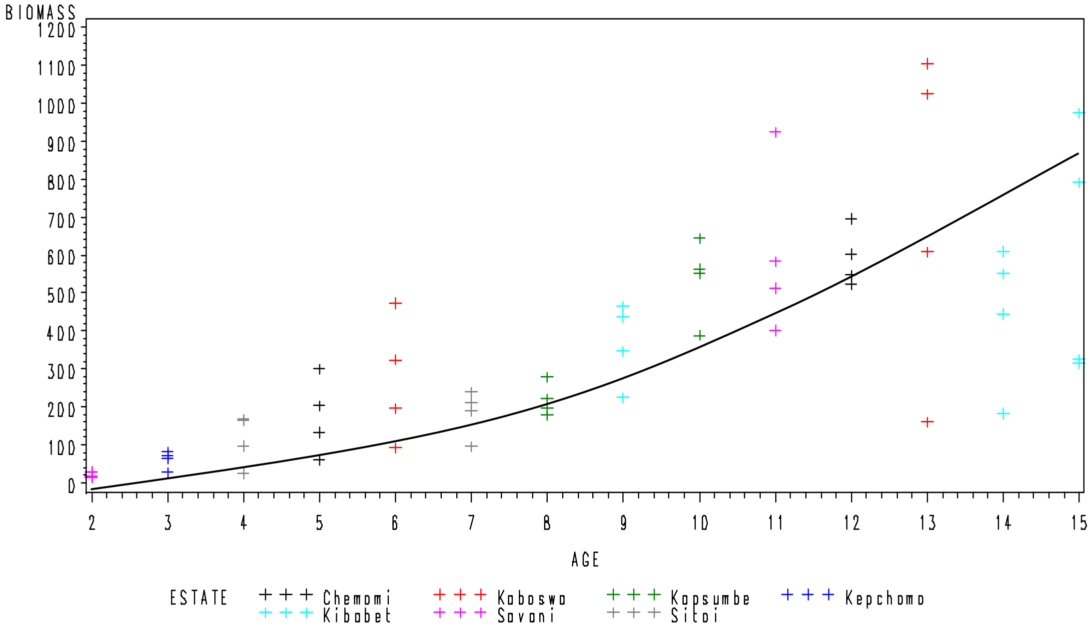

Figure 4.17: Scatterplot of the relationships between biomass and age of the forest

The relationships between tree biomass and volume was also determined (Figure 4.18). Tree biomass was positively associated with tree volume. Increased volume of the trees resulted in increased biomass.

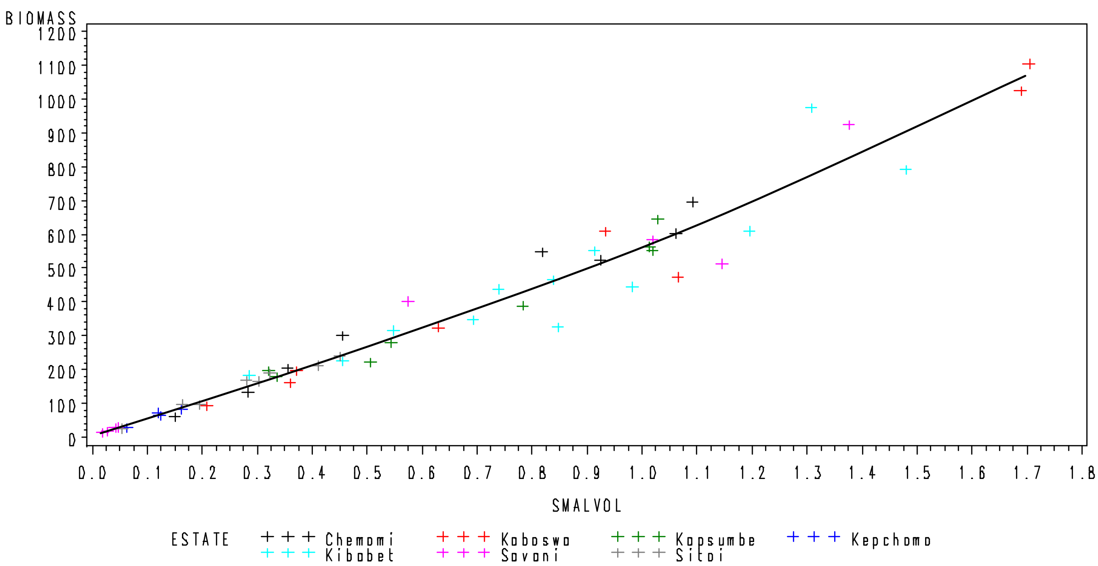

Figure 4.18: Scatterplot of the relationship between tree biomass and volume

The regression output showing relationships between the biomass and volume of the plantation establishment is provided in Annex 23. Tree biomass increased with volume of the forest plantation, where the biomass was fitted using the equation AGB = 601.6V +-147.6V^2, with standard errors 34.9636 and 35.2718 respectively. Based on ANOVA (Annex 25) biomass and volume were related. Regression between biomass and volume yields a significant ($P_r < .001$) positive linear relationship with a regression coefficient of 0.9736 (Annex 26).

