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Evaluation Of Heating Value And Biomass Production Of Eucalyptus Plantations For Fuelwood Supply To Tea Factories In Nandi County, Kenya

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ABSTRACT

Trees and woodlots in plantation establishments produce biomass for energy supply. In developing countries where fuelwood is the main source of energy, the properties of wood in relation to energy supply are important. However, little is known about the proximate value and biomass production for energy supply of several species of trees in plantation establishments. The objective of this study was to determine the biomass energy supply of eucalyptus plantations from Eastern Produce Kenya (EPK) to Nandi Tea Factories. Specifically, the study determined the standing volume of the existing eucalyptus plantations of ages ranging from 1 years to 15 years old at EPK, the within tree 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 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, 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, where the biomass was fitted using the equation $Y = bx + cx^2$ with estimates for b and c being 601.7 and c being -147.6. 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. 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.

1. INTRODUCTION

Energy is important driver of economic growth (Kowsari and Zerriffi, 2011; Caputo *et al*., 2015). At the individual and household levels, energy satisfies basic human needs for cooking, lighting and heating, while at the national levels, it plays a decisive role in employment and income creation (Wolfram *et al*., 2012). However, in several developing countries several aspects of energy tend to be largely speculative (Legros *et al*., 2009). The most important area of research in energy currently is the sources of energy. There are numerous sources of energy supply ranging from electricity, 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 fossil fuels cannot be used in large scale by the rural community due to its exorbitant value while coal is limited to particular countries where mining coal deposits requires more complex machinery than can be afforded by the poor rural folks (International Energy Outlook, 2016). The technology and cost of production biofuels on the other hand eludes the rural communities and are currently used as energy sources in industrialized countries (Molino *et al*., 2016). Energy from biomass sources therefore remains more relevant to 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 from biomass is the single most important source of renewable energy providing over 9% of the global total primary energy supply with more than two billion people depending on it for cooking and/or heating (Field *et al*., 2018). Most if not all of the people in the developing countries rely on biomass energy (Barnes and Floor, 2018). According to FAO (2006), the total wood biomass is utilized globally was estimated at 3 billion m^3 with the proportion of fuelwood being 40% on average, but varying greatly on a regional basis. In Africa it was 88%, in North and Central America it was 13%. Woodfuel provides more than 70% of energy in 34 developing countries and more than 90% in 13 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*., 2018).

Recent estimates of biomass energy in Kenya's is approximately 68 to 74% (Kiplagat *et al*., 2011; Torres-Rojas *et al*., 2011) which is slightly lower than 80% 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 the rural areas, low income and moderately easy access to free biomass, encourages the use of biomass as a source of cooking energy (Barnes *et al*., 2016). Indeed in the year 2000, the average annual firewood consumption in rural and urban areas was 3394 and 2701 kg per household, respectively while the equivalent per capita consumption was 741 and 691 kg, respectively. The wood fuel demand was estimated to be growing at 2.7% per year while the sustainable supply was growing at a slower rate of 0.6% per year (MoE, 2002). Thus it is expected to remain the major source of energy for the foreseeable future, albeit other sources of energy are beginning to make major inroads as sources of energy in the country.

The wood biomass energy supply in Kenya is derived from closed forests, woodlands, bush lands, farm lands, plantations and agricultural and industrial residues (Martinot *et al*., 2012). According to data compiled 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, but 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 equivalent 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. 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).

In the analysis of biomass energy balances per county in Kenya, majority of the residents use wood biomass and therefore the biomass deficit might have been higher than estimated. According to the Nandi County development plan 2013-2017, Nandi County has two forest ecosystems. The largest forest cover in Nandi County is the South Nandi forest which is a tropical rain forest. It covers an area of 20,150 ha. The North Nandi forest which is also a tropical rain forest covers a total of 16,004 ha and extends from Nandi Central to Nandi North (http://nandi.go.ke/forestry-agro-forestry/). 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. The Nandi County Development plan, 2013-2017 indicates that 90% of the population in Nandi County is rural who rely on wood fuel as the major source of energy. It is not clear how much woody energy biomass is provided by these plantation establishments to the industries in Kenya. Information on the biomass energy from such establishments is still not clearly documented.

