MODELLING GROWTH AND YIELD OF PLANTATION-GROWN *Cupressus lusitanica* AND *Pinus patula* IN CENTRAL REGION OF KENYA

BY

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DECLARATION

Declaration by the Candidate

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

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DEDICATION

This thesis is dedicated to my dear wife Alice, for her encouragement and perseverance.

ABSTRACT

In this study, forest inventory data as well as data from destructive sampling of *Cupressus lusitanica* and *Pinus patula* from Central Kenya was used to develop growth and yield models for the two species. The main aim of the study was to update the models currently in use thereby enhancing plantation forest management. Data from forest plantation inventory carried out by Kenya Forest Service between 2009 and 2011 was used to derive growth variable relationships. In addition, destructive sampling was carried out where trees were randomly selected from plantations of different ages in Kiambu and Nyandarua counties. Tree diameters were taken at butt end, 30cm, 60cm, 1m, 1.3m and subsequently at every 1m interval to the tip of the felled tree. This data was used to calculate volume of trees using the Smalian's formula which enabled comparing the performance of volume models currently in use with the volume models developed in this study for both species respectively. Goodness of fit of the models was determined by use of Coefficient of Determination, Root Mean Square Error and p-values. The study developed a set of growth models based on height against age, height against dbh as well as the dhb against age. Tree height and age showed exponential relationship of the form $H_t = b(Age)^c$, while the height and dbh was developed using models of the form $H_t = a + b(dbh)^c$ and dbh was related to the age by equation of the form $dbh = a(Age)^b$. The height and dbh of *P. patula* followed a linear trend of the form H = a + b(dbh). These results suggest that the new models and parameters were species specific. The relationship between the volume measured by Smalian's formula and dbh and height of *C. lusitanica* and *P. patula* was developed using third order differential equation. The predicted volume of the two tree species showed better model fit with measured volume than the models currently in use (RMSE = 0.0873 against 0.5065) for *C lusitanica* and (RMSE = 0.0902 against 0.4648) for *P.patula* respectively. The latter models overestimated volumes at extreme high or low values but underestimated most intermediate volumes for both species.

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ACRONYMS AND ABBREVIATIONS

AE	Agro-Ecological
^{0}C	Degrees Centigrade
CEC	Cation Exchange Capacity
DBH	Diameter at Breast Height
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
GPS	Global Positioning System
Ha	Hectare
KFMP	Kenya Forestry Master Plan
KEFRI	Kenya Forestry Research Institute
KFS	Kenya Forest Service
LH	Lower Humid
LM	Lower Medium
MAI	Mean Annual Increment
MENR	Ministry of Environment and Natural Resources, Kenya
MoA	Ministry of Agriculture, Kenya
PAMFA	Prince Albert Model Forest Association
PC	Point of Commencement
RMSE	Root Mean Square Error
SFM	Sustainable Forest Management
TA	Tropical Alpine
TSP	Temporary Sample Plots
UH	Upper Humid
UM	Upper Medium
UNCED	The United Nations Conference on Environment and Development
UTM	Universal Transverse Mercator

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CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Forests supply wood and non-wood products for human use (Bennett *et al*., 2018), water resources (Ernst *et al*., 2017) and enhance conservation of biological diversity (Naughton-Treves *et al*., 2015). 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, as well as for 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). Thus, the United Nations Conference on Environment and Development (UNCED) in 1992 on the Earth Summit in Rio de Janeiro, developed 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) to 160,000 ha (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 and *Vitex keniensis* (KFS 2011). The gazetted forest land is under the management of the Kenya government through the Kenya Forest Service.

By the year 2011, available statistics indicated that 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).

Plantation forestry was introduced in Kenya in the early 1900s as a means of providing wood for various uses through short rotations since the indigenous forests were believed to have long rotations. Eucalyptus species was the first to be introduced in the country in the early years of the 20th century with an aim of providing wood to fuel the railway steam engines after the completion of the construction of the Kenya - Uganda railway line. *C. lusitanica* was introduced 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. *P. patula* was introduced in the country in the 1940's but only extensively planted in the 1950's and 1960's to replace *Pinus radiata* D. Don which had been attacked by *Dothistroma* Blight (Mathu 1983). The latter two species are primarily used to supply saw-wood to privately owned forest industries in Kenya up to now.

Forests play a crucial role in the livelihood of people in Kenya. They provide building materials for the population, are a source of food for others, and provide employment opportunities in forest-based industries, among other direct uses. The forests are also a source of water, they help stabilize the soil and hold the crucial biodiversity that is so crucial to human life. Often, it is hard to put monetary value to forests in general, but it is easy to at least quantify in monetary terms some forest products extracted from a given forest. For some time now, it has been hard to quantify the value of our forests or quantify their contribution to the national economy, especially during the timber harvesting ban imposed in 1999. However, it is estimated that before the ban, the forestry sector in Kenya contributed approximately KShs. 320 million annually to the country's Gross Domestic Product (GDP), which is approximately 1% of the monetary economy and 13% of the non-monetary economy (Mathu, 2011).

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 land 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 the required forest products at the required rate, sustainable forest management is imperative. This means production and use of the forest products in perpetuity such that enough is produced for the present without compromising the potential for future production.

To attain this kind of management, it is necessary to accurately quantify the amount of resources available against the demand at a given time and the rate of production of the same resources (Siry et al., 2005). This helps in planning for extraction and general management of the resource (in this case timber resource). In the past, use of local volume tables to estimate the volume of a given forest was the norm. The volume tables were developed for particular areas while using a given set of the prevailing levels of tree growth factors at the time of their development. The tables were only accurate for the plantation used to develop them and only as long as the prevailing level of tree growth factors persisted. The tables were cumbersome and were much generalised. The data for development of these yield tables was obtained from forest inventories, which needed to be carried out now and then to update the tables. Typically, forests cover large areas and it is often difficult to survey them entirely in a short period of time. This then calls for efficient tools to capture data and estimate the parameters with the ever-limited resources.

With the advent of recent technological innovation, a more accurate, less cumbersome and easier to use method has been developed. This involves development of forest growth and yield models which give the rate of growth of the trees as well as the amount of a given tree product expected at a given time in the life of the plantation. These are important for sound decision making in forest management.

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.

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1.2 Statement of the problem

In Kenya, estimation of wood yield for *C. lusitanica* and *P. patula* is currently based on Technical Note No. 143 (Provisional Yield Table for *Pinus patula* grown in Kenya), and Technical Note No. 144 (Variable Density Yield Tables for the Cypresses of the *Cupressus lusitanica* Group in Kenya) which are used to estimate stumpage volume of tree plantations of these species (Alder, 1979; Mathu, 2011). They have not been revised since their development in 1975. Attempts at validating the models in the past (Ngugi *et al*., 1998; Tennent, 1990) indicate large disparities in their yield estimation. Changes in climatic conditions since 1975 may have influenced the growth rates of trees therefore rendering the models less accurate in estimating the volumes. Further, there have been changes in the forest management regimes resulting in changes in tree growth dynamics hence making the old models less accurate tools for estimating the volumes of the current crop. Further, the yield tables cannot be used to predict growth and yield of the plantations and therefore are inadequate for forest management decisions.

1.3 Justification of the study

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 balance or deficit, and by implication, any interventions would be based on faulty data. The current equations used to calculate stumpage volume are not region or site specific and are just general equations for the whole country. There is need to develop region-specific models for all the different forest plantations regions in the country, which would consider the unique growth factors found in different regions including climatic and edaphic factors. This is in a bid to improve the predictive power of the models and improve accuracy in volume estimation. All the above factors make it necessary to develop new growth and yield models for Kenya's forests.

1.4 Objectives of the study

1.4.1 Main objective

To develop region-specific models for accurate determination of stand volumes and proper prediction of tree growth in *Cupressus lusitanica* and *Pinus patula* plantations in Central Kenya.

1.4.2 Specific objectives

i. To develop *Cupressus lusitanica* growth and yield models for use in forest plantations in the Central region of Kenya.
ii. To develop *Pinus patula* growth and yield models for use in forest plantations in Central regions of Kenya.
iii. To compare the performance and accuracy of developed models with those currently in use by Kenya Forest Service.

1.5 Hypotheses

H_{01}: The current growth and yield models for *Cupressus lusitanica* accurately estimate the volume of current crop.

H_{02}: The current growth and yield models for *Pinus patula* accurately estimate the volume of current crop.

H_{03}: The current models give accurate growth and yield predictions.

