Growth and Yield Models for Plantation-Grown *Cupressus lusitanica* for Central Kenya

Kuria N. Charles[a], Kirongo B. Balozi[b] and KipkoreWilson[c]
Department of Forestry and Wood Science, University of Eldoret,
P.O. Box 1125 – 00217, Eldoret
Email: kuriangure@yahoo.com[a]; balozibk@hotmail.com[b]; kapyas@gmail.com[c]

ABSTRACT

The demand for timber in Kenya is increasing. However, forest managers do not have an effective tool for estimating the growth and yield of the resource against the demand to enable sustainable management. In this study, a method for estimating growth and yield of Cupressus lusitanica plantations in Central Kenya based on a statistical model that directly relates volume to other parameters such as diameter and total height is considered. The study developed a set of growth models based on height against age, height against diameter at breast height (dbh) as well as the dhb against age. Tree height and age showed exponential relationship of the form $H_t = b*Age^{\wedge c}$*, while the height and dbh was developed using models of the form* $H_t = a + b(dbh)^{\wedge c}$ *and dbh was related to the age by equation of the form* $dbh = a*(Age)^{\wedge b}$*. The relationship between volume and dbh and height was fully fitted with third order differential equation of cubic function. At dbh lower than 0.2 m the volume increased at slower rate, followed by an exponential increase in volume between dbh 0.2 to 0.45m and then a plateau thereafter. Using diameter at breast height and height, the volume equation was developed as;* $V = -0.1247+ 0.02233*dbh^2-0.0233*H+ 0.0012*H^2$*, which showed higher model fit to volume than the model currently in use, with the latter overestimating volumes at extreme high or low values but underestimated most intermediate volumes. The developed models are recommended for integration into forest information systems for Cypress plantations management in Central Kenya.*

Key words: Sustainable forest management, growth and yield modeling, Silviculture, Forest inventory.

INTRODUCTION

Forests supply wood and non-wood products for human use (Bennett *et al*., 2018), enhance conservation of biological diversity (Naughton-Treves *et al*., 2015), and water resources (Ernst *et al*., 2017). In the past, forests have faced dramatic loss in terms of biodiversity, extent, and coverage due to increase in demand for land for agriculture, timber and other construction materials, wood fuel, medicine and other tree products. Some forest land was also converted to settlement areas (Hosonuma *et al*., 2017; Keesstra *et al*., 2018). Globally, forests in Africa were the most severely affected (Abernethy *et al*., 2016). Africa's forests covered an area of about 650 million hectares, or 21.8% of Africa's land area by the turn of the millennium (FAO, 2003) but from 1980 to 2010, the forest cover reduced on average by 10.4 million hectares per year (FAO, 2010; FAOSTAT, 2014). In the Sub Saharan African (SSA) countries, Kenya was one of the most affected in terms of forest resources declined during the same period (Mogoi *et al*., 2012). These challenges led the United Nations Conference on Environment and Development (UNCED) in 1992 on the Earth Summit in Rio de Janeiro, to develop a nonbinding statement of forest principles on the guidelines to sustainably manage and protect the world's forests (Summit, 1992). Since then, there have been international, regional and local criteria to achieve sustainable forest management.

Kenya consists of about 2 million hectares of gazetted forest land, which comprises approximately 3% of the total land area of the country. This gazetted forest land consists of about two thirds protection forest (consisting of indigenous tree species), and about 150,000 ha (Mathu, 1983; MENR, 1994) consisting of exotic softwood plantations. *Cupressus lusitanica* Miller, also called Mexican cypress, is the most widely planted species comprising about 55% of this area, with *Pinus patula* Schlecht and Cham, also called Patula pine; and *Eucalyptus* species taking 25% and 15% respectively. The rest of the area is taken by other species including *Casuarina* species, *Vitex keniensis*, among other few (KFS 2011). The gazetted forest land is under the management of the Kenya government through the Kenya Forest Service.

By year 2011, Central Highlands of Kenya consisting of Nyeri, Muranga, Kirinyaga, Kiambu and Nyandarua counties had 36,158.5 ha. of gazetted plantation forests, which translated to about 22% of the total forest plantation area in Kenya. This was the largest forest plantation area in a single conservancy in Kenya (Mathu, 2011).

C. lusitanica was introduced into the country in 1936 but it was only planted extensively in the 1950's to replace *Cupressus macrocarpa* which had been introduced in 1930's but was susceptible to Cypress Canker (Mathu 1983). This species, together with *Pinus patula*, is primarily used to supply saw-wood to privately owned forest industries in Kenya, for production of timber for construction and furniture industries, roundwood for plywood making and fibre for pulp and paper industry.

Over the years, there has been a steady increase in the demand for timber and timber products in the country. This is largely due to the steady increase in population. The situation is worsened by the continued decrease in the area under industrial forest plantations, mainly due to lack of replanting of harvested areas especially in the 1990's; and the unwelcome de-gazettement and subsequent conversion of forest land to other uses. The ban on forest harvesting imposed through a presidential decree in 1999 to 2011 further compounded the problem.

Mathu (2011) estimated the total demand for sawn timber by 2010 to be 2.35 million cubic metres (at 32% recovery level) against a supply of 1.8 million cubic metres.

In order to produce timber at the required rate and at the opportune time, sustainable forest management is imperative. To attain this kind of management, it is necessary to accurately quantify the amount of timber available against the demand at a given time and the rate of production of the same (Siry *et al*., 2005). This helps in planning for extraction and general management of the timber resource. Growth and yield models help to address the above concerns more effectively and accurately as opposed to the more cumbersome. hard to develop and more generalised yield tables.

Growth is the increase of a certain parameter in a given period (Weiskittel *et al.*, 2011) such as the increase of $100m^3$ of wood in a given stand in one year of growth. Yield refers to the amount of a given parameter which is expected in a forest stand at a given age, usually the rotation age (Tewari, 2008; Cheboiwo *et al.*, 2015). As such these models enable resource forecasts. With a growth model, forest managers can examine the likely outcomes, both with the intended and alternative cutting limits, and can make their decision objectively. The process of developing a growth model may also offer interesting new insights into stand dynamics.

In Kenya today, estimation of wood yield for *C. lusitanica* is based on Technical Note No. 144 (Variable Density Yield Tables for the Cypresses of the *Cupressus lusitanica* Group in Kenya) which is used to estimate stumpage volume of tree plantations of these species for the whole country (Alder, 1979; Mathu, 2011). They have not been revised since their development in 1975. Atempts at validating the models in the past (Ngugi *et al*., 1998; Tennent, 1990) and based on current trials (trial unpublished data) indicate large disparities in their yield estimation. There have been changes in the forest management regimes which may have rendered them inaccurate tools for estimating the volumes of the current crop. Notable among these is the change in land preparation method from *Shamba* system (a form of Taungya system) to bush clearing thus affecting initial growth of trees (Kagombe and Gitonga, 2005) and imposition of forest plantation harvesting ban from 1999 to 2010 which disrupted scheduled silvicultural treatments (Mathu, 2011). Climatic change over the years may have affected tree growth rate over the years, as has been observed in Europe (Pretzsch *et al*., 2013; Spiecker *et al*., 1996). Finally, the yield tables cannot be used to predict growth and yield of the plantations and therefore are inadequate for forest management decisions. Vospernik (2017) observed that development of regional individual tree models is one way of improving the prediction power of the models by reducing prediction uncertainty.

There is considerable work done on demand of wood and wood resources in Kenya (Mathu, 2011; KFS, 2017) as well as data on per capita consumption. However, without reliable prediction of wood resources supply, one cannot meaningfully evaluate the balance or deficit, and by implication, any interventions would be based on faulty data. In addition, there is need to review forest management tools from time to time (Subasinghe, 2008), including updating plantation inventories and growth and yield data as a means of having clear modalities of executing concessions and leases of forest plantations as envisaged in the Forests Act, 2005 (Mathu, 2011) and subsequent Forest Management and Conservation Act, 2016.

Therefore, this study aimed at generating new region-specific growth and yield models for *C. lusitanica* which are valid for the prevailing conditions; and compare the accuracy of the developed volume equation with that of the equation currently in use.

METHODOLOGY

Study Area

The Central Region of Kenya covers an area of 13,220 km^2 which is 2.3% of the total Kenya's landmass. It has a population density of 307 persons/km^2 (KNBS, 2010). The study area has a total gazetted forest of 317,139.61 ha out of which 36,158.49 ha compose of forest plantations (KFS, 2009). The forest plantation area in Central region represents about 21.9% of the total plantation area of 164,000ha in Kenya. The area falls within Nyandarua, Kiambu, Murang'a, Nyeri and Kirinyaga counties.

The temperature is variable, with the mean annual temperature being as high as 28°C in the lower southern and south-eastern areas and along the Laikipia plateau, to as low as 12°C in Nyandarua on the western slopes of the Aberdare Range. The nightly flow of cold air from Aberdare Range accumulates in depressions and flat areas like the Kinangop Plateau and decreases the mean minimum temperature for almost 3°C making the area prone to frost. However, the Mean Annual Temperature in the forest area is 15°C. The average annual rainfall varies from 400 mm in the low eastern plains to more than 2200 mm on the south-eastern windward side of the Aberdare Ranges. The rain distribution is bi-modal; with the first season peaking in April and the second one in November. The intervening season is distinctly dry, except in the misty and cloudy attitudes above 1800 m, and west of the Aberdare Range, where rains induced from Western Kenya occur (MoA, 2006).

The pattern of the Agro-Ecological Zones is typical for the highlands east of the Rift Valley; starting from the Aberdare Range with the Tropical Alpine Zones TA I and II, which form part of Aberdare forest and National Park. Other forest parts are on steep wet areas on Upper Humid Zones UH 0 and UH 1. Then AE zones Lower Humid (LH 1), Upper Medium (UM 1-5) and Lower Medium (LM 3-4) occur at descending order in the eastward direction (MoA, 2006). However, the Mean Annual Rainfall in the forest area is 1800 mm.