The important properties of wood biomass include heating value of wood that may be determined either by calculation from a chemical analysis or burning a sample in calorimeter. Chemical properties for heating value include proximate and ultimate analysis, where an ultimate analysis reduces fuel to its elementary constituent of carbon, hydrogen, nitrogen, sulphur while proximate analysis involves determination of values of ash, moisture, volatile matter, absorption, desorption, and fixed carbon (Ragland *et al*., 1991). Therefore knowledge of proximate and calorific values is important in evaluating the wood biomass properties (Mitchual *et al*., 2015). Characterization of the biomass components is important to achieve efficient utilization of wood biomass residues. However, characterization of wood biomass properties of several species in developing countries such as Kenya has rarely been done.

Eastern Produce of Kenya Ltd. (EPK) in Nandi County is one of the tea producing industries that uses energy from wood. The company has currently 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 currently under short-rotation and the main species are *Eucalyptus grandis*, *Cupressus lusitanica* and *Pinus patula*. *Eucalyptus grandis* covers almost 90% of the area planted (Paterson *et al*., 1998). Eucalypts produce wood with lignin content of about 34%, which is higher than most hardwood species; thus suggesting that *Eucalyptus* species can be 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 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 in Kenya.

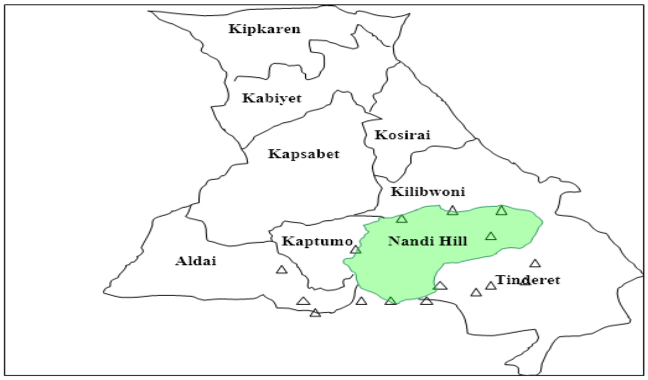
2. MATERIALS AND METHODS

2.1 STUDY AREA

This study was done in Nandi Hills in Nandi County (Figure 1). The study area is the tea estates that are owned and managed by Eastern Produce Kenya Ltd (EPK). EPK tea estates are located in Nandi County, west of the Rift Valley and about 350 km north-west of Nairobi, Kenya. It lies within the Kakamega- Nandi forest complex. 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 EPK estates cover a total area of 7,942.664 ha, of which 48% is under tea, 42% is under forest (indigenous and fuelwood plantations) and 10% under infrastructure.

The area experiences an equatorial climate and bimodal rainfall. Long rains begin at the end of March through to early June and the short rains are during October and November. Mean annual rainfall for the area is 1,500mm. The area experiences mean temperatures of between 18°C and 22°C during the rainy season while higher temperatures averaging 23°C are recorded during the drier months of December and January. The coolest temperatures, as low as 12°C, are experienced during the cold spell in July and August. The mean relative humidity ranges from 60-67%. The economic activities in this zone are growth of tea, sugarcane, coffee, horticultural crops and maize. Livestock is also kept. , playing a dual role as both a cash crop and a food crop. The farmers also keep livestock.

Figure 1. Map of Nandi County showing the position of the study area



2.2 EXPERIMENTAL DESIGN

2.2.1 EUCALYPTUS PLANTATION INVENTORY

Data for number of stems per hectare, diameter at breast height (dbh) and mean height for all plantations 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, using the following criteria (this is the inventory protocol of EPK Ltd): < 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 and 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 the plantations such as date of planting (or last coppice, where relevant), and total hectares were also recorded.