Comparison of the tree biomass against the calculated biomass based on volume equations are provided in Figure 4.19. The current model equation and biomass estimated from Volume*0.5 accurately predicted biomass of the tree upto age 6 years. However, after 6 years of age, the current model was more precise in predicting biomass than the earlier used Vol*0.5 for biomass estimate.

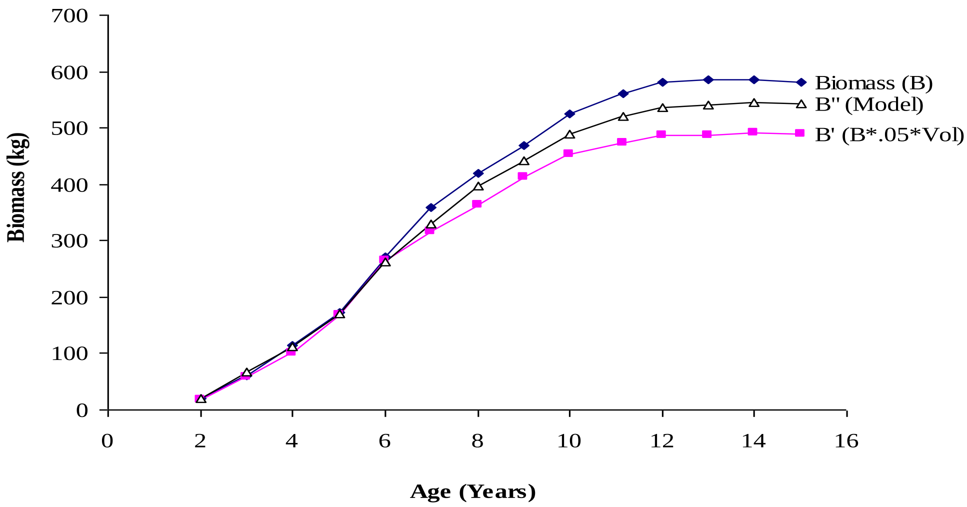

Figure 4.18: Measured biomass (B), and calculated biomass from the volume equations against tree age

CHAPTER FIVE

DISCUSSION

5.1 Standing volume of the existing eucalypt plantations of various ages at EPK

This study employed tree height and dbh of the plantations to establish the volume of the tree plantations, which concurs with studies by various researchers (McRoberts and Westfall, 2014; Segura and Kanninen, 2015; Kalliovirta and Tokola, 2017). In Kenya, such attempts have been rare (Henry *et al*., 2010). Based on the current estimates, it was established that there was a total of 1783.02
ha of land with an estimated total volume of 606,049.09 m^3. Based on the estimation, it was established that the largest area and hence highest volume was obtained in stations with largest tree height and dbh suggesting that plantations that are older and have larger diameters tend to have more volume. The area covered by the plantation was not necessarily the predictor of volume since areas such as Kibwari Station, Siret Station and Kaboswa Station had larger area coverage, but had less tree volume than Kaboswa, which clearly indicate that area coverage cannot be the basis of volume of the plantation. However, the height of the tree height and dbh appeared to play more significant role in the determination of tree volume which concurs with studies conducted elsewhere (Malimbwi *et al*., 1994; Komiyama *et al*., 2005; Henry *et al*., 2011).

The study also determined that volume was positively related to area of the establishment which indicates that understanding the area under plantation farming is important in explaining the volume of the plantation. In the current study the dbh of the plantation was significant in explaining up to 86% of the variation in the volume in concurrence with studies conducted by Akindele and LeMay (2006) and Chen *et al*.