The soils in Central Kenya are variable. MoA (2006) describes the lower southern and south-eastern region as mainly characterised by Acrisols, Arenosols, Ferralsols and in some areas, Cambisols. Most of these soils are strongly leached, with low fertility and high sesquioxide content. Higher up the altitude, Luvisols are found on the lower foot-slopes South-East of Mt. Kenya and some parts on the slopes west of the Aberdare Range. The drier semi-humid and Semi-arid high-level savannah plains north-west of Mt. Kenya (Laikipia plains) and north-west of Aberdare Ranges (Ol Kalou and Nyahururu areas) are on the leeward side of the mountains. Phaeozems, which are clayey soils with high content of humic and organic substances characterise these regions. The soils are deep, well drained with a high Cation Exchange Capacity (CEC). On the Western side of the Aberdare Range, the soil changes to Planosols on the Kinangop Plateau next to the range.

Higher up are the UH and Tropical Alpine zones on both Mt. Kenya and the Aberdares; which are occupied by Humic and Mollic Andosols and Histosols. This region is usually occupied by natural forests on steep slopes. On top of the mountains are the Regosols and Lithosols which are shallow soils associated with rock outcrops. These regions form the Aberdare and Mt. Kenya National Parks

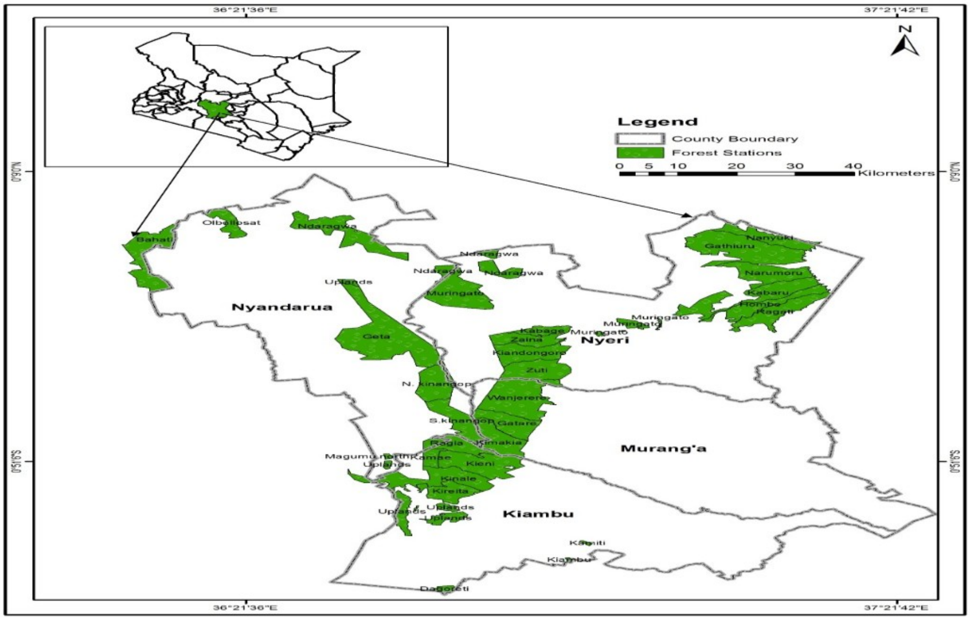

Figure 1: Gazetted forest area in Central Kenya (Courtesy: KFS)

Experimental Design

Forest inventory data

Secondary data from a national forest plantation inventory (2008 -2011) carried out by KFS during the harvesting moratorium (Hess, 2008), was used to develop relationships between various tree parameters, important in model construction.

As stipulated by Hess (2008), the inventory design focused on a stand inventory rather than a national inventory with the aim of maximizing accuracy in each sub-compartment. Point samples were established by overlaying a dense systematic grid of 150m (North-South) by 125m (East-West) over a Universal Transverse Mercator (UTM) map of the sub-compartment with a scale of 1:10,000, and marking each sample point on the map, whichcorresponded with each intersection of the grid lines. The position of each sampling point was located on the ground by use of GPS set and circular plots were established around the sample point whose radius differed depending on the tree density of the sub-compartment as below;

For all sub-compartments which were 10 years and over Circular plot with a radius of 11.28m was used if two or more thinning operations had been carried out on the plantation and recorded in the compartment register, or the density was less than 500 trees per hectare, where no thinning records were available. A circular plot with a radius of 7.98m was used if one thinning is recorded in the compartment register, or the density was more than 500 trees per hectare and no thinning records were available.

In all sub-compartments less than 10 years of age, the smaller plot of 7.98m radius was used regardless of evidence of thinning and a tally of the number of trees in each plot taken. The sampling intensity of this inventory was about 2%.

In each plot, diameter at breast height (DBH) was taken for each tree in the plot for sub-compartments at least 10 years old and only DBH of two dominant trees in tally sample (sub-compartments less than 10 years old) using the standard diameter tape. Total heights of four (4) dominant trees (usually largest DBH) for larger plots with radius of 11.28m, and two dominant trees in smaller plots of 7.98m radius were taken using Suunto Clinometer. The same instrument was also used for slope measurement in every sampling point

For the purpose of this study, data from a total of 94 plantations of *C. lusitanica* (3154 individual trees) were considered as the sample. They were distributed across the Central region as shown in Table 1. The ages of these plantations ranged from 4 to 42 years.

Table 1: The distribution of sample plots (Extracted from Field Inventory Sheets (unpublished) from Forest Inventory Section – KFS Nairobi)

County	Station	No. of Plantations	No. of plots
Nyeri	Chehe	5	19
	Gathiuru	6	34
	Zaina	8	25
Muranga	Gatare	14	30
Kiambu	Kerita	14	62
	Kamae	9	28
	Kinale	12	33
	Uplands	4	11
Nyandarua	Geta	12	50
	North	5	14
	South	5	15

Data from destructive sampling

Data was collected through destructive sampling where trees were felled from some plantations in different forest areas and measurements made on the fallen tree. The procedure involved randomly selecting *C. lusitanica* plantations from among plantations whose data was recorded in the plantation forest inventory referred above. A total of 11 plantations from Kiambu; and 7 from Nyandarua County were randomly selected (Table 2). The age of selected trees ranged from 4 to 32 years.

Table 2: Distribution of plantations Sampled for Tree Volume Estimation

County	Station	No. of plantations	Ages of plantations (years)
Kiambu	Kerita	5	7, 9, 11, 20,23
	Kamae	5	4, 5, 14, 16, 26
	Kinale	1	32
Nyandarua	Geta	7	5, 7, 10, 14, 18, 22, 30

The randomly selected tree was felled using a chainsaw at a stump height of 15 cm from the ground. Diameter measurements of the log were taken, first at the butt end of the tree, then at 30 cm, 60 cm, 1 m, 1.3 m, 2 m, then after every 1 m interval up to the tip of the tree, and recorded to the nearest 0.1 cm. Two measurements were taken at every point using a diameter tape. The length of the logs was measured using a measuring tape. A total of 37 trees were felled and measured.

Current Volume Model for C. lusitanica (KFS model)

The current volume model developed in 1975 is:

$\tilde{V} = 0.013152 - 0.00005069*dbh^2 + 0.0001769*dbh*H + 0.00002895*dbh^2*H$ (Wanene and Wachiori, 1975).

Data Analysis

Volume models

Data taken by destructive sampling was used to construct volume models where the volume of each tree was first calculated by summing the volumes of short logs making up each tree. The volumes were calculated using the Smalian's formula, thus: $V = L\frac{(g_1 + g_u)}{2}$

where; V is the volume, L is the length of the log, g_l is the cross-sectional area of the log at the lower end, g_u is the cross-sectional area of log at the upper end (West, 2009). The volume models were constructed by Gauss-Newton method (Least Squares Approach) using SAS/STAT (2002) software. The Goodness of Fit of the models was determined using the Residual Means Square Error (RMSE)(Zar, 2010), p-values and Residual plots (Kirongo, 2000), thus

$$RMSE = \sqrt{\sum \frac{(y_i - y)^2}{n}}$$

where y_i = predicted value, y = observed value, n = sample size.

Other Models

The forest inventory data was used to construct the Height-Diameter, Height-Age and Diameter-Age models and to test the use of the developed volume model.

Comparison of volume models

The newly constructed volume model was compared with the existing volume model currently being used by KFS for calculating stumpage volume. This involved comparison of the Mean Squared Error, Residual plots and Coefficient of Determination (R^2) between new model and the KFS model.

RESULTS

Growth Models

Height – Age Relationship

Scatter diagram and model fit showing the relationship between tree height and age of *C. lusitanica* is shown in Figure 2. The relationship between tree height and age was curvilinear with exponentially increasing trend observed between 0 to age of 8 years, constantly increasing trend observed between age of 8 years to age of 28 years and no increasing trend thereafter.

There was a steady increase of height with increasing age up to about age of 26 years after which the height remained relatively constant.

The equation significantly described the relationship between height and Age on ($F_{1,205}$ = 199.1, $p < .01$) with a model R^2 of 0.7019.

The residual plots of the relationships between tree height and age are shown in Figure 3.

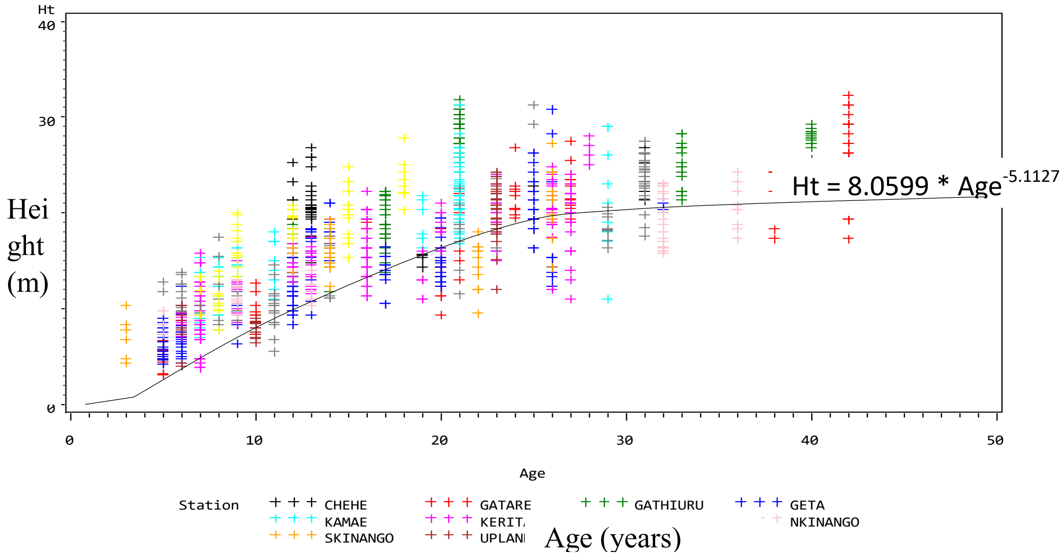

Figure 2: Scatter diagram showing the relationship between tree height (m) and age (y) of *C. lusitanica*.