2.2.2 PROXIMATE AND CALORIFIC VALUE MEASUREMENT

Eucalypt trees of different age groups ranging from 4 to 14 years old were used in this test. The trees obtained for these experiments were grown under similar soil and climatic conditions. For each age group (4, 6, 8, 10, 12, and 14,) three trees were randomly selected. The plantations where the research was conducted were randomly selected. The locations of the selected 18 trees were identified randomly in the office. The selected trees were felled and six wood sample discs, measuring 60mm in length, were obtained from different positions: stump height (0.15m); DBH; 20%; 40%; 60% and 80% of the total tree height and labeled. Total of 108 discs were transported to the chemistry laboratory at University of Eldoret.

Calorific value was determined according to standard methods described in ASTM (2012). To determine the moisture content, a disc A samples were chipped and milled to pass No. 60 (250 mm) sieve in accordance with method D2013 or practice D346. The crucible was first reconditioned by putting it into muffle furnace at 900ºC 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 the oven at 105°C until a constant weight was obtained.

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

In determining 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°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°C and dried to constant weight. This was deemed to be when there was less than ± 0.3 mg change in weight upon re-heating of the crucible. Weights of the empty crucibles were also measured. Final weight of the sample = weight of crucible containing sample - weight of empty crucible

$$\text{Ash\%} = \left\{\frac{M3 - M1}{M2 - M1}\right\} * 100$$

Where: M1= Mass of empty crucible + lid

M2= Mass of empty crucible + lid +sample before heating

M3= Mass of empty crucible + lid+ ash

To determine the volatile matter, approximately 1.00 g of thoroughly mixed samples that were oven-dried at a temperature of 105°C was weighed in the crucible in triplicates. The crucibles were covered with a tight lid and placed in the muffle furnace at 900C 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 back into the muffle furnace at 900°C and dried to constant weight. This was deemed to be when there was less than ± 0.3 mg change in weight upon one hour of the crucible being in the furnace. Weight of the empty crucible with lid was also measured

$$\text{Volatile matter \%} = \left\{\left[\frac{M2 - M3}{M2 - M1}\right] * 100\right\} - \text{MC}$$

Where: M1= Mass of empty crucible and lid

M2= Mass of empty crucible + lid +sample before heating.

M3= Mass of empty crucible + lid +sample after heating.

MC = Moisture content on wet basis

Moisture content was determined by weighing 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°C, then their weights were measured in crucibles in triplicates. Hydrated cupper 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.

$$\text{Moisture absorption \% calculation; Ma} = \left\{\frac{M3 - M1}{M2 - M1}\right\} * 100$$

Where:

M1= Mass of empty crucible.

M2 = Mass of crucible + samples

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

Moisture desorption was determined by weighing 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 cupper 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 % calculation; $Md = \left\{\frac{M3 - M1}{M2 - M1}\right\} * 100$

Where: M1= Mass of empty crucible

M2 = Mass of crucible + samples

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

Fixed carbon content (FC %) was calculated from the equation:

FC (%) = 100 - (% Ash content + % Volatile matter content+ %moisture content).

To obtain above ground biomass and volume model, the representative tree samples, age distribution was taken into account during tree selection. The plantations where the research was conducted were randomly selected. Four trees were randomly selected from each age group and used for destructive sampling. The age distribution ranged from 2 to 15 years, thus, totaling 56 trees. 56 sample trees were felled. After felling, Diameter was measured at 2m interval for stems and big branches with diameters of more than 10cm. In addition, the stump height and its diameter were also measured.

The volume of each section was calculated using Smalian's formula. The total volume was obtained by summing the volume of each section. The fresh (green) weight of the whole trees were determined immediately in the field after felling using spring weighing balance and recorded. Sample discs of 30 mm thickness were taken 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 weighed in the field using spring weigh scales and a kitchen scale was used to weigh small specimens and recorded. The sections were labeled according to: replicates, number, age, plantation, branches, leaves and stem. The samples from the partitioned trees were taken in three replications and stored in sealed plastic bags, taken to the laboratory to determine their moisture content. Dry weights were achieved by drying the sample at a temperature of $105^{o}C$ until a constant mass was obtained. After achieving the constant dry weight, the ratio of dry to wet weight was determined (Mbelase 2012).