(2007). The volume values reported by various studies at different Teak ages includes the study at 2 years old Teak by KFRI (2011) with volume value ranging from 1.87 - 6.57 m^3 /ha, at age of 5 years by Perez and Kanninen (2005) in Costa Rica the values was 28.4 - 32 m^3/ha, by Perez (2005) at age of 16 volume of 420.33 – 466.35 m^3/ha and at 40 years by KFRI (2011) of about 236 m^3/ha. A study by Zambrana (1998) estimated the volume at age of 4, 10, 17 and 25 years by using volume equation to be 22 m^3/ha, 89 m^3/ha, 159 m^3/ha and 214 m^3/ha respectively. Furthermore, on study by Picado (1998) in Costa Rica estimated the volume of 48.59 m^3/ha, 140.04 m^3 /ha and 198.87 m^3/ha at age of 8, 15 and 20 years respectively. The expected high correlation between area and volume therefore seems to suggest that to enhance yield, of the plantation, volume of the plantation appears more important parameter which need to be enhance. Therefore the assumption that area of the plantation is the determinant of volume and yield should be discouraged.

There was a sigmoid relationship between the standing volume and tree age which is the traditionally accepted relationship between volume and age of the tree (Sillett *et al*., 2010). Using the sigmoid curve, it was possible to estimate the optimal volume to harvest the tree which is based on the point where the gradient of the curve start to move closer to zero. A study carried out in Kitale, Uasin Gishu and Kericho showed that wood are harvested from age 5 to 8 for *E. grandis* with production figure of 75 to 360 m^3 ha^{-1} (Oballa *et al.*, 2010) while in this study, it ranged from 247.44 to 384.59 m^3 ha^{-1} at same age range. But according to Cheboiwo and Langat (2010), the total growth of a 5 year old *E. grandis* in Kericho was observed to be 12.2 cm dbh and height of 13. 2 m compared to the dbh and height at EPK that was observed to be 15.1 cm and 21.42 m at the same age and volume growth per hectare of 5 years and 13 years stood at 151.8 m^3 and 985 m^3 respectively. There were variations in terms of height, dbh and volume at the same age. The differences may be as result of differences in site factor and weather conditions.

In this study, best age to harvest the tree was established to be in the range between 8.5 to 10 years, which concurs with other studies (Saint-André *et al*., 2005; Forrester *et al*., 2010; Lindenmayer *et al*., 2017). However, harvesting exact of trees is always determined by CAI and MAI. In this study, the interaction between the CAI and MAI occurred at age 8.5 years which falls within the 5 to 10 years optimal age of harvesting. At this age of harvesting, the volume is at the maximum as tree growth has started to decline and therefore there is no significant height increment to warrant increment of volume of the trees, which is in agreement with previous studies on tree volume (Almeida *et al*., 2007; Du Toit, 2008; Tandon *et al*., 2015).

Although dbh was the mainly applied predictor of volume, it is recommended that care should be taken whenever applying the equations. Harja *et al*. (2011) in trying to fit the Chave *et al*. (2005) and Basuki *et al*. (2009) equations found the best model fit at lower diameter range less than 60 cm, but there was overvaluation of biomass of trees measuring over 60 cm. Various equations have partial relevancy due to the fact they are originated from local studies and as of inadequate diameter range. The biomass of the tree can be estimated according to its value using the following variables; height, diameter, forest type and wood density (Chave *et al*. 2005). There are studies that have found out that addition of height into allometric equations yielded no increase the accuracy of the estimation (Basuki *et al*., 2009). In another study, incorporation height into biomass approximation reduced the estimates of tropical carbon content (Feldpausch *et al*., 2012). Nevertheless, Goodman *et al*. (2014) verified that modeling tree volumes without incorporating height overvalued above ground biomass, when heights were incorporated, then biomass were undervalued significantly.

5.2 Variation in proximate and calorific value as a function of age of the eucalypt trees in EPK plantations

It is extremely important to understand fuel properties such as ash content, ultimate carbon, calorific value, fixed carbon content, volatile content, and hydrogen for consumption of every substance as fuel (Kumar *et al*., 2010). This study determined parameters associated with proximate values and calorific values. The parameters for calorific value were ash, moisture content, volatile content, desorption, absorption, fixed carbons and fixed carbons.

Ash content ranged from 0.5 to 0.95% and decreased with the tree age. The more quantity of ash in biomass renders it less advantageous for energy (Shafizadeh, 1981). The mean ash content of *E. grandis* plantation ranged from 0.49 to 0.97% and varied negatively with age of the tree from age 4 through to ages 6, 8 and 10 and 14 years. The quantity of ash was found to be more in younger trees. The little and minimal unevenness in ash content of wood shows that ash quantity might not be a suitable standard for deciding the biomass and harvesting age of tree.