CHAPTER TWO

LITERATURE REVIEW

2.1 Importance of forest growth and yield models

Forests play a crucial role in the livelihood of people and their ecosystem. They provide tangible benefits such as wood, fodder, timber for construction, food, water and non-wood forest products for domestic or commercial use. They also provide intangible and value benefits to people living near or interacting with them. For these forests to continuously provide for the needs of the people, it is necessary to manage them sustainably (Alvalez-Gonzalez *et al*., 2013).

Sustainable Forest Management (SFM) means managing the forest in order to provide for the needs of the present generation without compromising their potential to provide the same resources for the future generations. However, there is a modern paradigm of multifunctional silviculture as reflected in the Helsinki Resolution (H1) of 1993 which defines SFM as "The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions at local, national and global levels, and that does not cause damage to other ecosystems" (Pretzsch, 2009).

To achieve sustainable management, certain management tools are needed. In the case of wood production, it is important to know the amount, type, quality and general status of wood in each forest estate at any one time. It is also necessary to know the rate of growth of the available wood to understand when it will be ready for harvest and what amount will be available. As Bi (1994), Mabruvira & Miina (2001), Tickle *et al*. (2001), Yahya *et al*. (2012) and Westfall *et al.* (2004) observed, prediction of growth and yield is the foundation of effective forest management planning and decision making. According to PAMFA (1994), understanding of growth and yield is crucial for formulating long-term strategies for forest management. Knowledge of growth allows the forest manager to link rates of harvest to volume increment, hence ensuring the product sustainability. Knowledge in yield is crucial for the forest manager to link harvest rates to sawmill requirements and by large, the general resource demand allowing volumes, species mix and product sizes to be forecasted.

Growth and yield models, which rely on functions derived from measurement data from a sample of the forest population of interest, are the tools that have mainly been used to provide decision-support information that meets basic operational needs for evaluating various forest management scenarios (Muller-Landau *et al*., 2006). The need for specific information for forest managers and planners are one of the reasons for the increase of the demand for forest models. They are used for operational and strategic planning in nations that own and manage forest lands. Modeling is also good for decision making regarding buying, selling, and trading in forest resources. Inventories taken at one instant in time provide information on current wood volumes and related statistics (Kikuzawa *et al*., 2016). The allometric relationship between tree diameter and total tree height is commonly used to estimate tree volume and thus is a fundamental component of many growth and yield, functional, and forest planning models (Condit *et al*., 2016).

2.2 Growth models

A model is an abstraction or a simplified representation, of an aspect of reality. However, it should not be confused with the normal meaning of the word - something worthy of being imitated or emulated. People often use models unconsciously, for example by making mental models to conceptualize cause-effect relationships to help explain and predict the behaviour of systems. Models may be in verbal (for example a description) or material forms (for example a scale model). A mathematical model uses mathematical language which is more concise and direct than natural language. Computers have become useful tools to assist in modelling though they are not central to the modelling process. A good model makes a good representation, and the computer is just a convenient tool to realize this. García (1994) likened "computer modelling" to "typewriter poetry".

A mathematical model consists of sets of equations and or graphs illustrating the quantitative relationships between variables. The model fitting process may be statistical, for example using linear regression, or subjective by drawing lines through data plotted on graphs. The types of curves drawn, or the equations fitted may be premised on the natural law of growth, or it may be empirical. In the latter case, the function or equation is chosen purely for its ability to represent a given shape.

2.3 Components of a Growth Model

The more detailed approaches of forest stand modelling are not based on the overall growth of a forest stand but need to discriminate several growth components in order to model these processes effectively. The nature of the components distinguished depends upon the forest type and the approach used. In mixed forests, especially naturally regenerated, an obvious requirement is to discriminate individual species or several species groups. Mortality and recruitment may frequently be ignored in models for intensively managed plantations. However, in many natural forests, these form an important aspect of the stand dynamics, and may have considerable influence on volume yield of the stand. In addition, the components identified in whole stand models tend to differ from those of single-tree models.

In size class and single-tree models, the components usually considered are diameter (or basal area) increment, mortality and recruitment. Diameter increment is a simple concept and is relatively easy to measure and to predict. Forecasts of mortality must not only estimate the number of trees, but also the species and sizes of trees dying. Another aspect of change to be modelled is the deterioration of merchantable stems, which can be modelled in the same way as mortality. Recruitment may be predicted as ingrowth of trees reaching breast height, but some models may simulate seedlings from germination, while other models may adopt a larger threshold size such as 10 cm diameter.

Modelling growth and yield is an intrinsic part of active forestry research (Porte & Bartelink, 2002). Forest growth models are very useful tools for updating inventories, evaluating silvicultural treatments, harvest scheduling, and management planning (Amaro *et al*. 2003). With access to the computational facilities and input data, forest growth models may be developed either at stand level or at individual tree level, depending on management objectives (Porte & Bartelink 2002). Stand growth can be modelled on the basis of stand variables such as site index, stand age, stand diameter (for example quadratic mean diameter) stand basal area, stand density index, and number of stems per unit area (Pienaar, Rheney 1995; Huuskonen, Miina 2007; Gizachew, Brunner 2011). Since stand growth models do not describe the growth dynamics of individual trees, they are usually applicable to even aged and homogeneous stands. The individual tree growth models describe the growth dynamics of individual trees in a stand. The growth of an individual tree within a stand varies due to competition from other trees. Competitive stress to any tree within a stand varies with species, number, size and location of its competitors. The individual tree growth models are useful in describing growth dynamics for structurally complex and heterogeneous stands (Pretzsch, Zenner 2017; Uzoh, Oliver 2006; Bollandsås, Næsset 2009). In these models, the potential growth of individual trees is reduced by competition index, which is either distance dependent (Biging, Dobbertin 1992; Lebermann, Stage 2001; Rivas *et al*. 2005) or distance independent (Uzoh, Oliver 2006; Bollandsås, Næsset 2009). Growth series data taken over a long time in longitudinal or radial growth of individual trees are needed to develop individual tree growth models. Such data are obtained either from long-term research plots or one-time national forest inventory or from stem form analysis.

The individual tree radial growth models (diameter or basal area) are useful to estimate volume growth where information on height growth is available. The individual tree radial growth models are mostly used as sub-models in growth simulation models (Sterba, Monserud 1997; Pretzsch 2002; Hasenauer *et al*. 2006; Lacerte *et al*. 2006; Gobakken *et al*. 2008). These growth models present a good opportunity for examining detailed management alternatives, because they adequately describe the forest growth dynamics (Uzoh, Oliver 2008; Subedi, Sharma 2011; Wagle, Sharma 2012). Basal area growth models are preferred to diameter growth models because basal area growth has a high correlation with volume growth, (Schröder *et al*. 2002; Andreassen, Tomter 2003; Anta *et al*. 2006). As a result, most silvicultural considerations, for example, thinning intensities, are based on the quantification of basal area growth. Further, the curves of mean basal area growth form useful tools to help in estimating the timing of intermediate and final cuts (Hong-gang *et al*. 2007). Basal area possesses a high degree of exactness on measurement and prediction as compared to stand attributes such as mean diameter, mean height, and mean crown diameter. Therefore, use basal area is important and applies to a wide range of conditions (Hong-gang *et al*. 2007).

Management decisions are made based on current and future conditions (Peng 2000). The main objective of forest management is to actualize an ecologically and economically sound future stand based on the present stand. Growth and yield models should adequately describe the present stand and estimate the future conditions for the same stand. Since a model is an “abstract or simplified representation of some aspect of reality”, Vanclay (1994) observes that a model that represents certain key characteristics or behaviors of a system can be used to show the resulting real effects of alternative conditions and courses, on the same system (predicting into the future). Different approaches of models are available in forestry. First, yield tables assume a specific form of silvicultural practices and constant growth conditions throughout the rotation period. Thus, yield tables assume long growth periods and changes in growth conditions are not considered (Hasenauer 1994). However, due to changes in technique, silviculture and management, dynamic models are required to give the true picture. Dynamic models also enable reaction to change in growth conditions due to pest, disease, fire outbreaks or climate change. Furthermore, it is possible find the optimized age at which to cut down a tree or stand when an economic model is added (Loisel and Dhote 2011). The integration of different models in computer-based packages leads to complex and dynamic growth simulations. Vanclay (1994) categorizes models into the following based on their level of detail: whole stand models - simple and robust but may involve complex details not possible in other categories; no details about individual trees in the stand. Size class models - compromise between whole stand models and single tree models. Single-tree models - the individual tree is used as the basic unit of modeling.