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

2.2.3 DATA ANALYSIS

Density per hectare, mean height and dbh per age were calculated using secondary data. Standing volume per ha, per plantation and total per age, and total volume of all plantations were calculated applying tree volume models from Schumacher and Hall model (Bredenkamp and Loveday, 1984). The volume curve was used to estimate current annual increment (CAI) and mean annual increment (MAI) curves. CAI is the yearly growth rate, while MAI informs on the growth over the whole period from origin to a specific age. Together these curves inform on growth pattern of the stand within each cell, as the intersection of CAI and MAI curves informs on theoretical optimal harvest age that maximizes timber productivity (Avery, 2002). The optimal harvest age was estimated for each cell and summarized with mean, median, mode, and standard deviation. The effect of age and tree position was analyzed using Analysis of variance (ANOVA) with age as fixed factors using SAS/STAT (2002) was used 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. 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.

3. RESULTS

3.1 STANDING VOLUME OF THE EXISTING EUCALYPT PLANTATIONS OF VARIOUS AGES AT EPK

Information on the height and dbh used to derive the volume is shown in Figure 2. There was an increase in height and dbh with age of the tree plantation following a polynomial distribution curve. The regression outputs showing relationships between the mean height and age of the establishment are provided in Table 1 while the dbh against age of the plantation is shown in Table 2. Based on the tables, there were significant (*P* < .001) positive relationship between mean height and dbh and age of the plantations.

Figure 2. Tree height and dbh of the plantation establishment of EPK tea factory

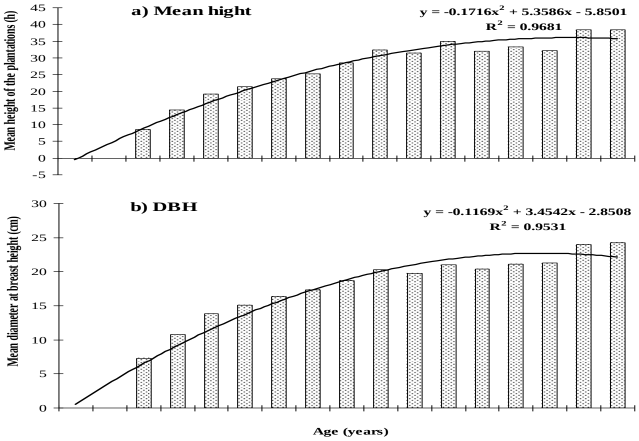


Table 1: Summary outputs for simple linear regression between mean height and age of the plantation

Regression Statistics						
Multiple R	0.9352					
R Square	0.8746					
Adjusted R Square	0.8589					
Standard Error	23415.0372					
Observations	15					
		ANOVA				
	df	SS	MS	F	Pr > F	
Regression	1	3.06E+10	30592019212	55.79797	0.000071	
Residual	13	4.39E+09	548263971			
Total	14	3.5E+10				
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-12669.2587	12207.16	-1.0378	0.03296	-40819.0202	15480.5
Age	406.5806	54.4299	7.46980	7.13E-05	281.0651	532.0963

Table 2: Summary outputs for simple linear regression between dbh and age of the plantation

Regression Statistics						
Multiple R	0.9452					
R Square	0.8755					
Adjusted R Square	0.8645					
Standard Error	26415.0372					
Observations	15					
ANOVA						
	df	SS	MS	F	Pr > F	
Regression	1	3.14E+10	33444321212	50.83666	0.00054	
Residual	12	4.33E+09	657877971			
Total	14	3.66E+10				
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-11129.2587	14609.23	-1.3378	0.0247	-36239.0223	15783.544
Age	423.5806	43.2137	8.55982	7.13E-05	304.0234	555.0963

The relationship between standing volume of the trees and age are shown in Figure 3. The optimal volume to harvest the trees range between 6 to 8 years. The exact age of harvesting is determined by the interaction between the CAI and MAI (Figure 4). Most appropriate harvesting volume is where there is a convergence between CAI and MAI which is at age 6.5 years where the volume from the area harvested will be optimized.