The volatile content of the forest ranged from 70.10 to 70.67% and increased with age of the tree plantation while Kumar *et al*. (2010) found out that volatile content of Eucalyptus hybrid age 4 to 6 ranges from 82.0 to 81.64%. High volatile matter content of a biomass material may suggest that during incineration, most of it will volatize. The observed increase in the volatile matter is due to increase in the wood extractives that essentially increase the volatile compounds (Senelwa and Sims 1999).

The desorption and absorption PCT content of the forest varied from 0.03 to 0.09% and 0.02 to 0.09% respectively decreased significantly with age. As the trees grow old, the wood become more compact and thus its ability to absorb moisture become less effective (Skaar, 1988). The absorption content of the forest was established to vary negatively with age of the forest establishment. The trend were however moderate slope. Popper *et al*. (2008) when conducting absorption and desorption measurement on selected exotic tree species noted that desorption values was higher as compared to absorption values when the relative humidity was below 93% but the trend changed immediately the relative humidity reached 93% and the absorption values emerged higher than desorption values.

The mean fixed carbons of the forest of ranged from 10.64 to 10.09% that is near to the fixed carbon value of various tree types (Senelwa and Sims 1999), thus are likely to rise with the maturity of the stand. High carbon content of trees indicate that they are suitable for woodfuel due to the high energy content per unit volume and slow nature of burning for these trees (Kumar *et al*., 2010).

Mean calorific value of the forest ranged from 18.5317 to 19.57Mj/kg and increased with age of the forest plantation until age of 10 years which render age of 10 years the most suitable for harvest. Likewise a boost in the calorific value was experienced in ageing trees (20 years) as compared with younger trees (2−6 years). A feeble and depressing correlation between calorific value and age of trees from 11 and 21 years has been reported (Lemenih and Bekele (2004). The younger trees have less calorific value due to high ash content. The calorific value has been noted as one of the vital characteristics for distinguishing a fuel from others. The tree-age variability in calorific value of *Eucalyptus* can be attributable to lower ash content and high fixed carbon content in trees.

5.3 Tree biomass models for eucalypts in EPK plantations

In forest mensuration, direct measurements of biomass often pose a challenge resulting in estimates of the biomass based on known volume of the tree. In absence of a biomass equation of trees or stand, biomass may be estimated from equation: Biomass' = Volume*0.5. However, the simple formula has often been criticized in the past as too simplistic and may not accurately estimate biomass at certain age. This study therefore developed an equation to estimate the biomass from volume. This is justified because volumes for most species usually exist and it is much easier to develop volume than biomass equation. During the study, it was established that tree biomass increased with age of *E. grandis*, which agrees with studies of Zerihun *et al*. (2006) and Bradstock (2017). This observed increase may be attributed to higher number higher density and increased woody mass (Singh and Lodhiyal, 2013). Tree biomass increased with volume of the forest plantation, where the biomass was fitted using the equation AGB = $601.6V +-147.6V^2$, which concurs with Mugasha *et al*. (2013). Biomass and volume was positively correlated with a regression coefficient (R^2) of 0.9736 suggesting that increased volume of the trees resulted in increased biomass. In this study, model variables varied according to age, which may be due to adjustment in tree ageing and social condition, leading toe proliferation in stem biomass (Ognouabi and Fouty, 2012).

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

The estimated standing volume of EPK estates ranged from 15.86 to 736.88 m^3 ha^{-1}. There was an increase in tree volume, height and dbh with age of the tree plantation. It was established that there was a total of 1783.02ha of land with an estimated total volume of 606,049.59 m^3. Based on the table, there was a significant positive linear relationship between volume and age of the plantations yielding a regression coefficient of 0.8003. There was a sigmoid relationship between the standing volume and tree age. The result in the figure indicate that the most appropriate harvesting volume is where there is a convergence between CAI and MAI is age 6.5 years where the volume from the area harvested will be optimized.

This study also determined parameters associated with proximate values and calorific values. The mean ash content ranged from 0.49 to 0.97%, volatile content was 70.1 to 70.67%, desorption ranged between 0.03 to 0.09%, absorption content ranged from 0.02 to 0.09%, fixed carbon was 10.64 to 10.09% and calorific value ranged from 18.53 to 19.57 Mj/kg. The mean ash content, desorption and absorption of *E. grandis* plantation varied negatively with age of the tree while the volatile content, fixed carbon and calorific value of the forest ranged increased with age of the tree plantation.

Tree biomass increased with volume of the forest plantation, where the biomass was fitted using the equation $AGB = 601.6V +-147.6V^2$, standard errors 34.9636 and 35.2718 respectively. Biomass and volume was positively correlated with a regression coefficient (R^2) of 0.9736 suggesting that increased volume of the trees resulted in increased biomass.