Single-tree growth models are quite useful for research and management decisions. All values are calculated for the single tree and then a summary for the stand is calculated. This makes it possible to combine different tree species and/or different age classes inside one area (Hasenauer 1994).

2.4 Development of growth and yield modelling

According to Pretzsch, 2009, the oldest models of forest science and management were yield tables for homogenous stands developed over 250 years ago. The stand parameters used then were stem number, mean height, mean diameter, basal area, form factor, mean annual increment, cumulative annual increment, and total production in tabular form in 5-year intervals for different site indices. With the advent of improved computerisation technology, the yield tables evolved to more complex individual tree models and uneven aged stand models to the present eco-physiological process models (Pretzsch, 2009). Growth and yield models are generally divided into stand models and individual tree models. The difference between the two is the type of information needed to develop the models and the detail of output they produce (Dale and Hilt, n.d.). In between the above two, the stand class models may be found (Vanclay, 1995). This classification uses the level of resolution of the models. Growth and yield models can also be divided into empirical or mechanistic developed with the interest of tree growth theory; deterministic that estimate the expected amount of growth of a tree or stand given certain initial characteristics or stochastic that attempt to account for natural variation of tree growth; and spatially dependent or independent (Vanclay, 1994; Higgins, 2011). The type of model chosen will depend on the purpose for which the model is being developed and the type of information used to develop it. For example, empirically based models are based on rather limited input and output variables. However, they allow useful predictions for those forest managers who are closely involved in managing forests primarily for wood production (Pretzsch, 2009).

Yield prediction systems, or models, estimate the timber yield from a stand, given information on initial stand conditions. Growth and yield prediction systems have different complexity ranges. For example, both the simple graphical volume-age curve and the comparatively complex computerized stand growth model are growth and yield prediction systems. Growth and yield predictions are useful in updating forest inventories, inform forest management planning, evaluate stand management opportunities, and interrogate the impact of pests, diseases and fire on timber yield. Dimensional growth in terms of diameter and height is one of the three constituents of an individual tree model and is subject to complex interactions (Andreassen and Tomter, 2003; Soares and Tomé, 2002). It is influenced by growth vigor, past growth conditions, microenvironment, genetic traits and competitive status (Tomé and Burkhart, 1989). In models at the level of the individual tree, growth is often estimated via the potential growth function or growth equations (Davis *et al*., 2005), in which growth is obtained by multiplying potential growth by a modifier function (fm) (Soares and Tomé, 2002). Potential growth describes the maximum possible growth that a tree can attain, whereas modifier function describes the decrease in growth potential due to competition, among other factors (Kiernan *et al*., 2008). In contrast, growth equations use tree attributes such as tree size, competition indices, crown ratio, vigor; stand attributes such as age, site index, stand basal area and site characteristics as predictor variables, all combined in a single equation (Uzoh and Oliver, 2006). A number of equations are used to estimate growth. These include; linear or polynomial equations (Kiernan *et al*., 2008), the Bertalanffy equation

(Vanclay, 1994), the Richards equation (Amaro et al., 1998), the Gompertz equation, the logistic equation, the exponential equation (Zeide, 1993) as well as nonlinear functions (Zhang et al., 2004). However, it has not been proven that modifier functions are superior to growth equations. Many studies have been conducted on model growth in diameter and height at the individual tree level in forests in the USA and Europe (Biging and Dobbertin, 1992; Lynch and Murphy, 1995; Tomé and Burkhart, 1989; Vospernik *et al*., 2010).

It is important to quantify and predict tree growth because it has a direct relation to productivity and dynamics of forest stands. Furthermore, tree growth rate is an important dynamic parameter, as well as mortality and recruitment rates (Condit *et al*., 2016). Among various measurements of tree growth, diameter of tree stem has been most widely monitored because of the ease and accuracy of the measurement compared to tree height. There are several theoretical models to express stem diameter growth of individual tree. One of the simplest is a model based on the metabolic scaling theory. Enquist *et al*. (2009) predicted that stem diameter growth rate scales to the $^{1}/_{3}$ power of the diameter. This prediction was deduced from the assumption that growth rate of tree biomass is proportional to its gross photosynthetic rate, which in turn is determined by leaf biomass. This assumption means that both small and large trees have the same resource availability per unit leaf biomass. However, resource availability may depend on tree size. In a closed forest stand, light is a limited resource and tree growth is governed mainly by light conditions (Purves and Pacala, 2008; King, 2010; Kikuzawa *et al*., 2016). Availability and competition for light is size-dependent and asymmetric (Yokozawa and Hara, 2005; Muller-Landau et al., 2006; Weiner, 2015). Larger trees have an advantage over smaller trees, since the former shade the latter but the latter rarely do so (Kikuzawa and Umeki, 1996). In some extreme cases, competition is one-sided: larger trees suppress the growth of smaller trees but not vice versa (Kikuzawa, 1999; Weiner, 2015; Hara, 2017). However, such modelling is common in development of biomass models.

The accuracy and the model's usefulness depend on the quality of the data used to develop the model (Vanclay, 1994). This then calls for one to ensure that, the available data is appropriate for the particular model. In order to obtain data, sample plots and stem analysis of felled sample trees are used to obtain data for growth models. Different sample plot networks are used depending on circumstances, including; 1. Sample plots for resource inventory – Where the design is based on temporary plots; 2. Continuous forest inventory using permanent plots – The inventory is usually aimed at assessing the extent, condition and sustainable development of forests at national of regional level in a timely and accurate manner; 3. Sample plots from field experiments – These are usually trial plots e.g. thinning, pruning, spacing trial plots; 4. Permanent Sample Plots (PSPs) networks – These are established and maintained as sample plots used for data collection over time. (Bravo *et al*., 2011; Alvalez-Gonzalez *et al*., 2013).

According to PAMFA (1996), the ideal data for growth and yield modelling includes a complete set of chronological data of the forest area from establishment to harvest. In cases where PSP data is not available, temporary sample plots (TSPs), covering a wide area of sites and ages in the area being modelled are established to provide data for growth and yield modelling.

Growth models are of limited use on their own and require ancillary data to provide useful information. With suitable inventory and other resource data, growth models provide a reliable way to examine silvicultural and harvesting options, to determine the sustainable timber yield, and examine the impacts of forest management and harvesting on other values of the forest. Forest managers may require information on the present status of the resource (e.g. numbers of trees by species and sizes for selected strata), forecasts of the nature and timing of future harvests, and estimates of the maximum sustainable harvest. This information can be compiled from three sources: **1**. area estimates of the existing forest, **2**. stand level inventory of the present forest, and **3**. growth and harvesting models based on dynamic inventory data.

Growth and yield models are important for predicting temporal and future growth of forest stands. In forestry, it is important to make accurate future predictions of the mean values of growth variables based on repeated measurements through time. In many forest jurisdictions, forest management decisions are based on yield projections of plot level averages of tree height, basal area, and other morphometric variables (Hall and Bailey, 2001). Diameter at breast height (DBH) and tree height are fundamental parameters for both developing and applying growth and yield models. Measurement of tree variables and gathering of other data form some of the challenges in model development. DBH of a tree can be measured quickly, easily, and more accurately, but the estimation of tree height is relatively complex, time consuming and requires great care (Sharma and Parton, 2007). In some instances, especially in tropical forests, site conditions and tree composition may prevent accurate height measurements on all trees measured for DBH as it may not be possible to observe the top tip a given tree unhindered or access an appropriate vantage point. Therefore, in many instances, DBH is conventionally measured for all trees sampled, but height is taken for only a small sample of trees selected across the range of observed diameters (Huang et al., 1994). Height-diameter relationship models developed from the collected data are then used to estimate the heights of trees for which only diameter was measured within the plot. A number of height-diameter models have been developed using only DBH as a predictor variable for estimating total or merchantable tree height (Fang and Bailey, 1998; Jiang and Li, 2010; Ahmadi et al., 2013). However, the relationship between the diameter and its height varies among stands (Calama and Montero, 2004) and depends on the growing environment and stand conditions (Sharma and Zhang, 2007; Bermejo et al., 2014).