Figure 3. Relationship between standing volume of the trees and age

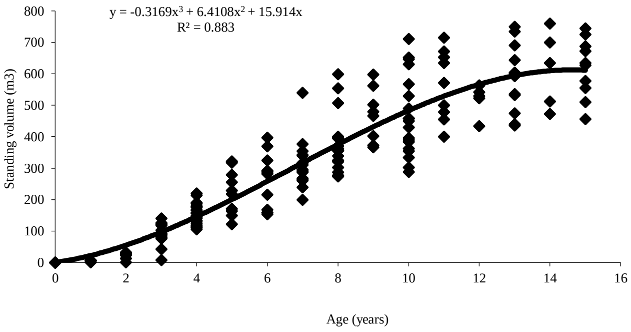
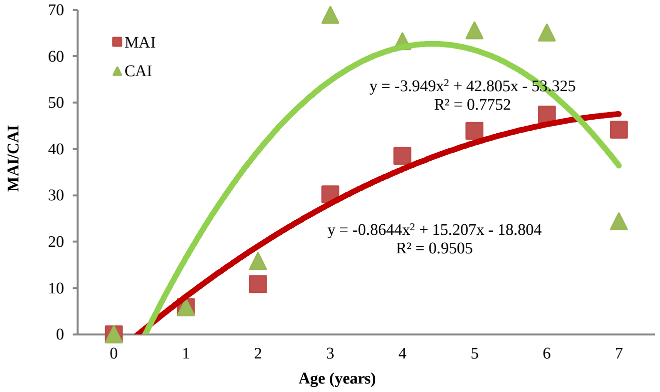


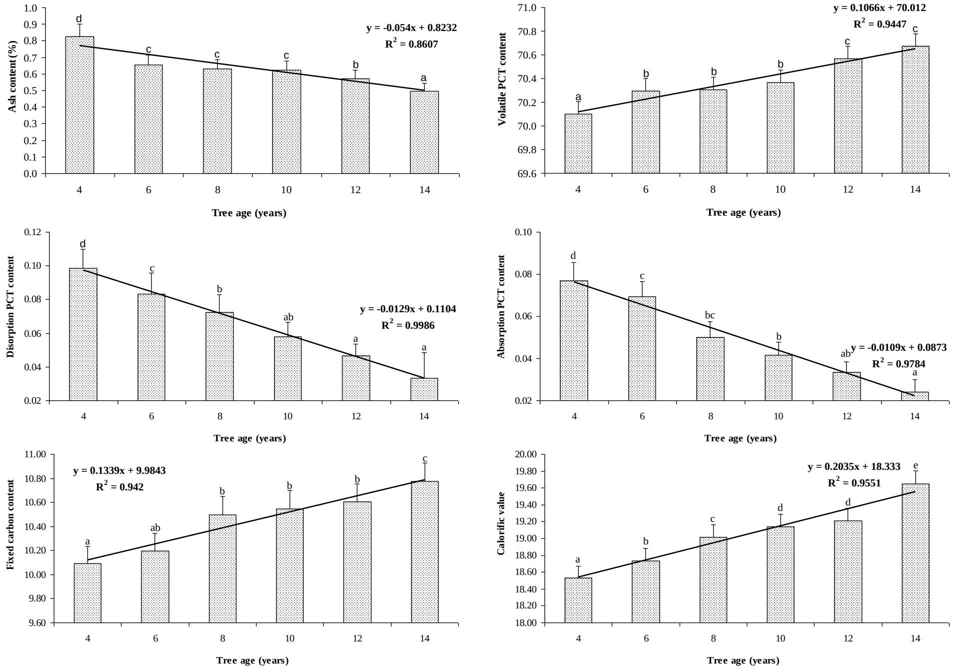
Figure 4. Relationship between CAI and MAI at the EPK Nandi