6.2 Recommendations

Based on the CAI/MAI relationships the harvest age should is 6.5 years where the volume from the area harvested will be optimized while according to proximate and calorific values, the study recommends that determination of harvest age should be 10 years as determined by the energy content of the trees. So harvesting age depends on the management object.

The study estimated tree component biomass in the plantation, further research is needed to know the contribution of the soil organic component and management practices in *Eucalyptus* plantation establishment.

To advance the biomass research, broad spectrum of such problems must be attend to. Studies are required to give unambiguous meaning of the biomass compartments and forest categories.

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ANNEXES

Annex 1: Summary outputs for simple linear regression between standing volume and dbh of the tree plantations

Regression Statistics	
Multiple R	0.9377
R Square	0.8793
Adjusted R Square	0.8787
Standard Error	74.4711
Observations	200

ANOVA

	df	*SS*	*MS*	*F*	*P value*	
Regression	1	8001424.74	8001424.74	1442.7528	0.0000	
Residual	198	1098096.74	5545.94			
Total	199	9099521.48				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-243.2122	15.9294	-15.2681	0.0000	-274.625	-211.799
DBH	35.6817	0.9394	37.9836	0.0000	33.829	37.534

Annex 2: Summary outputs for simple linear regression between standing volume and height of the tree plantations

Regression Statistics	
Multiple R	0.9392753
R Square	0.8822381
Adjusted R Square	0.8816433
Standard Error	73.566334
Observations	200

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	8027944.393	8027944.39	1483.358	6.449E-94	
Residual	198	1071577.098	5412.00554			
Total	199	9099521.487				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-143.79071	13.3043	-10.8077	1.07E-21	-170.0271	-117.5542
Tree height	19.7396	0.51252	38.5143	6.45E-94	18.7289	20.7504

Annex 3: Summary outputs for simple linear regression between standing volume and age of the tree plantations

Regression Statistics	
Multiple R	0.8946
R Square	0.8003
Adjusted R Square	0.7993
Standard Error	95.7788
Observations	200

ANOVA

	df	*SS*	*MS*	*F*	*P value*
Regression	1	7283149.786	7283149.79	793.9254	0.0000
Residual	198	1816371.701	9173.59445		
Total	199	9099521.487			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	17.1203	12.9408	1.3230	0.1874	-8.3993	42.6398
Age	42.6796	1.5147	28.1767	0.0000	39.6926	45.6667

Annex 4: ANOVA table showing differences in the ash content with age of the E. grandis at the EPK forest plantations

Source	**df**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	10	0.9652	0.0965	112.94	<.0001
Error	97	0.0828	0.0008		
Corrected Total	107	1.0480			

Annex 5: Tukey's Studentized Range (HSD) Test for ash content

Parameter	Value
Alpha	0.05
Error Degrees of Freedom	97
Error mean square	0.0086
Critical Value of Studentized Range	4.1118
Minimum Significant Difference	0.0283

Annex 6: Regression analysis result showing variation of ash content with age

	R-Square	Coefficient of Variation	Root MSE	Mean Ash content PCT	
	0.9209	4.6912	0.0292	0.6231	
ANOVA					
Source	df	Total Sum of Squares	Mean Square	F Value	*Pr* > F
Age	5	0.9467	0.1893	221.57	<.0001

Annex 7: ANOVA table showing differences in the volatile PCT content with age of the *E. grandis* at the EPK forest plantations

Source	**df**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	10	4.5282	0.4528	46.23	<.0001
Error	**97**	0.9501	0.0097		
Corrected Total	**107**	5.4784			

Annex 8: Tukey's Studentized Range (HSD) Test for volatile PCT content

Parameter	Value
Alpha	0.05
Error Degrees of Freedom	97
Error mean square	0.0097
Critical Value of Studentized Range	4.1118
Minimum Significant Difference	0.0959

Annex 9: Regression analysis result showing variation of volatile PCT with age of the trees

	R-Square	Coefficient of Variation	Root MSE	Mean volatile PCT	
	0.8265	0.1406	0.09889	70.3742	
ANOVA					
Source	df	Total Sum of Squares	Mean Square	F Value	Pr > F
Age	5	4.3487	0.08697	88.79	<.0001

Annex 10: ANOVA table showing differences in the desorption content with age of the *E. grandis* at the EPK forest plantations

Source	**df**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	10	0.05289	0.0052	10.03	<.0001
Error	97	0.05115	0.00052		
Corrected Total	107	0.1040			