In designing a model, it is important to understand how the model will be applied and the principles influencing the system being modelled. There is need to keep the model simple and apply the principle of parsimony which emphasizes that unnecessary variables and parameters should not be included in the model (Vanclay, 1994; O'Hehir,2001). This will, among other things, ensure acceptance by practitioners and ease of use. After models are designed, simple construction methods are used either singly or in combination depending on the need and available construction tools and knowledge. Such simple methods include graphical techniques, expert models and use of statistical methods for parameter estimation. Graphical methods enable fitting of regression lines while statistical methods enable statistical hypothesis testing and assessment of bias and precision. Regression and Ordinary Least Squares methods are widely used statistical methods (O'Hehir, 2001). Often, it becomes necessary to place constraints to model parameters to improve the model once it is constructed. This often requires knowledge of the system being modelled, such that the parameters are constrained within a given range of values which are biologically sound (Kozak *et al*., 1969; Tang *et al*., 2016; O'Hehir, 2001).

To ensure the validity and usefulness of developed models, O'Hehir (2001) notes that the residuals are assumed to: have a homoscedastic variance (they have a constant variance which is independent of the magnitude of both dependent and independent variable), be normally distributed with mean of zero, be uncorrelated; and that the independent variable is error free and there is a linear relationship between the dependent and independent variables. Homoscedasticity is first inspected by residual plots. In tree measurements, there is a tendency of the variance of residuals to increase with increase in data magnitude. Kolmogorov-Smirnov statistic is used to test for normal distribution of residuals though cumulative frequency bar charts can help in initial examination of the residual distribution. In cases where PSP's data is used, there is likely to be correlation of residuals due to repeated measurements of the same trees in time series. This makes the efficiency of the least squares estimates to be reduced because of bias in standard error estimates. There is need to spend time and resources in training data collection crew to ensure the measurements taken are as accurate as possible in order to produce error free independent variables. In order to statistically evaluate models where one is faced with making a choice between models, Vospernik (2017) proposes comparing observations and prediction of individual equations. Measures that are usually used in this comparison include; bias, precision, root mean square error (RMSE), and efficiency. Bias is described as the expected deviation of the prediction function from the truth and is the mean of differences between model predictions and the observations. The precision of a model is its prediction variance and the RSMSE is the model's prediction variance plus bias squared. Model efficiency was proposed by Loague and Green (1991) and it tests whether the model's predictions are better than the mean of the observed values where an efficiency of one indicates a perfect model; zero denotes a mean of observed values which is as good as the model predictor, and a negative efficiency means that the model is inefficient as its explanatory power is less than the mean of observed values.

2.5 Models development in Kenya

In the colonial days in Kenya, as in other colonies in Africa e.g. Angola, volume tables and other management concepts adopted from other countries were used to estimate growth and yield of the forest exotic plantations (Delgado-Matas 2010). Several attempts have been made since then to develop yield equations for forest plantations. Wright (1965) developed tree volume equations for the three most commonly planted exotic tree species in Kenyan forests, namely *Cupressus lusitanica* Mill., *Pinus patula* Schlecht and *Pinus radiata* D. Don. The equations thus developed compute total overbark volume of the tree and a reduction factor was also developed to reduce the volume to merchantable levels of 15 and 20 cm top diameter limits for the three tree species. The equations were not applicable to situations of varying tree stocking due to different thinning intensities.

Wanene (1975) and Wanene & Wachiuri (1975) developed variable density yield tables for *P. patula,* and C. *lusitanica* respectively and published as Technical Note 143 and 144 by the then Kenya Forest Department and adopted for planning of management of exotic species plantations in Kenya. The yield tables are in use to date to calculate stumpage volume at clear-fell and thinning. The tables have also been used for estimating yield of these tree species under varying conditions of stand densities, which was a considerable improvement over the yield tables produced previously. Gor-Kesiah (1978) studied volume and taper of *P.patula* and C. *lusitanica* trees grown in Kenyan forest plantations. All the data were collected from Elburgon forest area and based on 120 and 165 trees of *P. patula* and C. *lusitanica* respectively.

He compared volumes obtained from his models with the one obtained from traditional methods of volume measurement of felled trees. Of the popular volume models tested, the logarithmic volume equation was found to give better volume estimates. Regressions provided volume of trees at different utilization limits and he concluded that there is a strong relationship between DBH and diameters at any given height above the DBH. The total volume given by the models was found to approximate Smalian’s formula. Mathu (1977) improved on the methodology used by Wanene and Wachiuri by incorporating a growth function which was based on the rate of change of the stand basal area using C. *lusitanica* as the test crop. The study finding was meant to guide the Kenya Forest Department in its silvicultural programme, particularly thinning, to increase volume of harvested wood in forest areas.

In a further study, Mathu (1983) investigated yield of *C. lusitanica, P. patula and P. radiata* in overstocked and understocked stands in different sites of the country. He used data obtained from permanent sample plots established in 1964 to monitor growth of the three tree species. He called his models "EXOTICS". He observed that the most promising thinning regimes are those with thinning intensities of 20 and 30% (thinning intensity refers to the percentage of basal area removed to the basal area before thinning). These thinning intensities resulted in higher mean annual increment and low culmination ages. Merchantable volume could be increased by between 5 and 10% using 20% thinning intensity, depending on site. He also examined the effect of stocking levels of 1,000, 1,200, 1,400, and 1,600 stems per hectare in respect to *P. patula* grown up to age 15 years in both "shamba" and grassland sites. He also reported that overall volume yield increased with increase in stocking level in all sites and that culmination age for *C lusitanica* in respect to mean annual increment (MAI) decreased from 30 to 19 years for site index 12 and 24 respectively with corresponding MAI of 16 and 28.1 nr/ha for site index 12 and 24.

A single tree yield prediction model referred to as "VYTL-2". was developed by Alder (1977) using *C. lusitanica, P. patula, and P. radiata.* The model dealt with diameter distribution for the different site indices (measured by dominant tree heights). Growth was for diameter classes rather than individual trees. The output from the model ranged from 40% underestimate to 20% overestimate of the total volume yield. The model was capable of simulating different thinning treatments and hence making it useful in yield manipulation through thinning regimes. He developed a non-linear equation to estimate maximum basal area in m^2/ha from hand-drawn curves for *C. lusitanica*. the most commonly planted exotic tree species in forest plantations. Ngugi also developed growth and yield models for *Cupressus lusitanica* and *Pinus patula* for use in Kenya’s forest plantations (Ngugi *et al*., 1998).

A serious attempt to review the growth and yield models for the country was made through the development of Kenya Forest Master Plan (KFMP) in the period between 1990 and 1994. The National Forest Inventory Project assessed plantation resources, developed growth and yield models for plantation species (Tennent, 1990). However, the recommendations of the KFMP were never implemented (FAO, 2010)

Since the development of the above models, little has happened in this area. Mathu, (2011) attributes this scenario to the change in emphasis towards “agroforestry, conservation and rural afforestation aspects (away from plantation management) in forest curricula in most forestry institutions; the disruption in forest management (limited planting, thinning and pruning in most areas) arising from the ban in forest harvesting; and the reduced emphasis on silvicultural/forest management research due to shortage of financial resources” which is well demonstrated by “neglect and resulting degradation” of the permanent sample plots (PSPs) which existed by then (and were used to make all the models and studies referred above), but are no longer there. Establishment of permanent sample plots started in 1964 to monitor the growth of the first rotation crop and provide data for yield prediction. Some of the data collected until 1974 have been previously used for subsequent yield analyses (Wanene and Wachiori 1975, Alder 1977, Mathu and Philip 1979). However, more data for the later stages of stand growth were collected until 1985, necessitating development of more comprehensive growth and yield models. Tennent (1990) developed growth models from the entire data set and fitted single multivariate equations for each species for the whole of Kenya. The equations were characterized by poor fit for the data set and errors associated with the use of derived variables as predictor variables were found to be propagated as projections were made using the equations. Further, these equations failed to characterize growth differences between regions. As a result, yields of some regions have been found to be overestimated and others underestimated. The consequences of this problem have been most critical when establishing sustainable levels of wood supply and preparation of felling plans (Ngugi *et al*., 1998).

Indufor Oy (2011) also noted that among other weaknesses of the Kenya Forest Service (KFS) in monitoring forest management was lack of permanent sample plots for monitoring forest growth and yield. The same author noted that KFS lacked adequate information on the status of forest resources in terms of quality, quantity and trends in growth and yield necessary for informed decision making in forest management.