3.2 PROXIMATE AND CALORIFIC VALUE OF THE EUCALYPT TREES IN EPK PLANTATIONS

The mean calorific values of the eucalyptus of various ages are shown in Figure 5. All proximate values of the wood biomass significantly ($P < 0.05$) differed with age. Ash content, desorption and absorption reduced with age of the forest plantation. Meanwhile volatile content and fixed carbon increased as a function of forest age. The mean calorific value of the mean calorific value showed moderate positive relationship with the age of the forest.

Figure 5. Proximate and calorific value of the tree species of various ages at NPK, Nandi, Kenya



3.3 TREE BIOMASS AND VOLUME MODEL FOR EUCALYPTS IN EPK PLANTATIONS

Tree biomass as a function over age over 15 years is shown in Figure 6. Tree biomass increased with age within the seven estates where the study was conducted. Tree biomass increased with volume of the forest plantation, where the biomass was fitted using the equation $Y = bx + cx^2$ with estimates for b and c being 601.7 and c being -147.6 and standard errors 34.9636 and 35.2718 respectively. Regression between biomass and volume yields a significant ($P < .001$) positive linear relationship with a regression coefficient of 0.973. The relationships between tree biomass and volume was also determined (Figure 7). Tree biomass was found to be positively correlated with tree volume. Increased volume of the trees resulted in increased biomass.

Figure 6: Scatterplot showing the relationships between biomass and age of the forest

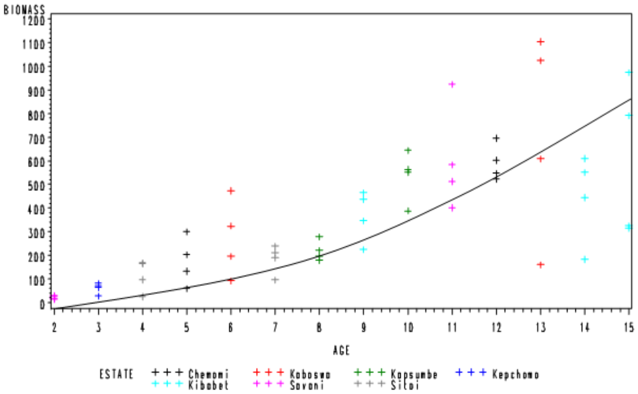
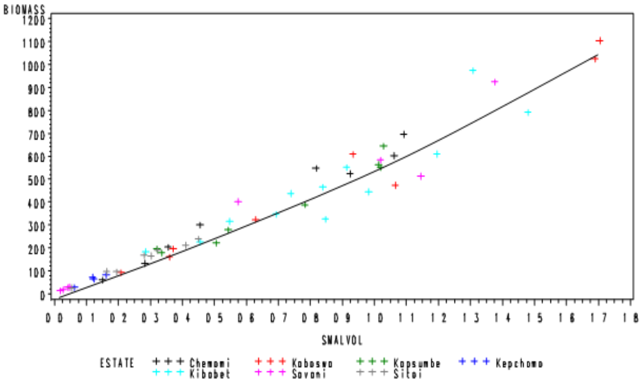


Figure 7: Relationship between tree biomass and volume



4. DISCUSSION

This study employed tree height and diameter at breast height (dbh) of the plantations to establish the volume of the tree plantations, which concurs with studies by various researchers (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 1783.04 ha of land with an estimated total volume of 598,257 m^3, which differs with routine measurements done by the company (Internal Unpublished Reports of the Company). 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 but the tree height and the diameter at breast height appear 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 the volume of wood that can be produced under various conditions from age 5 to 8 for *E. grandis* varies from 75 to 360 m^3 ha^{-1} (Oballa *et al*., 2010) while in this study, it ranges from 219 to 317 m^3 ha^{-1} at same age range.