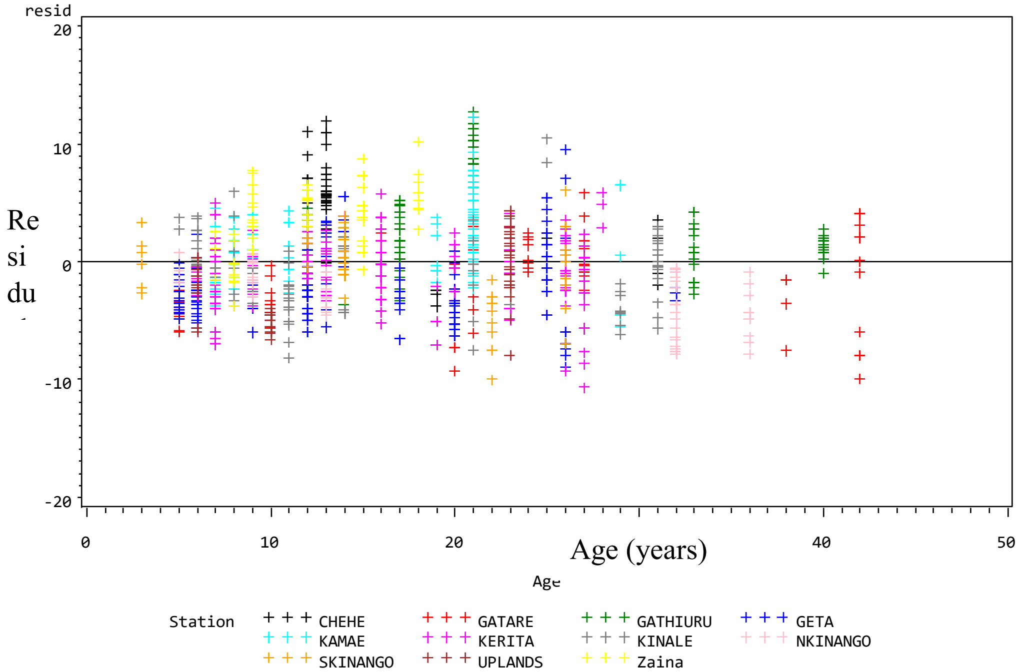

Figure 3: Residual plots of the relationships between tree height and age of *C. lusitanica* in forest plantations in Central Kenya

Analysis of the scatter diagram, using normal and frequency plots of the residuals showed that the slope was not significantly different from the zero.

Using equation 1, predicted height ($\hat{H}_t$) was derived from age data. The relationship between $\hat{H}_t$ and age is shown in Figure 4.

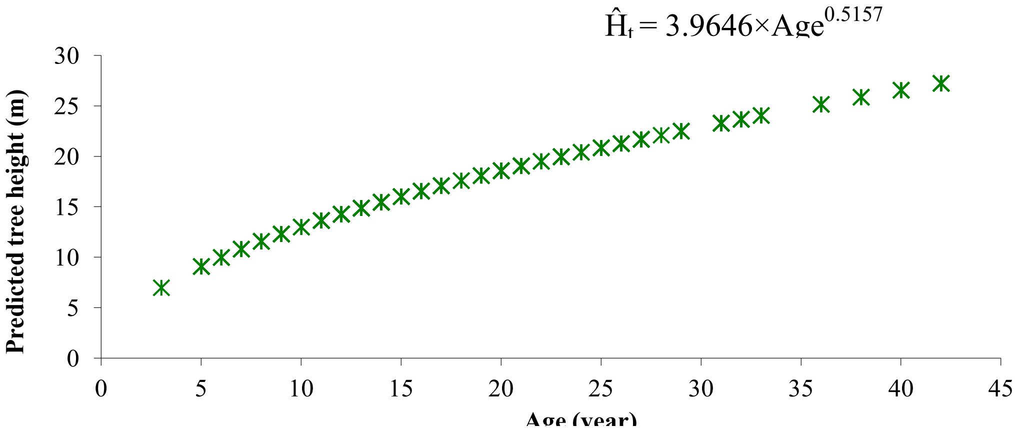

Figure 4: Scatter diagram showing the relationship between predicted tree height and age.

Based on the ANOVA of the regression slope > 0, the derived equation significantly described the relationship between $\hat{H}_t$ and Age ($F_{1,317} = 361.1$, $p < .0001$).

The residual plots of the relationship between predicted tree height ($\hat{H}t$) and age of *C. lusitanica* is shown in Figure 5. The residual plots were distributed within the zero slope line of the scatterplot with a maximum residual occurring at +40 and minimum at -30.

Further analysis of the residuals from the scatterplot using moments, normal cumulative plots and residual frequency distribution plots (Figure 6) of the relationship between predicted tree height ($\hat{H}t$) and age of *C. lusitanica*, all indicate that the slope was not significantly different from zero.

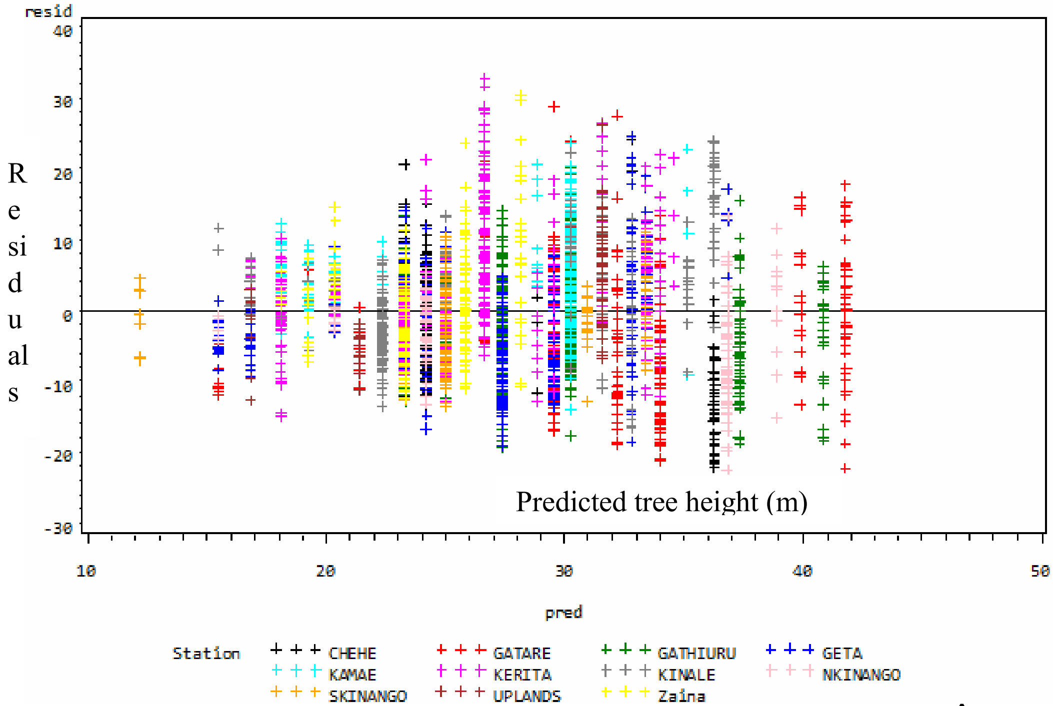

Figure 5: Residual plots showing the relationships between predicted tree height ($\hat{H}_t$) and age of *C. Lusitanica*

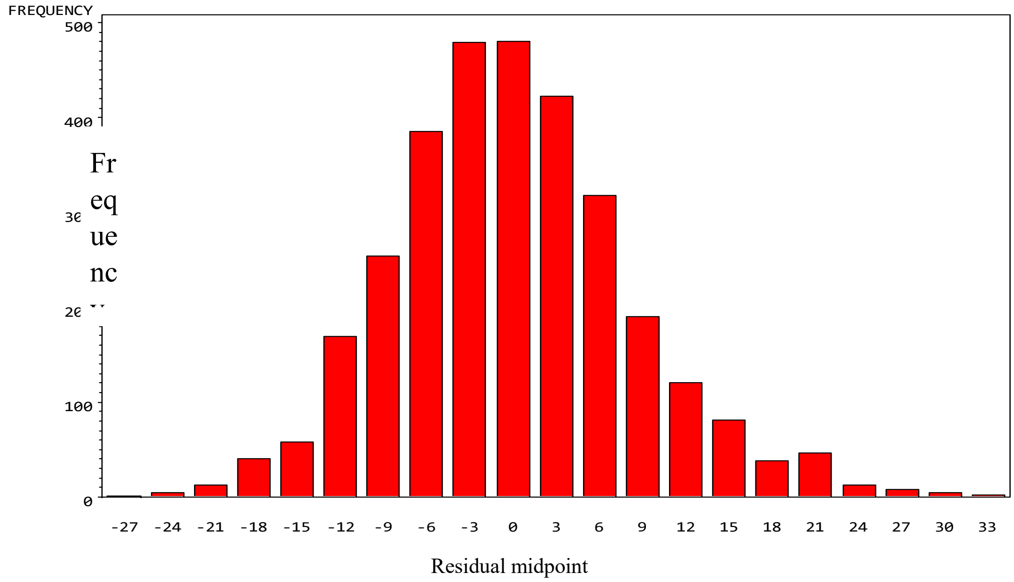

Figure 6: Frequency distribution plots of residuals between predicted height and age of *C. lusitanica*

Height – Diameter Relationship

The relationship between tree height (H_t) and diameter at breast height (DBH) of *C. lusitanica* in forest plantations in the Central Kenya is shown in Figure 7. The relationship between tree height and DBH showed exponential relationship where there is linear increase in height as DBH increase up to a DBH of 50 cm, after which there is no subsequent increase in height in tandem with increase in DBH.