The 1999 ban on timber harvesting in public forests affected silvicultural operations. As a result, plantations of poor health, often over-aged are a common sight in the forest. The thinning backlog was over 8,000ha by 2008. The ban also led to high market price of timber, which led to illegal poaching of timber in public forests which led to low stocking in these forests. This, combined with lack of timely maintenance and treatment, predisposed the plantations to other hazards like game damage, fires and diseases, leading to plantations of poor quality and health (Mathu, 2011; Wasike. 2010). The ban also led to accumulation of 38,000 ha of over-mature and mature plantations by 2010, with an estimated value of KSh. 36 billion and an approximately 18,000 ha of softwood plantations between the ages of 10 and 22 years due for commercial thinning with wood materials from thinning worth over KSh. 3.5 billion. (Wasike 2010; Makhanu 2010).

2.6 Need to update growth and yield models

Although no study is available on the changes in soil fertility through several rotations of forest plantations in Kenya, there is evidence of decrease in yield of *P. radiata* in successive rotations in Southern Australia (Keeves, 1966 as reported by Mathu, 2011); and *P. patula* in Swaziland (Evans, 1975 as reported by Mathu, 2011). This resulted from removal of large amounts of mineral nutrients in harvests. Other changes to the soil productivity may be as a result of soil degrading processes like soil erosion after clearfell and before canopy closure of successive crop (Evans, 2000).

Stiebert *et al*. (2012) reported that like anywhere else in the world, Kenya’s forests are vulnerable to climate change which is expected to have affected the composition, growth rates and regenerative capacity of the forests over time. In Europe, there have been reports of evidence of increased growth rates of Oak (Pretzsch *et al*., 2013); other species (e.g. Spiecker *et al*., 1996; Battles *et al*., 2008; Ciais *et al*., 2008; Kahle *et al*., 2008 Luyssaert *et al*., 2010 as reported by Etzold *et al*., 2013), Pretzsch *et al*., 2018 and Charru *et al*., 2017. This is attributed generally to rising level of CO_2 and Nitrogen deposition (Pretzsch, 2013; Etzold *et al*., 2013). However, increased Ozone levels and Sulphate deposition, nitrogen saturation (Nellman and Thomsen, 2001 as reported in Etzold *et a*l., 2013) are expected to have a negative impact on forest health which could offset a further increase in forest productivity. This makes it very likely that there has been a change in growth rate of plantation trees since 1975 when the current yield tables were made. And as Pretzsch (2009) reports, changes in environmental conditions quickly outdate yield tables and static models which assume constant site conditions.

Research conducted by the Kenya Forestry Research Institute (KEFRI) in Uplands forest in Kiambu District showed that plantations established through the *Shamba* system had the highest growth rates as compared to slashing, and spot hoeing. In this experiment, the mean diameter at breast height (dbh) at 3 years of age was 1.9cm when no land preparation was done, 2.1cm where slashing of weeds only was carried out, 2.6cm where spot hoeing (1m diameter) around the planted seedling was done and 4.7cm where *Shamba* System (complete cultivation) was used as land preparation method (Kagombe and Gitonga, 2005). Though the cost of plantation establishment was highest under the *Shamba* system, the Forest Department saved on labour since tending was done by the cultivators as they tended their crops. It has been estimated that over 80 percent of plantations established in the 1980’s during the *Shamba* system suspension failed to establish due to weed competition (Sedjor 2005)

An earlier research at Muguga, Kenya on *Grevillea robusta* growth rate had shown that the trees performed better in both height and diameter, and hence bole volume under the *Taungya* system as compared to clearing in plantation situation (Kiriinya, 1994). Mathu (1983) also noted that height growth was significantly lower in plantations established on grasslands than those established on *shambas* for both *C. lusitanica* and *P. patula*.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

3.1.1 Background, location and size

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 is composed 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 as shown in Figure 3.1.

3.1.2 Climate

The temperature of the region 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 Nyandarua Range (Aberdare Ranges) accumulates in depressions and flat areas like the Kinangop Plateau and decreases the mean minimum temperature to 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.

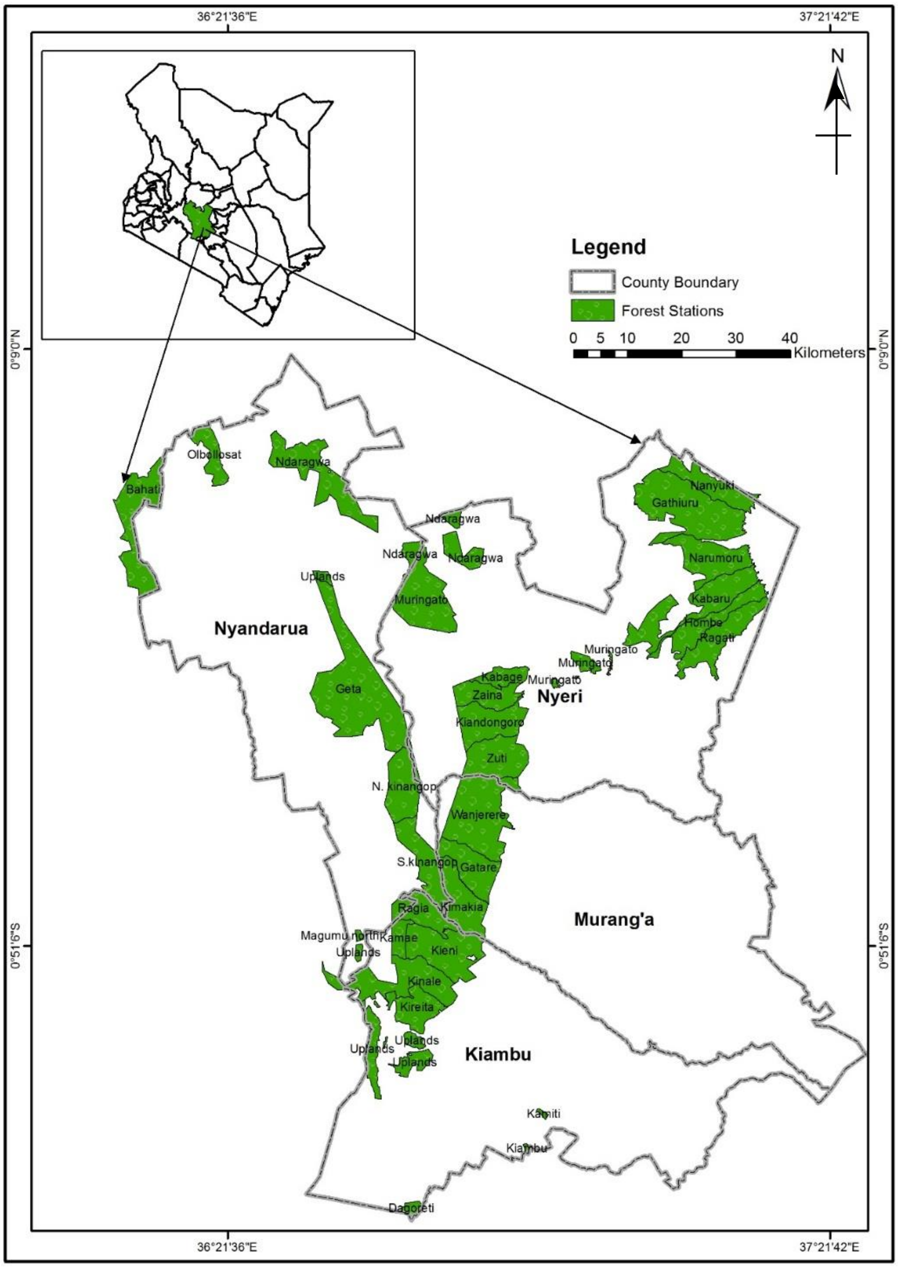

Figure 3.1**:** Gazetted Forest Area in Central Kenya (Courtesy: KFS)

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 in descending order in the eastward direction (MoA, 2006). However, the mean annual rainfall in the forest area is 1800 mm.

3.1.3 Soils

The soils in Central region of Kenya are variable. The lower southern and south-eastern region is 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 each mountain respectively. 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). These are some of the areas where forest plantations are located. On the Western side of the Aberdare Range, the soil changes to Planosols on the Kinangop Plateau; a high plateau just next to the ranges.

Higher from the above region 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.

3.2 Experimental Design

3.2.1 Forest Inventory Data

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

According to Hess (2008), the main goal of the inventory was to gather reliable information on species and age distribution, diameter distribution, basal areas in compartments and sub-compartments, stocking volume, estimation of damage classes and allocation of merchantable timber. It also aimed at getting the impression of the total annual timber increment and use this data for forest management decisions especially in managing the effects of the shortcomings of the management issues encountered during the moratorium.