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 21.41 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 according Cheboiwo and Langat (2010), but volume growth per hectare of 5 years and 13 years at EPK stood at 219.36 and 590.36 respectively. There were variations in terms of height, dbh and volume at the same age.

In this study, best age to harvest the tree was established to be in the range between 5 to 10 years, which concurs with other studies (Saint-André *et al*., 2005; Forrester *et al*., 2010; Lindenmayer *et al*., 2017). However, the exact age of harvesting is always determined by the current annual increase (CAI) and mean annual increment (MAI). In this study, the interaction between the CAI and MAI occurred at age 6.5 years which falls within the

5 to 10 years optimal age of harvesting. At this age of harvesting, it is widely believed that 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 diameter at breast height (dbh) was the most widely used predictor of volume, caution should be applied when using such equations. A comparative study carried out by Harja *et al*. (2011) using the equations from Chave *et al*. (2005) and Basuki *et al*. (2009) showed that all the equations performed equally well at the lower diameter range below 60 cm, while three equations overestimated the biomass above 60 cm. Among these, Kettering's equation showed the highest level of overestimation due to the lower diameter of the data sets. Many equations have limited applicability as many of these are derived from local studies and from a limited diameter range. According to Chave *et al*. (2005), the biomass of the tree can be predicted in order of importance using diameter, wood density, height, and forest type. Analysis by Feldpausch *et al*. (2012) shows that the integration of height into biomass estimates reduced estimates of tropical carbon storage by 13%. Other studies have also cautioned against inclusion of height in regression equations (Leuschner *et al*. 2007). In a study in southwestern Amazon, Goodman *et al*. (2014) found that models without height overestimated AGB, but models that included height underestimated AGB substantially. Similarly, Basuki *et al*. (2009) noted that adding height into allometric equations did not increase the accuracy of the estimation. Moreover, measuring height of trees accurately in tropical dense forest is difficult. This suggests that models with only diameter and height may be more universal than models with diameter, wood density, and height. Chave *et al*. (2005) also noted that use of diameter and wood density considerably increased the prediction capacity for a generalized/mixed species stand.

The understanding of fuel properties i.e., calorific value, ash content, volatile content, fixed carbon content, ultimate carbon and hydrogen is very important for utilization of any material 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.

The fuel quality reduces with the amount of ash present in the biomass. The higher amount of ash in biomass makes it less desirable as fuel (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 amount of ash was higher in lower age trees. The low and minimum variability in ash content of wood indicates that ash content may not be an appropriate criterion for determining 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 indicates that during combustion, most of it will volatize and burn as gas. 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 since at higher age, since as the trees grow old, the wood become more compact and thus its ability to absorb moisture become less effective. Fibre saturation point is the moisture content level which corresponds to the lumen containing no free, while no bound water while has been desorbed from the cell wall material (Skaar, 1988). The absorption PCT 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. Factors affecting absorption and desorption of moisture by wood include: wood variables such as the variability of among wood species due to the variation in extractives content and possibly also to variability of cellulose, hemicelluloses and lignin content (Skaar, 1988); environmental factor like the surrounding environmental elements including temperature, relative humidity and wind movement also play part.

The mean fixed carbons of the forest of ranged from 10.64 to 10.09% which is close to the fixed carbon content of many tree species (Senelwa and Sims 1999) and tended to increase with the age of the forest. The species with higher carbon content are preferred as fuel because of their high energy content per unit volume and their slow burning property (Kumar *et al*., 2010). The quality of fuel is known by the amount of heat (energy) generated from a unit mass of fuel (MJ/kg), which is a function of the calorific value. The mean calorific value of the forest ranged from 18.5317 to 19.57j/g and increased with age of the forest plantation. Similarly an increase in the calorific value was observed in mature trees (20 years) compared with lower age trees (2−6 years). Lemenih and Bekele (2004) reported a weak and negative correlation between calorific value and age of trees between 11 and 21 years. The lower calorific value observed in the work in lower age trees can be attributed to high ash content. The calorific value is one of the important parameters for differentiating one fuel from others. The calorific value of biomass is dependent on its chemical composition i.e., cellulose, hemicellulose, lignin, extractives and ash forming minerals (Shafizadeh, 1981). Lignin and extractives have lower degree of oxidation and considerably higher heat of combustion in comparison with cellulose and hemicellulose (Kumar *et al*., 2010). The tree-age variability in calorific value of *Eucalyptus* hybrid trees was found to be practically marginal. The calorific value of mature tree (20.16 MJ/kg) was higher than that of lower age group trees (19.10−19.50 MJ/kg). This can be attributed to lower ash content and high fixed carbon content in the mature trees.