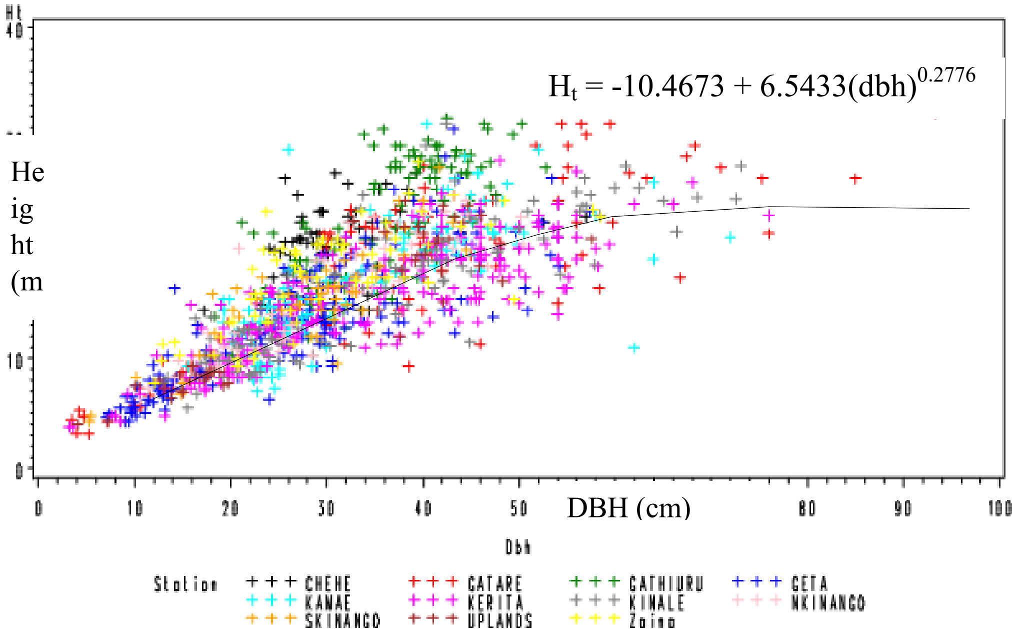

Figure 7: Scatterplot showing relationship between tree height and DBH of *C. lusitanica* in forest plantations in Central Kenya

The equation significantly described the relationship between H_t and DBH ($F_{2,1156} = 9444.1$, $p < .0001$).

The residual plots between tree height and DBH are shown in Figure 8. Analysis of the scatter diagram, using normal and Frequency plots of the residuals from the zero slope was not significantly different.

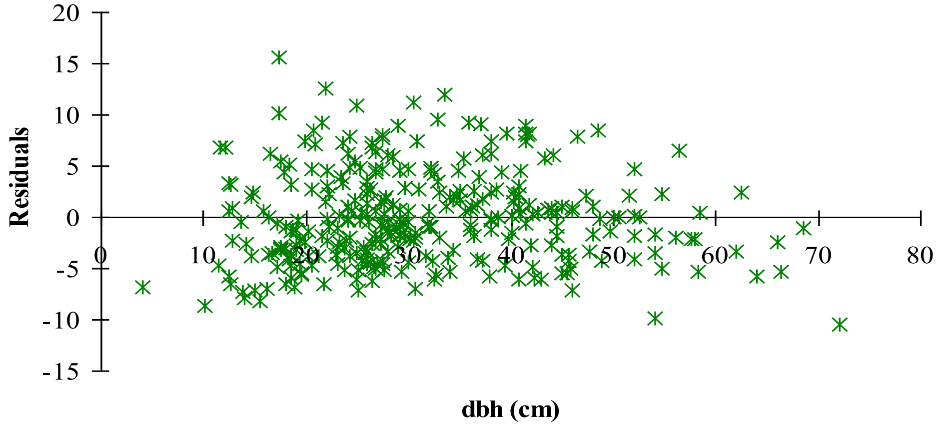

Figure 8: Residual plots of the relationships between tree height and DBH

Using equation 3, the predicted height ($\hat{H}_t$) was derived from DBH data. The relationship between $\hat{H}_t$ and DBH is shown in Figure 9.

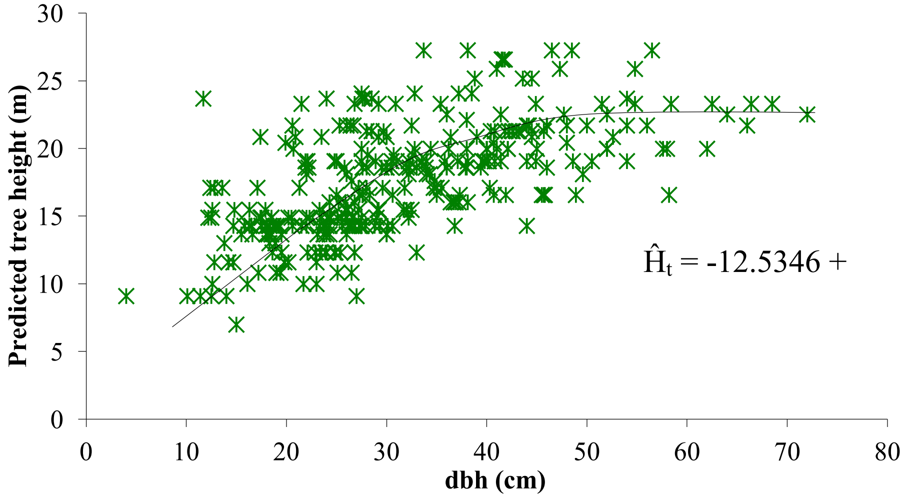

Figure 9: Scatter diagram showing the relationship between predicted tree height and DBH

The relationship between predicted tree height and DBH showed exponential relationship where there is linear increase in predicted height as DBH increase up to a DBH of 50 cm, after which there is no subsequent increase in height in tandem with increase in DBH.

Based on ANOVA ($p < 0.05$) of the regression slope > 0, the equation significantly described the relationship between $\hat{H}_t$ and dbh ($F_{2,1155} = 886.5$, $p < .0001$). The residual plots of the relationships between predicted tree height ($\hat{H}_t$) and dbh is shown in Figure 10. The residual plots were distributed within the zero slope line of the scatterplot.

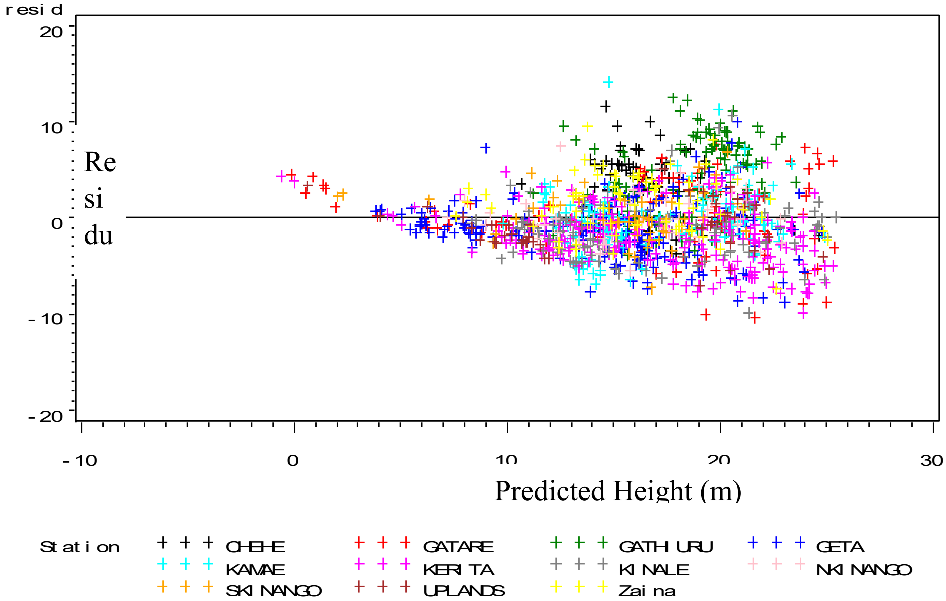

Figure 10: Residual plots showing the relationships between predicted tree height ($\hat{H}_t$) and dbh of *C. lusitanica*

Further analysis of the scatterplot of the residuals, using moments, normal cumulative plots and residual frequency distribution plots (Figure 11), all indicated that the slope was not significantly different from zero.

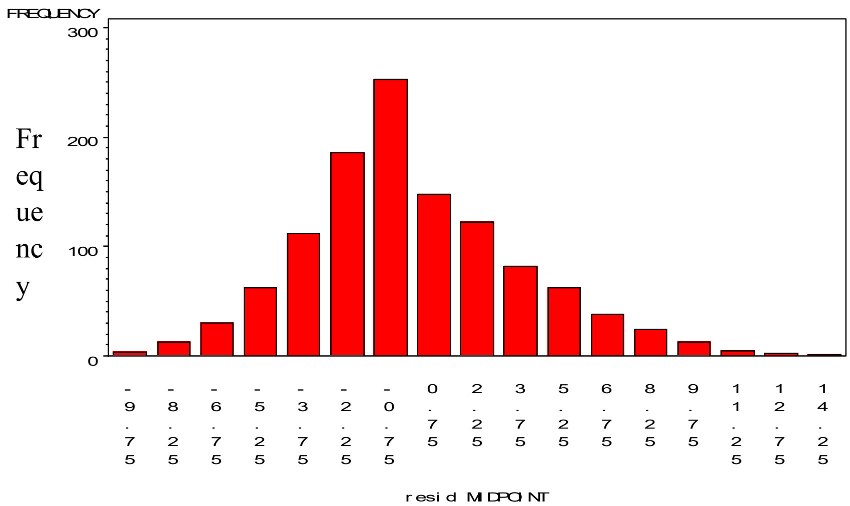

Figure 11: Residual frequency distribution plots of predicted height ($\hat{H}$) and dbh of *C. lusitanica*

DBH – Age Relationship

The scatter diagram and model fit showing the relationship between DBH and age of *C. lusitanica* in forest plantations on the Central region of Kenya is shown in Figure 12.