As stipulated in 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, which corresponded with each intersection of the grid lines. The coordinates of each sampling point were also determined on the map and recorded. To get to the first sample point on the ground, a point of commencement (PC) was identified on the map, and its UTM coordinates recorded. The PC was then located on the ground using the GPS set and marked with a peg. The line from the PC to the nearest sample point formed the line of access. The length of this line was measured using a measuring tape and its bearing taken using a compass, to the first sample point. The compass and measuring tape were then used to locate the next sample point from the first, and so on according to their positions on the map.

At each sampling point, the centre was marked by driving a painted wooden peg in to the ground. Circular plots were established around the sample point whose radius differed depending on the tree density of the sub-compartment. There were two plot sizes used for all sub-compartments which were 10 years and over. First, circular plot with a radius of 11.28m was used where 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 and no thinning records were available. Secondly, a circular plot with a radius of 7.98m was used where 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 diameter of 7.98m 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 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 which was also used for slope measurement in every sampling point. It was taken in the direction of maximum slope at a distance of 15 metres uphill and downhill, and the average of the two readings calculated and recorded. The slope percentage of each sample plot was used to determine the slope distance to be used in the measurement of the tree heights. For the purpose of this study, data from a total of 94 plantations of *C. lusitanica* (3154 individual trees) and 51 of *P. patula* (1852 trees) from the inventory data set described above were used as the sample. They were distributed across the Central region as shown in Table 3.1. The ages of these plantations ranged from 4 to 42 years.

Table 3.1. The distribution of sample plots

County	**Station**	**No. of Plantations**		**No. of plots**	
		C. lusitanica	***P. patula***	***C. lusitanica***	***P. patula***
Nyeri	Chehe	5	2	19	3
	Gathiuru	6	1	34	11
	Zaina	8	6	25	12
Muranga	Gatare	14	10	30	46
Kiambu	Kerita	14	2	62	8
	Kamae	9	8	28	45
	Kinale	12	9	33	46
	Uplands	4	0	11	0
Nyandarua	Geta	12	6	50	18
	North Kinangop	5	2	14	6
	South Kinangop	5	5	15	14

3.2.2 Data from destructive sampling

During this study a set of primary 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 forest plantations from among plantations whose data was recorded in the plantation forest inventory referred above. However, due to limitation imposed by authority to fell trees from gazetted forests during the moratorium, only a limited number of trees were allocated for this exercise. This destructive sampling could only be authorised in only two counties out of the four targeted. A total of 11 plantations of *C. lusitanica* and 6 of *P. patula* from Kiambu; and 7 of *C. lusitanica* and 4 of *P. patula* in

Nyandarua County were selected by allocating a number to each plantation for each species in every county and then using a calculator to draw random numbers. The age of the selected trees ranged from 4 to 45 years. This information is summarised in Table 3.2.

Table 3.2: Distribution of plantations Sampled for Tree Volume Estimation

Species/County	**Station**	**No. of plantations**	**Ages of plantations (years)**
C. luitanica			
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
P. patula			
Kiambu	Kamae	5	4, 17,20,23, 27
	Kinale	1	45
Nyandarua	Geta	4	7, 10, 17,26

Each randomly selected sub-compartment was then identified on the ground with the help of the forest area map. At the identified site a proper point at a corner of the plantation was selected as the starting point or commencement point depending on the orientation of the sub-compartment. The first tree to be felled was identified by measuring out 50 metres to the north into the plantation from the selected commencement point and measuring the nearest un-forked tree to the right at the 50-metre mark. The second tree was identified by measuring out 100 metres from the first selected tree in a line perpendicular to the initial direction of movement either to the east or west, depending on the orientation of the plantation. The second tree was picked as the nearest un-forked tree to the left of the 100th metre mark.

The tree was felled using a chainsaw at a stump height of 15 cm from the ground. Diameter measurements of the log were taken by use of a diameter tape, 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. The length of the logs was measured using a measuring tape. A total of 37 *C. lusitanica* and 25 *P. patula* trees were felled and measured.

3.3 Data Analysis

3.3.1 Volume Models

Data obtained through destructive sampling was used to construct volume models where the volume of each tree was first calculated by summing the volumes of billets 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 for each species were constructed by Gauss-Newton method (Least Squares Approach) using SAS/STAT software. The Goodness of Fit of the models was determined using the Residual Means Square Error (RMSE), p-values and Residual plots (Kirongo, 2000), thus

$$RMSE = \sqrt{\sum \frac{(y_i - y)^2}{n}} \qquad \text{(Zar, 2010)}$$

3.3.2 Other Models

The forest inventory data was used to construct the Height-Diameter, Height-Age and Diameter-Age models and validate the developed volume models.

3.3.3 Comparison of volume models

The newly constructed volume models for both *C. lusitanica* and *P. patula* were compared with the existing volume models 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 for each species.

CHAPTER FOUR

RESULTS

4.1 Growth models for *Cupressus lusitanica and Pinus patula* used in forest plantations in the Central region of Kenya

4.1.1 Growth models for *Cupressus lusitanica*

In evaluation of the growth models, the height against age, height against DBH as well as the DBH versus age was considered and sets of equation relating them developed. The scatter diagram showing the relationship between tree height and age of *C. lusitanica* in forest plantations in the Central region of Kenya is shown in Figure 4.1.

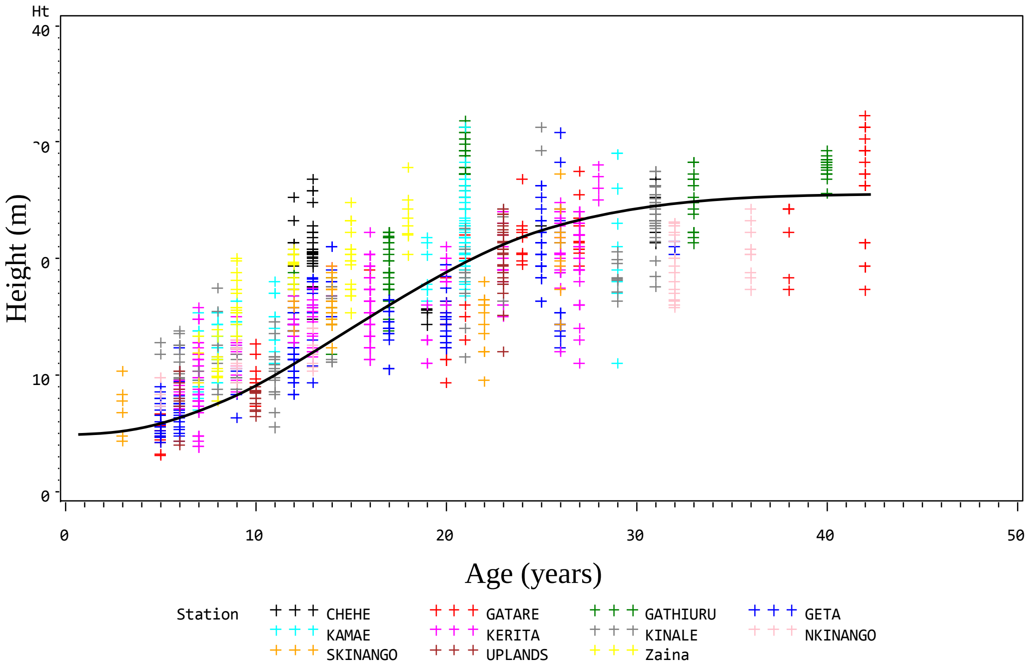

Figure 4.1: Scatter diagram showing the relationship between tree height and age of *C. lusitanica* in forest plantations in the Central region of Kenya

The relationship between tree height and age was curvelinear with exponentially increasing trend observed between 0 to age 8, constantly increasing trend observed between age 8 to age 28 and no increasing trend thereafter.

The exponential equation describing the relationship between tree height and age was:

$H_t = 8.0599(\text{Age})^{-5.1127}$ ………………………………………………………… Eq. 1

Where, H_t is tree height. There was a strong relationship between H_t and Age where age had a significant effect on height ($R^2 = 0.5325$, $p < .0001$) (Appendix 1). The residual plots of the relationships between tree height and age are shown in Figure 4.2. The residuals showed the residuals were normally distributed around the regression line.