Annex 11: Tukey's Studentized Range (HSD) Test for volatile PCT content

Parameter	Value
Alpha	0.05
Error Degrees of Freedom	97
Error mean square	0.0097
Critical Value of Studentized Range	4.1118
Minimum Significant Difference	0.0959

Annex 12: Regression analysis result showing variation of desorption with age of the *E. grandi* at EPK

	R-Square	Coefficient of Variation	Root MSE	Desorption	
	0.5083	35.8306	0.0229	0.0641	
ANOVA					
Source	df	Total Sum of Squares	Mean Square	F Value	*Pr* > F
Age	5	0.0442	0.0088	16.74	<.0001

Annex 13: ANOVA table showing differences in the absorption content with age of the *E. grandis* at the EPK forest plantations

Source	**df**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	10	0.0463	0.0046	10.78	<.0001
Error	97	0.04169	0.0004		
Corrected Total	107	0.0880			

Annex 14: Tukey's Studentized Range (HSD) Test for absorption content

Parameter	Value
Alpha	0.05
Error Degrees of Freedom	97
Error mean square	0.0004
Critical Value of Studentized Range	4.1118
Minimum Significant Difference	0.0201

Annex 15: Regression analysis result showing variation of absorption with age

R-Square	Coeff Var	Root MSE	Mean Ash content PCT		
0.5263	42.1182	0.02073	.00492		
ANOVA					
Source	df	Total Sum of Squares	Mean Square	F Value	Pr > F
Age	5	0.0381	0.0076	17.71	<.0001

Annex 16: ANOVA table showing differences in the fixed carbon content with age of the *E. grandis* at the EPK forest plantations

Source	**df**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	10	5.5845	0.5584	30.57	<.0001
Error	97	1.7719	0.0182		
Corrected Total	107	7.3564			

Annex 17: Tukey's Studentized Range (HSD) Test for fixed carbon content

Parameter	Value
Alpha	0.05
Error Degrees of Freedom	97
Error mean square	0.0097
Critical Value of Studentized Range	4.1118
Minimum Significant Difference	0.0959

Annex 18: Regression analysis result showing variation of fixed carbon with age of the *E. grandis*

R-Square	Coeff Var	Root MSE	Mean Ash content PCT
0.7591	1.2957	0.1351	10.4310

ANOVA

Source	df	Total Sum of Squares	Mean Square	F Value	*Pr* > F
Age	5	0.0381	0.0076	17.71	<.0001

Annex 19: ANOVA table showing differences in the calorific content with age of the *E. grandis* at the EPK forest plantations

Source	**df**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	10	4.5282	0.4528	46.23	<.0001
Error	**97**	0.9501	0.0097		
Corrected Total	**107**	5.4784			

Annex 20: Tukey's Studentized Range (HSD) Test for calorific value

Parameter	Value
Alpha	0.05
Error Degrees of Freedom	97
Error mean square	0.0097
Critical Value of Studentized Range	4.1118
Minimum Significant Difference	0.0959

Annex 21: Regression analysis result showing variation of calorific value with age of *E. grandis* at the EPK Nandi Tea Estates

R-Square	Coeff Var	Root MSE	Mean Ash content PCT		
0.5263	42.1182	0.02073	.00492		
ANOVA					
Source	df	Total Sum of Squares	Mean Square	F Value	Pr > F
Age	5	0.0381	0.0076	17.71	<.0001

Annex 22: Parameters derived from the volume equation of the trees

Parameter	Estimates	Std Error	95% Confidence Limits
b0	0.0000	-	-
b1	572.8	10.9401	594.7
b2	1.1169	0.0484	1.2139

Annex 23: ANOVA table for the volume equation

Source	df	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	10921293	5460646	1436.77	<.0001
Error	54	205234	3800.6		
Uncorrected Total	56	11126527			

Annex 24: Moments of the analysis between volume and area of the plantation

N	56	Sum weights	56
Mean	2.7096	Sum Observations	151.7412
Std Deviation	61.0249	Variance	3724.0496
Skewness	-0.1907	Kurtosis	2.47950
Uncorrected SS	205233.8970	Corrected SS	204822.7290
Coefficient of Variation	2252.12236	Std Error Mean	8.15480754

Annex 25: ANOVA table for the biomass and volume equation

Source	df	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	3257503	1628751	834.19	<.0001
Error	40	78099.4	1952.5		
Uncorrected Total	42	3335602			

Annex 26: Summary outputs for simple linear regression between biomass and volume of the plantations

Regression Statistics	
Multiple R	0.9736
R Square	0.9478
Adjusted R Square	0.9469
Standard Error	0.1036
Observations	56