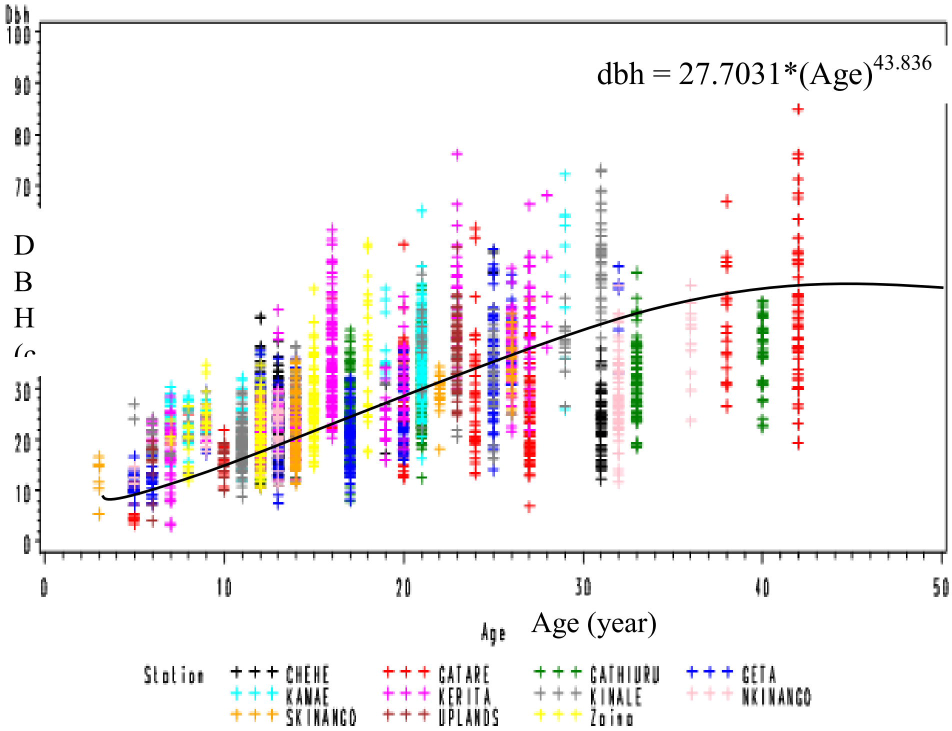

Figure 12: Scatterplot showing relationship between DBH and age of C. lusitanica

The relationship between DBH and age of the tree showed exponential relationship where there is linear increase in height as DBH increase up to age of 30 years, after which there was no subsequent increase in DBH in relative to the increase in DBH.

The equation significantly described the relationship between dbh and Age ($F_{1,317}$ = 1743.2, p < .0001). The residual plots between dbh and age are provided in Figure 13.

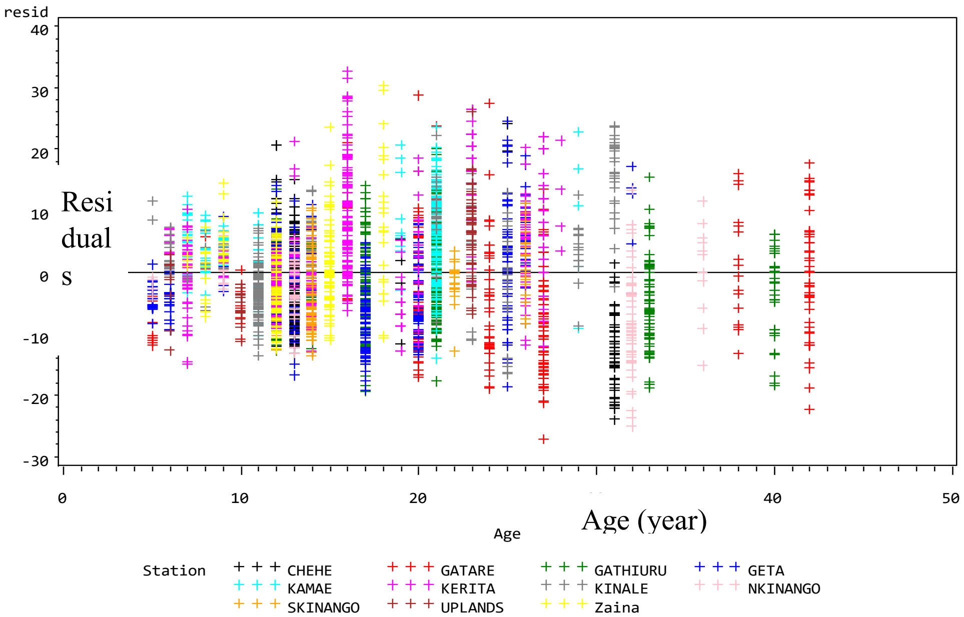

Figure 13: Residual plots of the relationships between dbh and age of *C. lusitanica*

Using equation 5, the predicted dbh (Ďbĥ) was derived from age data. The relationship between Ďbĥ and age of *C. lusitanica* is shown in Figure 14.

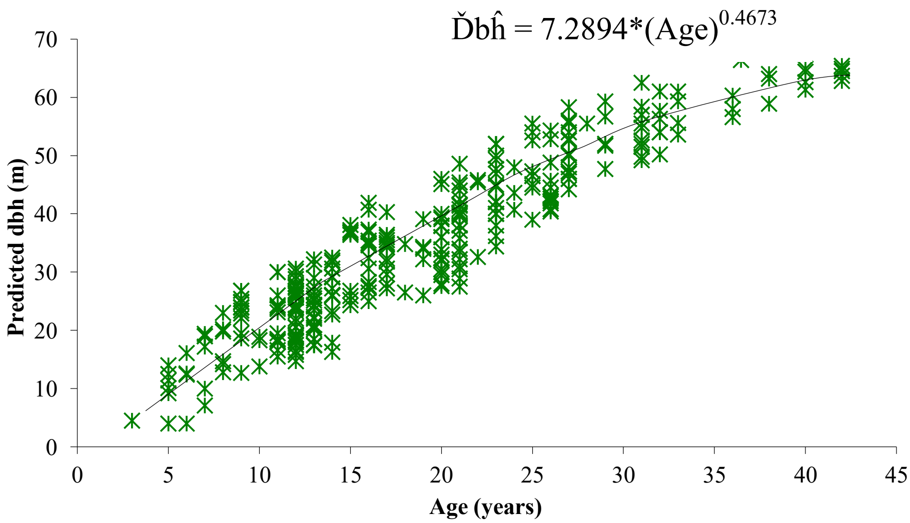

Figure 14: Scatter diagram showing the relationship between predicted dbh (Ďbĥ) and age of *C. lusitanica* in forest plantations in Central Kenya

The scatter diagram showed an exponential increase in predicted dbh with increase in age up to about age of 40 years where the increase in dbh decreases.

The residual plots between Ďbĥ and age are provided in Figure 15. The relationship between predicted dbh and Age was significant ($F_{2,3123} = 17828$, $p < .0001$). Analysis of the normal plots and frequency plots (Figure 16) of the residuals from the zero slope indicate that the slope was not significantly different from zero.

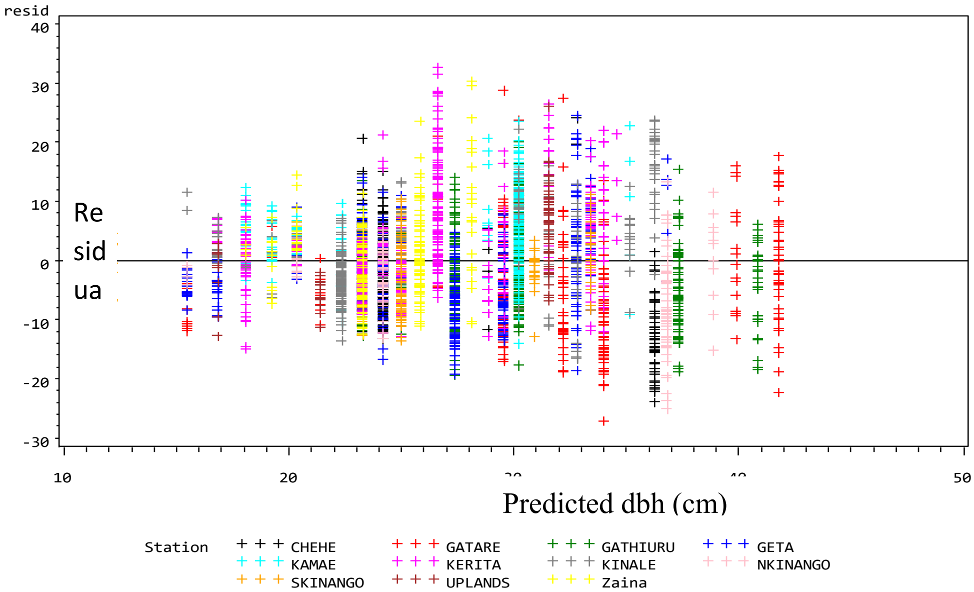

Figure 15: Residual plots of the relationships between Ďbĥ and age of *C. lusitanica*

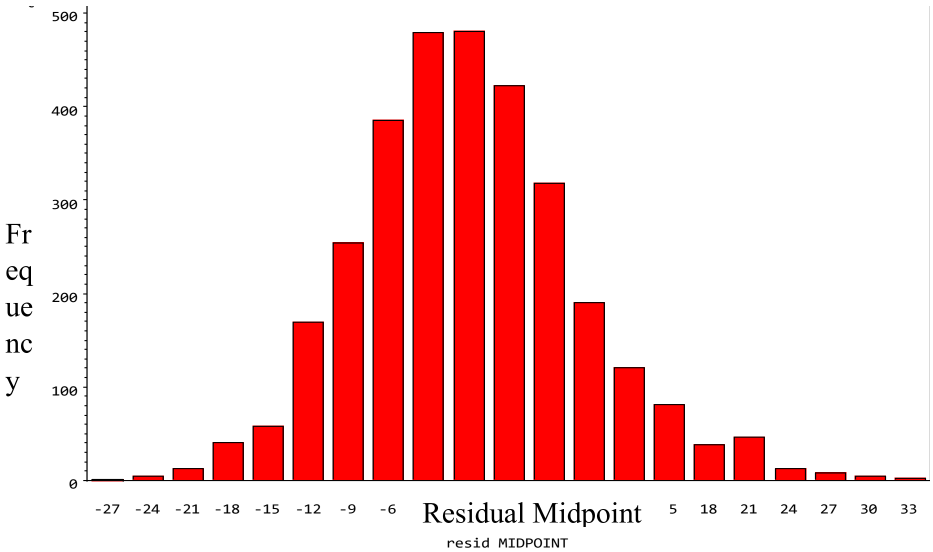

Figure 16: Probability plots the relationships between the residuals of Ďbĥ and age of *C. lusitanica*

Yield Models

Volume – dbh relationship

The relationship between Smalian volume and dbh is shown in Figure 17. The relationship between the smallian volume and dbh was fully fitted with third order differential equation of cubic function. At dbh lower than 0.2 m, smalian volume increased at slower rate, followed by an exponential increase in smalian volume between dbh 0.2 to 0.45m and then a plateau thereafter.