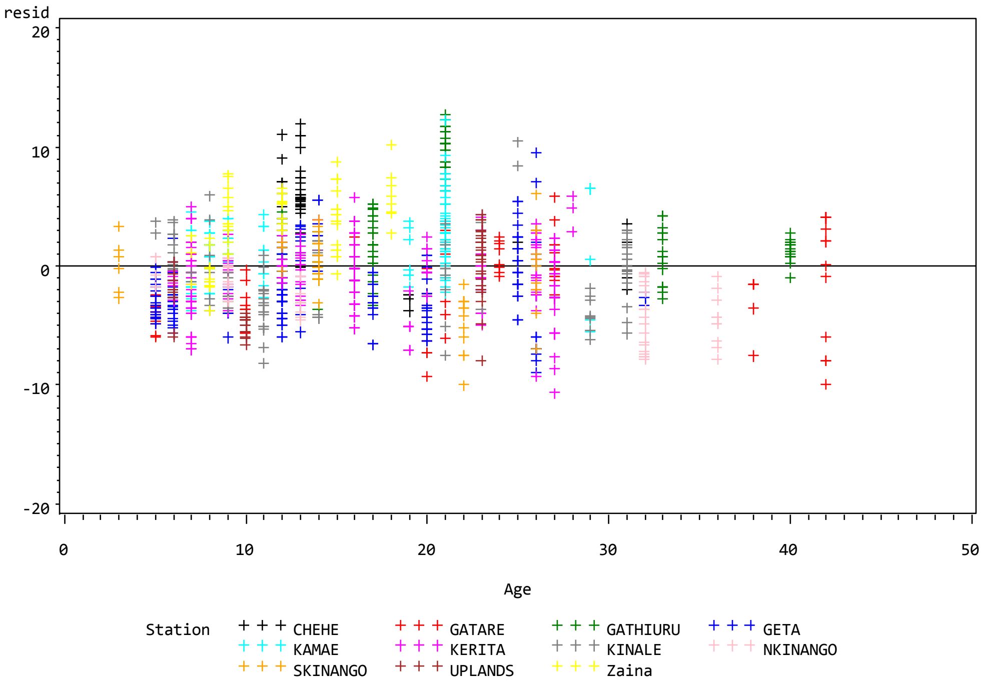

Figure 4.2: Residual plots of the relationships between tree height and age of *C. lusitanica* in forest plantations in the Central region of Kenya

Using equation 1, predicted height ($\hat{H}_t$) was derived from age data of an independent portion of the data not used in development of equation 1. The relationship between $\hat{H}_t$ and age of *C. lusitanica* in forest plantations is shown in Figure 4.3.

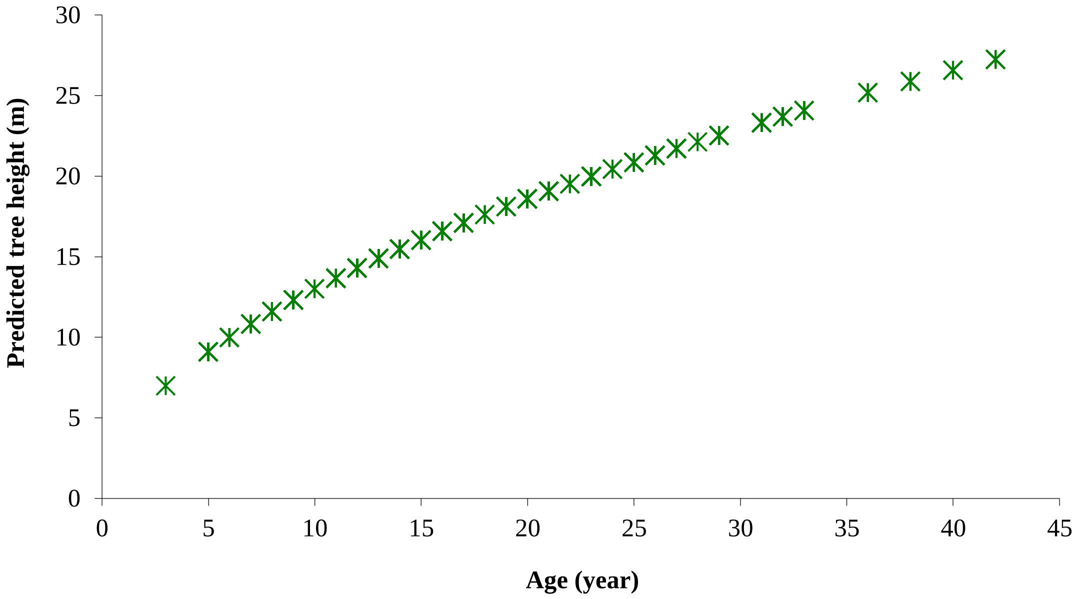

Figure 4.3: Scatter diagram showing the relationship between predicted tree height and age of *C. lusitanica* in forest plantations in the Central region of Kenya

The equation relating to the predicted tree height ($\hat{H}_t$) and age of *C. lusitanica* was derived as:

$\hat{H}_t = 3.9646 \times Age^{0.5157}$……….……………………………………………………Eq. 2

Where $\hat{H}_t$ is predicted height. The ANOVA showing the significance of the predicted model are provided in Appendix 2. There was a strong relationship between height and age with age having a significant effect on predicted height ($R^2 = 0.9532$, $p < .0001$).

The residual plots of the relationship between predicted tree height (Ĥt) and age of *C. lusitanica* is shown in Figure 4.4. The residual plots were evenly distributed along the regression line with a maximum residual occurring at +35 and minimum at -28 but were heteroscedastic.

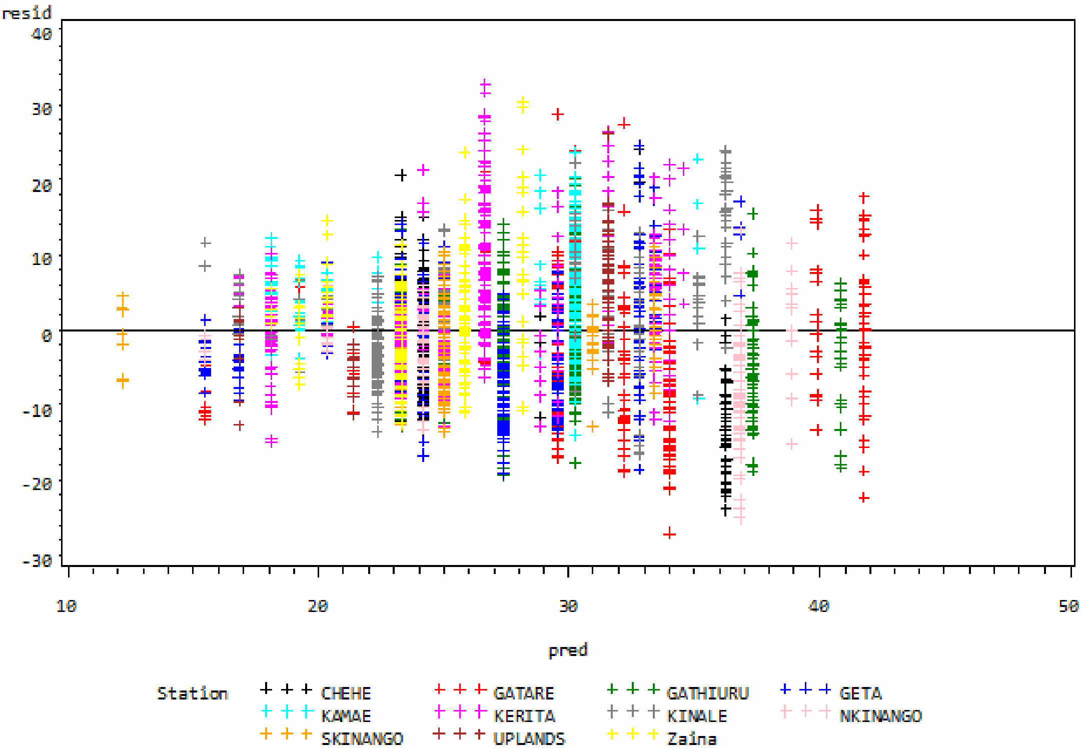

Figure 4.4: Residual plots showing the relationships between predicted tree height ($\hat{H}_t$) and age of *C. lusitanica* in forest plantations in the Central region of Kenya

Further analysis of the residuals from the scatterplot using moments (Appendix 3), normal cumulative plots (Appendix 4) and residual frequency distribution plots (Appendix 5) of the relationship between predicted tree height ($\hat{H}t$) and age of *C. lusitanica*, indicates that the residuals were normally distributed.

The relationship between tree height (H_t) and diameter at breast height (DBH) of *C. lusitanica* in forest plantations in the Central region of Kenya is shown in Figure 4.5. The relationship was exponential 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.