ANOVA

	df	*SS*	*MS*	*F*	*P_r > F*
Regression	1	10.5219	10.5219	981.1292	0.0000
Residual	54	0.5791	0.0107		
Total	55	11.1010			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.0659	0.0225	2.9271	0.0050	0.0208	0.1110
Tree Biomass	0.0016	0.0001	31.3230	0.0000	0.0015	0.0017

Annex 27: Biomass and volume data obtained from the field

Age (Years)	Height (m)	Dbh (cm)	Total vol (m3)	Weight (Kg)	Biomass (kg)
2	10.0	10.2	0.0419	60.6	26.27
2	10.0	7.2	0.0196	28	12.41
2	10.0	11.4	0.0464	64.6	8.5
2	10.0	8.1	0.0274	40.6	17.57
3	16.0	14.5	0.1234	144.3	63.33
3	16.0	17.1	0.1621	182.2	81.94
3	12.0	10.4	0.0631	65.9	27.27
3	16.0	14.0	0.1192	152.7	72.05
4	18.0	15.0	0.164	174	96.97
4	20.0	18.2	0.2802	322.5	167.87
4	20.0	19.2	0.3025	316.2	165.75
4	14.0	9.2	0.0548	47.8	25.25
5	22.0	18.0	0.2838	265.2	132.8
5	22.0	23.0	0.4551	436.1	299.88
5	22.0	19.5	0.3551	410.3	204.03
5	20.0	13.5	0.1506	129.3	58.63
6	30.0	22.6	0.63	562.2	324.02
6	26.0	17.4	0.3714	391	195.66
6	34.0	30.6	1.0653	963	473.38
6	22.0	15.5	0.2089	203.3	92.53
7	22.0	19.2	0.3231	331.4	189.58
7	24.0	21.5	0.4101	371	211.9
7	24.0	21.0	0.4501	434.2	239.67
7	22.0	14.5	0.196	170.4	94.48
8	26.0	18.0	0.3206	344.5	196.31
8	28.0	23.0	0.544	492.9	277.61
8	28.0	22.2	0.5066	448.1	221.45
8	2.0	19.2	0.3351	304.3	178.75
9	32.0	26.0	0.8397	766.5	465.11
9	30.0	24.8	0.6926	589.6	345.94
9	28.0	28.5	0.7389	750.6	437.8
9	26.0	19.5	0.4557	380.8	225.55
10	26.0	27.5	1.0133	902.8	563.35
10	38.0	29.0	1.0288	987.9	644.19
10	38.0	26.0	0.7831	660.5	388.64
10	34.0	28.2	1.0194	907.9	550.47
11	24.0	27.5	0.575	597.7	402.41
11	28.0	35.2	1.3762	1711.4	924.91
11	34.0	28.0	1.0192	950.9	583.18
11	32.0	30.9	1.1462	834.6	513.56
12	34.0	30.0	1.062	927.7	603.62
12	34.0	26.3	0.8179	787.2	547.68
12	34.0	30.5	1.0915	1059.7	696.02
12	32.0	29.0	0.9246	786.5	523.6
13	36.0	27.0	0.9329	943.7	609.33
13	40.0	34.5	1.7042	1649.5	1,105.66
13	22.0	20.9	0.3601	265.9	160.52
13	40.0	35.5	1.6887	1655.5	1,024.78
14	18.0	18.0	0.2854	295.2	183.32
14	32.0	26.8	0.913	794.9	551.1
14	32.0	26.6	0.9824	690.2	444.83
14	34.0	30.6	1.1956	1205.7	610.24

15	34.0	32.2	1.3082	1376.1	974.84
15	30.0	33.0	0.8468	491	324.85
15	38.0	34.8	1.4799	1220.9	792.47
15	30.0	25.0	0.5486	502.2	315.62

Annex 28: Volume per Age data used in the study

Age (yr)	SPH	Mean DBH (cm)	Mean Ht (m)	Area(Ha)	VS/Ha (m3)	SV(m3)
0	0	0	0	55.73	0	0
1	1667.82	5.28	5.33	155.93	15.86	2472.77
2	1557.14	7.30	8.62	39.48	40.19	1140.33
3	1635	10.76177	14.45	174.30	123.11	16052.51
4	1450.	13.86	19.14	135.04	194.51	25752.08
5	1465.	15.10	21.42	101.66	247.44	28355
6	1383	16.37	23.77	66.91	309.07	22971.38
7	1300	17.32051	25.29	176.74	325.81	58492.12
8	1245	18.66	28.45	149.1	384.59	55786.58
9	1176.25	20.26813	32.34955	54.19	457.61	23517.35
10	1238.71	19.72	31.30	193.88	456.21	95579.22
11	1269.61	20.73	34.57	78.42	532.82	42999.43
12	1290.75	20.34	32.35	56	509.35	28519.92
13	1306.96	20.87	33.41	124.6	552.87	69236.18
14	1218.50	21.07	32.49	74.88	529.74	38512.10
15	1154.50	24.01	38.44	110.31	733.98	72574.70
16	1067.86	24.92	38.48	29.77	736.88	20314.75
23	1003.75	23.75	33.92	6.08	591.56	3773.141
				1,783.02		606,049.6