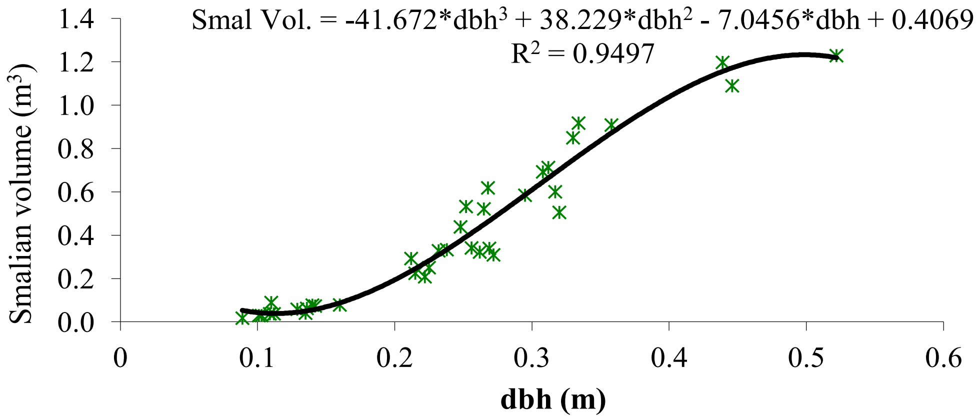

Figure 17: Relationship between smalian volume and dbh for *Cupressus lusitanica*

The residual plot depicting the smalian volume and dbh of *C. lusitanica* is shown in Figure 18. The residual plots were evenly distributed within the slope of the regression line and did not show any significant deviation from the slope (ANOVA, $F_{1,35} = 264.19$ $p < .05$).

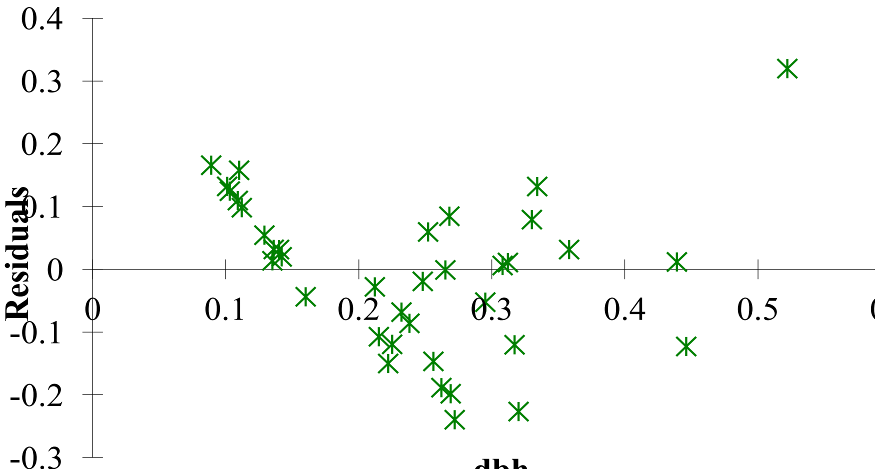

Figure 18: Residual plots for Smallian volume and dbh

Volume – Height relationship
The relationship between Smalian volume and height is shown in Figure 19. There was a general exponential increase in smalian volume with increasing height. The residual plot depicting the smalian volume and height is shown in Figure 20. The residual plots were evenly distributed within the slope of the regression line and did not show any significant deviation from the slope (ANOVA, $F_{1,35} = 69.4$, $p < .05$).

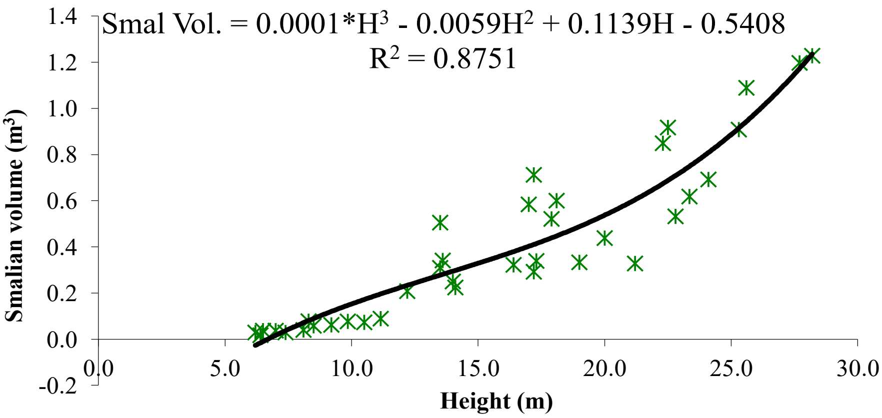

Figure 19: Relationship between smalian volume and height of *C. lusitanica*

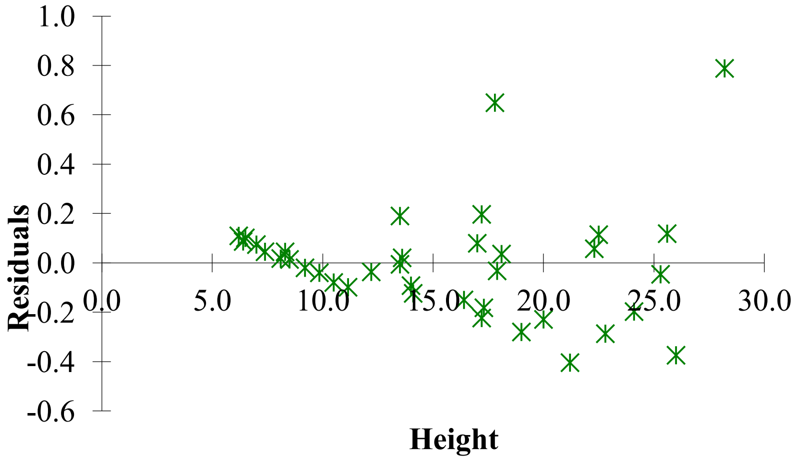

Figure 20: Residual plots for smalian volume and height for C. lusitanica

Volume – DBH – Height Relationship (Volume Model)
The equation describing the smalian volume, height and dbh for *Cupressus lusitanica* was developed as $V = -0.1247 + 0.02233*dbh^2 - 0.0233*H + 0.0012*H^2$

The above equation was used to predict the volume given H and dbh. The relationship between predicted volume (Ṽ) and Smalian volume is shown in Figure 21.

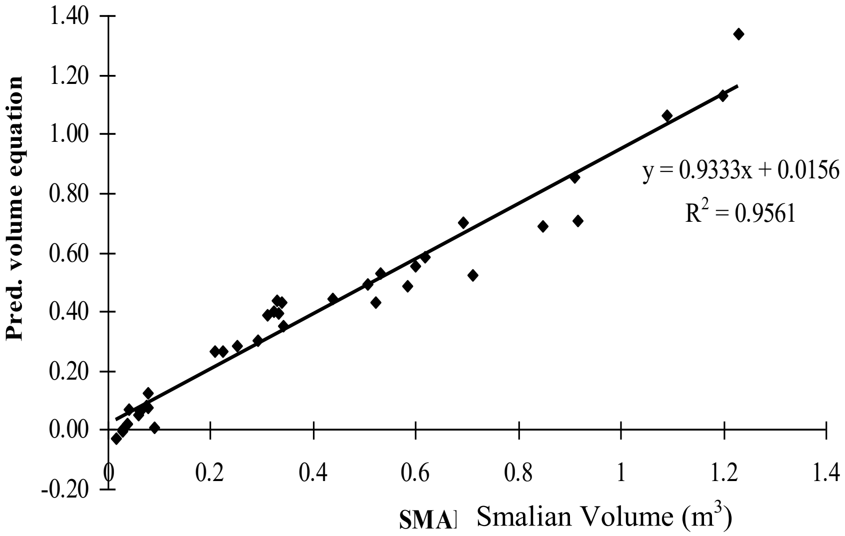

Figure 21: Relationship between predicted volume (Ṽ) against smalian volume of *Cupressus lusitanica*

There was a strong linear relationship between Volume predicted using the developed Volume Model and Smalian volume (R^2 = 0.9561).

Comparison between Developed Volume Model and Conventional KFS Model

The model developed for *Cupressus lusitanica* during this study was: Ṽ = -0.1247+ 0.02233*dbh^2 -0.0233*H+ 0.0012*H^2, while the KFS model developed in 1975 was: Ṽ = 0.013152 - 0.00005069*dbh^2 + 0.0001769*dbh*H + 0.00002895*dbh^2*H (Wanene and Wachiori, 1975).

The relationship between the Smalian volume and volume derived from the KFS model is shown in Figure 22. The relationship between the smalian volume and volume derived from the KFS model showed significant linear relationships, albeit with weak linear regression trends (Multiple R = 0.6077; RMSE = 0.0545). At lower smalian volume below 0.2 m^3 and higher volumes (> 1 m^3), the volume derived from KFS model was overestimated. However, for smalian volume between 0.3 to 0.8 m^3, the KFS model underestimated the volume of the tree.