Proximate analysis clearly shows that there was much variation in the elemental composition among trees of different ages. The variability in the proximate composition of different ages is responsible for low variability in the heating value of trees. In any fuel, carbon oxygen and carbon-hydrogen bonds contain lower energy than carbon-carbon bonds.

Developments of biomass and volume models have been widely used in forestry for both industrial and scientific purposes. These models have the same objectives: to evaluate some difficult-to measure tree characteristics from easily collected data such as diameter at breast height (dbh), total height, or tree age. Generally, equations are linear, exponential, allometric, or hyperbolic, and correlations are often very good ($R^2 > 0.8$). The developments of species specific allometric equations are necessary to achieve a higher value of accuracy (Basuki, *et al*., 2009). According Von Gadow and Brandenkamps (1992), the volume of individual trees is easily estimated from volume equations compiled from detailed measurements of a great many trees where each tree was cut into sections and the under-bark volume of each piece was accurately determined. Having the height and dbh of a tree, one can use a standard volume equation to estimate the total under-bark volume of a tree. According Von Gadow and Brandenkamps (1992), the biomass of individual trees is easily estimated from volume equations compiled from detailed measurements of a great many trees where each tree was cut into sections and the under-bark volume of each piece was accurately determined.

During the study, it was established 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 of stem/ha, 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 $Y = bx + cx^2$, which concurs with Mugasha *et al*. (2013), with estimates for b and c being 601.7 and c being -147.6 and 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.

In this study, model parameters were found to vary clearly with stand age. This is not only the result of a change in tree maturity but rather a combined effect of tree age and tree social status. In considering two trees of the same height and diameter but differing in age. They would also exhibit a difference in social status: the youngest tree must be dominant whereas the oldest one is probably suppressed. Both effects of age and social status, lead to an increase in stem biomass for the oldest tree because wood density increases with stand age and the form factor, ratio between stem volume and dbh, is higher for suppressed trees (Ognouabi and Fouty, 2012). Conversely, both effects tend to decrease leaf and living branch biomasses for the oldest and suppressed tree because leaves are closer to the crown periphery as and when the tree grows (Coudurier *et al*., 1995), and because the crown length is strongly reduced by social status.

5. CONCLUSIONS

There was an increase in tree volume, height and dbh with age of the tree plantation. The regression outputs showing relationships between the volume, height and dbh. It was established that there was a total of 1783.04 ha of land with an estimated total volume of 598,257 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 0.8589. 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, 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. Meanwhile tree biomass of the plantation increased with volume of the trees in the plantation. Tree biomass increased with volume of the forest plantation, where the biomass was fitted using the equation $Y = bx + cx^2$, with estimates for b and c being 601.7 and c being -147.6 and 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.

In order to improve the biomass research in the country, a wide range of such issues need to be addressed. Studies need to provide clear definitions of the biomass compartments and forest types. The studies restricted to minor biomass compartments (such as leaf and fruit) have limited use in the context of climate change mitigation as they do not cover large carbon pools of the system. The increase in sample size and the inclusion of trees that span large diameter ranges can reduce the error in the biomass estimates and make equations more generally applicable. The equation with single parameter (Dbh) for both volume and biomass tends to overestimate the biomass and volume especially for young stand more than old stand, so it is better to estimate the young stand volume and biomass by using equation with two parameters (Dbh and ht). 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.

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