Annex 29: Proximate and calorific values data collected from the field.

Estate	Age	Tree no	Calorific Value (mj/kg)	Ash Content (%)	Volatile Matter (%)	Moisture Desorption (%)	Moisture Adsorption (%)	Fixed Carbon %
Kaboswa	4	1	18.58	0.79	70.07	0.09	0.08	10.11
Kaboswa	4	2	18.46	0.79	70.10	0.09	0.07	10.10
Kaboswa	4	3	18.18	0.76	70.14	0.09	0.07	10.07
Kepchomo	6	1	18.64	0.69	70.22	0.08	0.07	10.20
Kepchomo	6	2	18.46	0.69	70.25	0.08	0.08	10.21
Kepchomo	6	3	18.50	0.70	70.20	0.08	0.07	10.18
Savani	8	1	19.23	0.63	70.26	0.07	0.05	10.48
Savani	8	2	18.73	0.63	70.25	0.08	0.05	10.49
Savani	8	3	19.42	0.63	70.23	0.07	0.05	10.52
chemomi	10	1	19.41	0.59	70.42	0.07	0.04	10.62
chemomi	10	2	19.20	0.59	70.43	0.06	0.03	10.53
chemomi	10	3	19.05	0.60	70.44	0.06	0.05	10.49
Kibabet BG 40	12	1	19.22	0.54	70.54	0.04	0.03	10.63
Kibabet BG 40	12	2	19.69	0.55	70.59	0.04	0.03	10.58
Kibabet BG 40	12	3	19.26	0.55	70.57	0.05	0.03	10.61
Kibabet BG 24	14	1	18.33	0.50	70.68	0.03	0.02	10.64
Kibabet BG 24	14	2	19.91	0.50	70.69	0.03	0.02	10.62
Kibabet BG 24	14	3	20.31	0.50	70.65	0.03	0.02	10.67

Annex 30: Regression models for equations

A: Model fit result for equation 1 (EPK Nandi Tea Estates data set)

Regression Statistics	
Multiple R	0.9860
R Square	0.9722
Adjusted R Square	0.9711
Standard Error	0.1835
Observations	56

ANOVA

	df	*SS*	*MS*	*F*	*P value*	
Regression	2	62.2832	31.1416	925.1950	0.0000	
Residual	53	1.7840	0.0337			
Total	55	64.0671				
	Coefficients	*Standard*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-9.2702	0.1972	-46.990	0.000	-9.666	-8.875
LN DBH	2.5942	0.0913	28.645	0.000	2.412	2.775
LNHt	0.1522	0.0701	2.170	0.035	0.012	0.293

B: Model fit result for equation 2 (EPK Nandi Tea Estates data set).

Regression Statistics	
Multiple R	0.7718
R Square	0.5956
Adjusted R Square	0.5881
Standard Error	0.2883
Observations	56

ANOVA

	df	*SS*	*MS*	*F*	*P value*	
Regression	1	6.6127	6.6127	79.5571	0.0000	
Residual	54	4.4884	0.0832			
Total	55	11.1011				
	Coefficients	*Standard*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.3627	0.0915	14.8878	0.0000	1.1792	1.5462
1/D	-14.4166	1.6163	-8.9194	0.0000	-17.6571	-11.1761

C: Model fit result for equation 3 (EPK Nandi Tea Estates data set)

Regression Statistics	
Multiple R	0.9471
R Square	0.8970
Adjusted R Square	0.8951
Standard Error	0.1455
Observations	56

ANOVA

	df	*SS*	*MS*	*F*	*P value*	
Regression	1	9.9574	9.9574	470.1242	0.0000	
Residual	54	1.1437	0.0212			
Total	55	11.1011				
	Coefficients	*Standard*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.6565	0.0621	-10.5723	0.0000	-0.7810	-0.5320
DBH	0.0566	0.0026	21.6823	0.0000	0.0514	0.0618