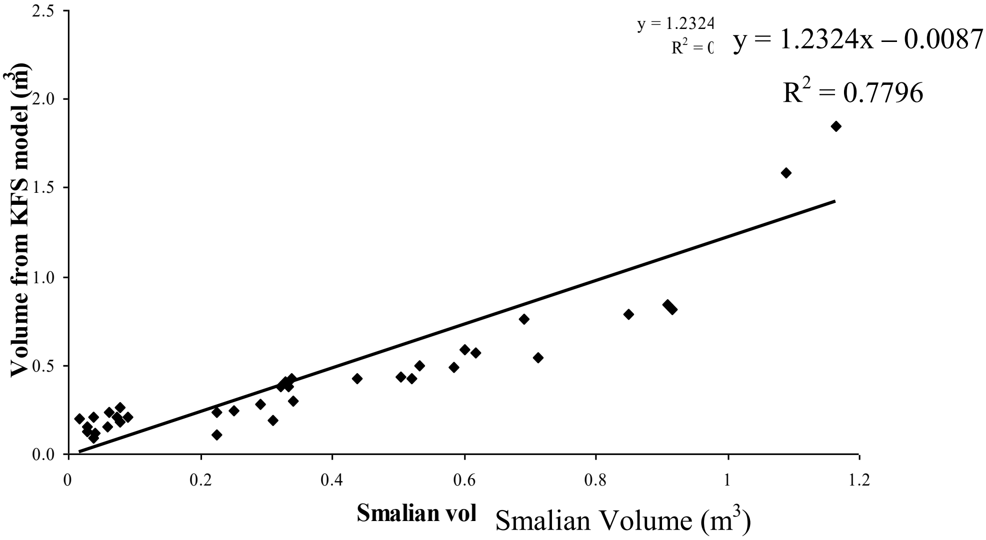

Figure 22: Relationship between the smalian volume and volume by KFS model

The residual plot of the smalian volume and predicted volume of *C lusitanica* based on KFS model is shown in Figure 23. The slope of the residuals was significantly different from zero. However, at low and high smalian volumes the residuals were positive while at smalian volume between 0.5 and 2 m^3 the residuals were negative.

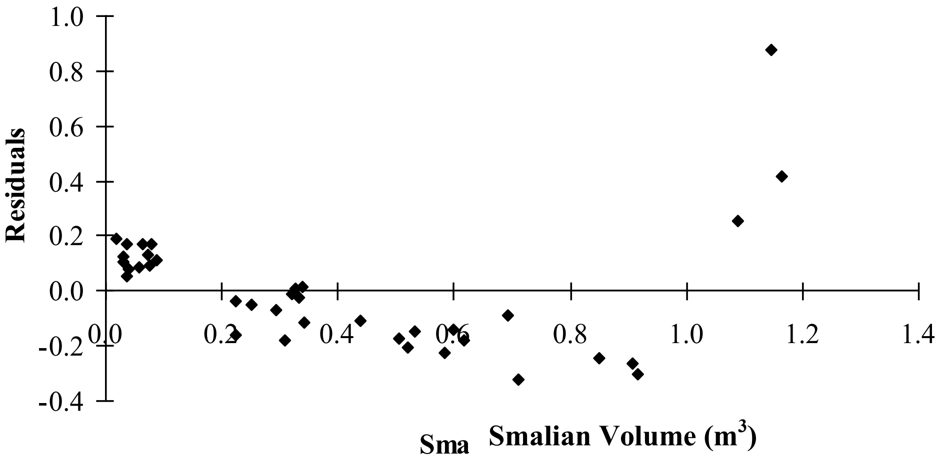

Figure 23: Residual plots for relationship between the smalian volume and KFS model derived volume

DISCUSSION

Growth Models for Cupressus lusitanica plantations for Central Kenya

Forest plantations often provide timber for economic purposes and therefore there is a constant need to establish methods of estimating the timber resources. In this study, the growth models of the main forest plantation tree species in Kenya (*Cupressus lusitanica*, Mathu, 2011) were determined. This was done through evaluation of the height against age, height against dbh as well as the dhb against age with a view of estimating one parameter in presence of data of the other parameter.

Forest inventory often involves predicting tree volumes from only diameter at breast height (dbh) and/or merchantable height, with less studies having been done based on age (Vanclay, 2009). Prediction equations based on these two factors from a small number of intensively measured trees can lead to significantly different inventory estimates. National forest surveys are particularly susceptible to these effects because of the interval between successive surveys and the importance of estimating inventory trends.

The relationship between *C. lusitanica* height and age showed that tree height increased exponentially up to age 8, and reduced thereafter, and reached a peak after 28 years, which agrees with previous studies of the same species in the tropical region (Pukkala and Pohjonen, 1993; Teshome and Petty, 2000). The observed growth trends correspond to the growth patterns described by Berrocal *et al*. (2004). The growth patterns of trees at early stages is higher since the nutrients taken up from the soil will be retained in the tree biomass, but as trees grow older the contribution of re-translocation to the nutrients required for new growth increases (Watt *et al.*, 2008).

Growth models can only provide good predictions if the input data are also reliable. Thus, users should take commensurate care in collecting the necessary input data. Sampling should be efficient and unbiased, and this requires decisions on stratification, plot size and tree measurement. Smith and Burkhart (1984) found that stratifying by both site index and stocking improved the precision of volume estimates by 2/3 over simple random samples. Mowrer and Frayer (1986) warned that errors in initial conditions may have a greater effect on overall precision than contributions from the growth model.

The equation describing the growth of *C. lusistanica* was therefore established to be exponential. The *C. lusistanica* equation took the form $H_t = 8.0599*Age^{-5.1127}$. This equation takes the first order or second order as equations earlier developed by Waldron *et al.* (2013), which suggests that growth of *C. lusitanica* follows three distinct growth patterns corresponding to studies by Boyden *et al.* (2005).

Based on the data collected from the field and relationships between tree height and age, the estimates of the tree height based on age data alone was done during the study. The equation relating to predicted tree height ($\hat{H}_t$) and age of *C. lusitanica* was exponential of the form, $\hat{H}_t = 3.9646 \times Age^{0.5157}$. The results suggest that height growth of *C. lusitanica* could be derived from age only without considering other parameters, which agrees with studies on the species (Domec and Gartner, 2003; Stephens and Gill, 2005).

The tree height and dbh for *C. lusitanica* showed exponential relationship where there is linear increase in height as dbh increase up to a dbh of 50 cm, after which there is no subsequent increase in height in tandem with increase in dbh as suggested by Varner and Kush (2004).

The equation describing height and dbh was fully fitted using a model $H_t = -10.4673 + 6.5433(dbh)^{0.2776}$. The equation relating predicted tree height ($\hat{H}_t$) and dbh was described using the equation: $\hat{H}_t = -12.5346 + 7.5589(dbh)^{0.3942}$.

The relationship between dbh and age showed exponential relationship where there is linear increase in dbht as age increases up to age of 30 years, after which there was no subsequent increase in dbh relative to the increase in age.

The equation describing the relationship between dbh and age was fully fitted using an exponential equation of the model: $dbh = 27.7031*(Age)^{43.836}$. Using the above equation, we were able to predict dbh ($\check{D}b\hat{h}$) from age data. The predicted $\check{D}b\hat{h}$ based on age data of *C. lusitanica* was used to derive an equation of the form: $\check{D}b\hat{h} = 7.2894*(Age)^{0.4673}$.

A growth model must not remain a sophisticated complexity, alien to the forest manager, but must be made available for use as an every-day tool for better forest management. In short, that means that the growth model should be easy to use, well documented and readily available.

Yield Equation for *C. lusitanica* plantations for Central Kenya

Prediction of yield is often the major application of several of the developed growth models. Growth models make it simple to estimate yields from single stands, but forest estate estimates also involve the spatial and temporal distribution of yields. In this study, the use of models was able to predict the relationship between tree volume estimated by the Smalian formula through destructive sampling method (Smalian volume) and dbh as well as Smalian volume and height of the tree. The study was able to fully fit the relationship with high model fit as has been reported in other studies elsewhere (Pereira-Miguel *et al*., 2017a, 2017b).

The equation describing the smallian volume, height (H) and dbh was developed for *Cupressus lusitanica* as $V = -0.1247+ 0.02233*dbh^2-0.0233*H+ 0.0012*H^2$, which was subsequently used to predict the volume given H and dbh with a full model fit. These results suggested that models are powerful tools that can be used to predict yield estimates even if only one parameter of the tree such as age, height or dbh alone is known. In many areas in the tropics, estimation of tree volumes or yields lag behind when only one parameter of the tree is known.

Yield predictions contain two sources of error (Leary *et al*. 1979): error in assessing the initial state, and error in the growth prediction. The former is a problem of resource inventory and may contribute most error associated with predictions (Mowrer and Frayer 1986, Mowrer 1989). Reynolds (1984) gave formulae for estimating errors associated with growth projections.

Comparison between the Developed and Conventional Model (KFS Model) for *C. lusitanica* plantations in Central Kenya

The relationship between the smalian volume and volume derived from the KFS model showed significant linear relationships, albeit with weak linear regression trends. At lower smalian volume below 0.2 m^3 and higher volumes (> 1 m^3), the volume derived from KFS model was overestimated. However, for smalian volume between 0.3 to 0.8 m^3, the KFS model underestimated the volume of the tree (Figure 22).

CONCLUSION AND RECOMMENDATIONS

Conclusions

The study developed a set of growth models for based on height against age, height against dbh as well as the dhb versus age.

Using dbh and height the volume equation was developed as V = -0.1247+ 0.02233*dbh^2-0.0233*H+ 0.0012*H^2. The predicted volume showed high model fit with smalian volume during validation of the model.

This study developed a volume model for *Cupressus lusitanica* ($\tilde{V}$ = -0.1247 + 0.02233*dbh^2 - 0.0233*H+ 0.0012*H^2) which had a better fit with Smalian volume than the KFS model as the latter overestimated low volumes below 0.8 m^3 and high volume above 1 m^3 while underestimating volume between 0.3 to 0.8 m^3.

Recommendations

It is recommended that the developed models be adequately documented and integrated into forest information systems for forest management decisions involving *C. lusitanica* plantations in Central Kenya.

Further research is recommended to investigate the application of the developed models to other forest areas where this tree species is grown. A better approach would be to develop region-specific models for all forest plantation areas in Kenya.

REFERENCES

Abernethy, K., Maisels, F. and White, L.J.T. (2016). Environmental issues in central Africa. *Annual Review in Environmental Resources*. 41: 1–33.

Alder, D. (1979). A Distance-Independent Tree Model for Exotic Conifer Plantations in East Africa. *Forest Science,* Vol.25, No.1. 59-71.

Berrocal, A., Baeza, J., Rodríguez, J., Espinosa, M. and Freer, J. (2004). Effect of tree age on variation of Pinus radiata D. Don chemical composition. *Journal of the Chilean Chemical Society*. 49: 251-256.

Boyden, S., Binkley, D. and Shepperd, W. (2005). Spatial and temporal patterns in structure, regeneration, and mortality of an old-growth ponderosa pine forest in the Colorado Front Range. *Forest Ecology and Management*. 219: 43-55.

Cheboiwo, J.K., Mugambe, R.O., Mbinga, J. and Mutiso, F. (2015). Potential Growth Yields and Socio-economic Benefits of Four Indigenous Species for Restoration of Moist Forests, Mau Kenya. *Journal of Environment and Earth Science* 5 (6):72-84.

Domec, J.C. and Gartner, B.L. (2003). Relationship between growth rates and xylem hydraulic characteristics in young, mature and old-growth ponderosa pine trees. *Plant, Cell & Environment*. 26: 471-483.

Ernst, C., Gullick, R. and Nixon, K. (2017). Conserving forests to protect water. *Opflow*. 40: 1-7.

FAO. (2003). Forestry Outlook Study for Africa. Regional Report – Opportunities and Challenges towards 2020. FAO Forestry Paper 141.

FAO. (2010). Global Forest Resources Assessment 2010 (FAO Forestry Paper 163) (Rome: Food and Agriculture Organization).

FAOSTAT. (2014). The FAO online statistical database for Forestry products. FAO, Rome.

Hess, P. (2008). Natural Resource Management Project (NRM) – Field Instruction for the Forest Plantation Inventory in Kenya. KFS/DFS/WB, Nairobi.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A. and Romijn, E. (2017). An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*. 12: p.044009.

Kagombe, J.K. and Gitonga, J. (2005) Plantation Establishment in Kenya: The Shamba System Case Study. Kenya Forestry Working Group., Nairobi.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z. and Cerdà, A. (2018). The superior effect of nature based solutions in land management for enhancing ecosystem services. *Science of the Total Environment*. 610: 997-1009.

Kenya Forest Service (KFS) (2009). A Guide to on-farm *Eucalyptus* Growing in Kenya. KFS. Pp 29.

Kenya Forest service (KFS) (2011). 2010/2011 Annual Report. KFS. Pp 76.
Kenya Forest Service (KFS) (2017). KFS Strategic Plan 2017 – 2022. KFS. Pp 68
Kenya National Bureau of Statistics (KNBS) (2010). *The 2009 Kenya Population and Housing Census*. Nairobi, KNBS.
Kirongo, B.B. (2000) Modelling Growth Responses of Juvenile Radiata Pine (*Pinus radiata* D. Don) Clones Subjected to Different Weed Competition Levels in Canterbury, New Zealand. PhD Thesis. University of Canterbury 2000.
Mathu, W. (2011). Forest Plantations and Woodlots in Kenya. African Forest Forum Working Paper Series Vol. 1 Issue 13. African Forest Forum, Nairobi.
Mathu, W.J.K. (1983) Growth, Yield and Silvicultural Management of Exotic Timber Species in Kenya. PhD Thesis. University of British Columbia 1983.
Ministry of Agriculture (MoA) (2006). Farm Management Handbook of Kenya Vol. II 2nd Edition. Part B Central Kenya, Subpart B2 Central Province. MoA & GTZ, Nairobi.
Ministry of Environment and Natural Resources (MENR) (1994). Kenya Forestry MasterPlan 1995-2020. MENR, Nairobi.
Mogoi, J., Obonyo, E., Ongugo, P., Oeba, V. and Mwangi, E. (2012). Communities, property rights and forest decentralisation in Kenya: Early lessons from participatory forestry management. *Conservation and Society*. 10: 182-194.
Mowrer, H.T. (1989). The Effect of Forest Simulation Model Complexity on Estimate Precision. In: H.E. Burkhart, H.M. Rauscher and K. Johan (Eds). *Artificial Intelligence and Growth Models for Forest Management Decisions*. Publications FWS-1-89, School of Forestry and Wildlife Resources, Virginia Polytechnic Institute and State University, Blacksburg, VA.
Mowrer, H.T. and Frayer, W.E. (1986). Variance propagation in growth and yield projections. *Canadian Journal of Forest Research – Revue Canadienne De Reserche Forestiere* 16:1196-1200. DOI:10.1139/x86 – 213.
Naughton-Treves, L., Holland, M.B. and Brandon, K. (2015). The role of protected areas in conserving biodiversity and sustaining local livelihoods. *Annual Review of Environmental Resources*. 30: 219-252.
Ngugi, M.R., Mason, E.G. and Whyte, G.D. (1998). New Growth Models for *Cupressus lusitanica* and *Pinus patula* in Kenya. *Journal of Tropical Forest Science* 12(3):524-541.
Pereira-Miguel, E., Rezende, A.V., Assis Leal, F., Trondoli Matricardi, E.A., Imana Ensinas, J.M. and Nunes Miranda, J.F. (2017a). Floristic, structural, and allometric equations to estimate arboreal volume and biomass in a cerradão site. *Semina: Ciências Agrárias*. 38: 45-52.
Pereira-Miguel, E., Rezende, A.V., Pereira, R.S., Brito de Azevedo, G., Menez Mota, F.C., Nogueira de Souza, Á. and Santos Joaquim, M. (2017b). Modeling and prediction of volume and aereal biomass of the tree vegetation in a Cerradão area of Central Brazil. *Interciencia*, 42: 34-43.
Pretzsch, H., Biber, P., Schultze, G. and Bielak, K. (2013). Change of forest stand dynamics in Europe. Facts from long-term observational plots and their relevance for forest ecology and management. *Forest Ecol. Manage.* (2013) *http://dx.doi.org/110.1016/j.foreco.2013.07.050*
Pukkala, T. and Pohjonen, V. (1993). Yield of *Cupressus lusitanica* in Ethiopia. East *African Agricultural and Forestry Journal*. 59: 57-73.
Siry, J.P., Cubbage, F.W. and Ahmed, M.R. (2005). Sustainable forest management: global trends and opportunities. *Forest policy and Economics*. 7: 551-561.
Smith, J.L. and Burkhart, H.E. (1984). A simulation study assessing the effect of sampling for predictor variable values on estimates of yield. *Canadian Journal of Forest Research* 14(3): 326 – 330.
Spiecker, H., Mielikainen, K., Kohl, M. and Skovsgaard, J.P. (1996). *Conclusions and Summary*. In: Spiecker, H., Mielikainen, K., Kohl, M. and Skovsgaard, J.P. (eds.) Growth trends in European forests – Studies from 12 countries. European Forest Institute Research Report 5. Springer-Verlag Berlin. 372p.
Stephens, S.L. and Gill, S.J. (2005). Forest structure and mortality in an old-growth Jeffrey pine-mixed conifer forest in north-western Mexico. *Forest Ecology and Management*. 205: 15-28.
Subasinghe, S.M.C.U.P. (2008) Growth models and their use in plantation forestry. Research Report. University of Sri Jayewardenepura, Sri Lanka.
Summit, E. (1992). Agenda 21. The United Nations programme for action from Rio.
Tennent, R.B. (1990). Forest Plantation and Management Planning Kenya: Growth Modelling, Volume and Taper Function Construction. MNR/FAO, Nairobi. 54p.
Teshome, T. and Petty, J.A. (2000). Site index equation for *Cupressus lusitanica* stands in Munessa forest, Ethiopia. *Forest Ecology and Management*. 126: 339-347.
Tewari, V.P. (2008) On the use of yield and growth models in forestry applications. Research Paper, Silviculture Division, Arid Forest Research Institute. Jodhpur.
Vanclay, J.K. (2009). A stand growth model for cypress pine. In: J.W. Leech, R.E. McMurtrie, P.W. West, R.D. Spencer and B.M. Spencer (eds) Modelling Trees, Stands and Forests. Proceedings of a Workshop in August 1985 at the University of Melbourne. School of Forestry, University of Melbourne, Bulletin No. 5. P. 310-332.

Varner, J.M. and Kush, J.S. (2004). Remanat old-growth longleaf pine (Pinus palustris Mill.) savannas and forests of the southeastern USA: Status and threats. *Natural Areas Journal*. 24: 141-149.

Vospernik, S. (2017). Possibilities and limitations of individual-tree growth models – A review on model evaluations. *Journal of Land Management, Food and Environment* Volume 68 Issue 2: 103-112.

Waldron, K., Ruel, J.C. and Gauthier, S. (2013). Forest structural attributes after windthrow and consequences of salvage logging. *Forest Ecology and Management*. 289: 28-37.

Wanene, A.G. and Wachiori, P. (1975). Technical Note No. 144. Variable Density Yield Tables for the Cypresses of the *Cupressus lusitanica* Group in Kenya. Forest Department, Nairobi.

Watt, M.S., Clinton, P.W., Coker, G., Davis, M.R., Simcock, R., Parfitt, R.L. and Dando, J. (2008). Modelling the influence of environment and stand characteristics on basic density and modulus of elasticity for young Pinus radiata and Cupressus lusitanica. Forest ecology and management, 255(3-4), pp.1023-1033.

Weiskittel, A.R., Hann, D.W., Kershaw, J.A. and Vanclay, J.K. (2011). Forest Growth and Yield Modelling, 2nd Ed. Wiley-Blackwell, Chicester.

Zar, J.H. (2010). Biostatistical Analysis, 5th Edition. Pearson Prentice Hall, New Jersey.