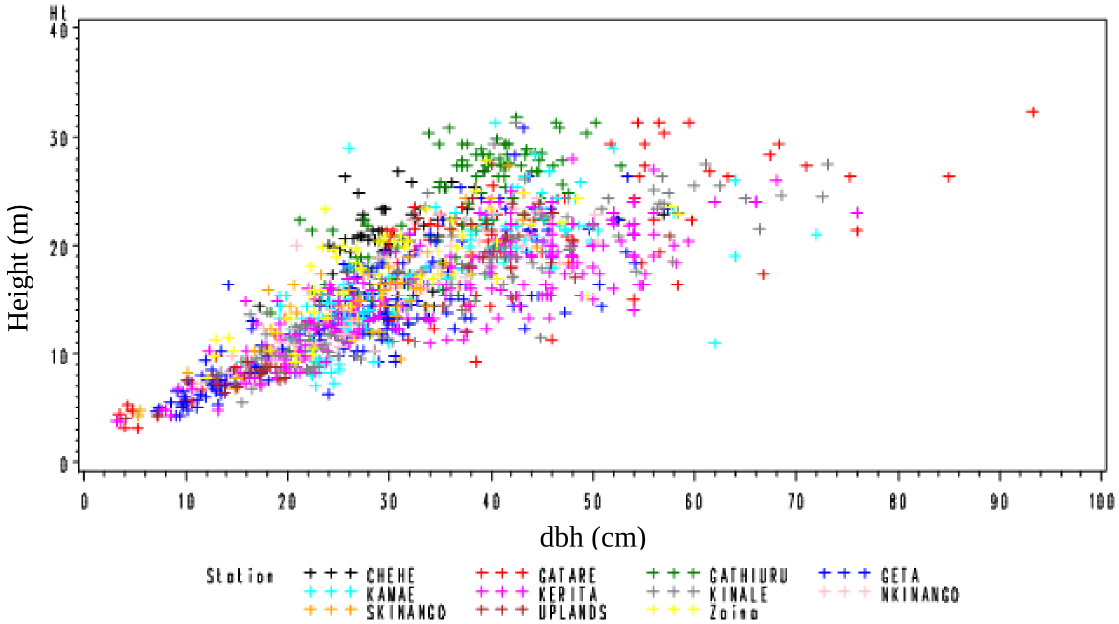

Figure 4.5: Scatterplot showing relationship between tree height and dbh of *C. lusitanica* in forest plantations in the Central region of Kenya.

The equation describing the relationship is:

$H_t = -10.4673 + 6.5433(\text{dbh})^{0.2776}$……………………………………………………. Eq. 3

Where, H_t is tree height and dbh is the diameter at breast height. The estimates, standard error and confidence limits of the model parameters as well as the ANOVA are provided in Appendix 6. The relationship between H_t and dbh was strong with dbh having a significant effect on height ($R^2 = 0.6744$, $p < .0001$).

The residual plots between tree height and DBH are shown in Figure 4.6. The residuals were fairly distributed about the regression line but there was greater variance for low dbh trees as compared to trees with larger dbh above 30cm. Analysis of the scatter diagram, using normal and frequency plots showed the residuals were not significantly different from the zero slope (Appendix 7 and 8).

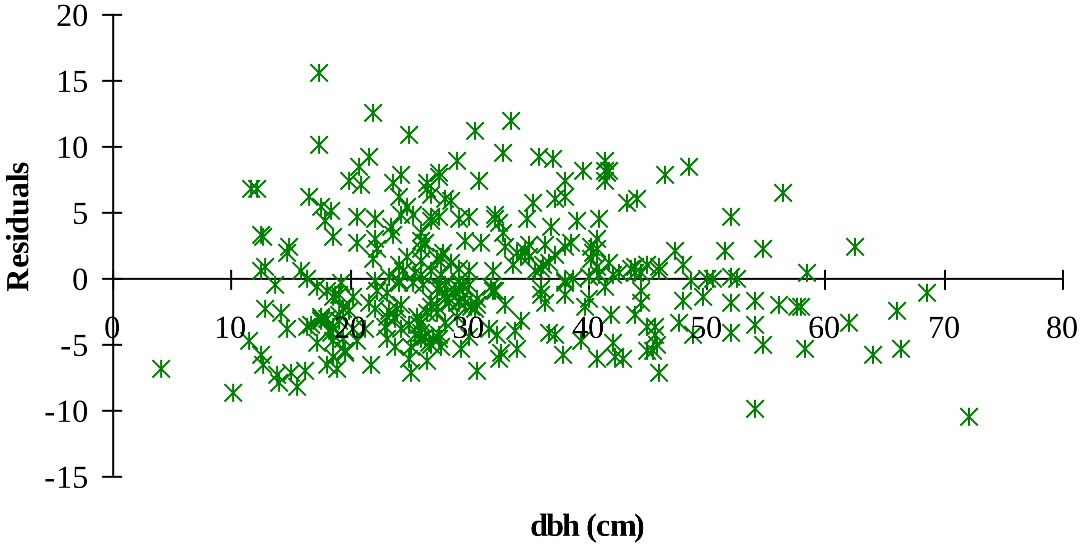

Figure 4.6: Residual plots of the relationships between tree height and DBH of *C. lusitanica* in forest plantations on the Central region of Kenya

Using equation 3, the predicted height ($\hat{H}_t$) was derived from DBH data of an independent portion of data not used in development of equation 3. The relationship between $\hat{H}_t$ and DBH of *C. lusitanica* in forest plantations in the Central region of Kenya is shown in Figure 4.7.

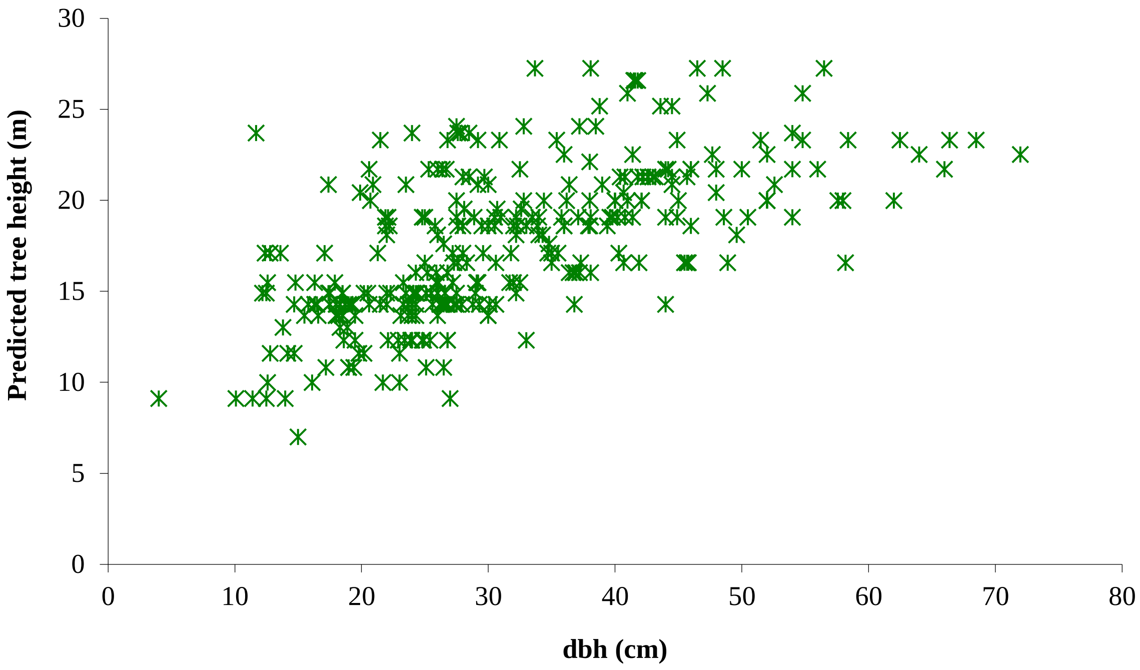

Figure 4.7: Scatter diagram showing the relationship between predicted tree height and DBH of C. lusitanica in forest plantations on the Central region of Kenya

The relationship between predicted tree height ($\hat{H}_t$) and dbh of *C. lusitanica* was described using the equation:

$\hat{H}_t = -12.5346 + 7.5589(dbh)^{0.3942}$……………………………………………… Eq. 4

Where $\hat{H}_t$ is the predicted height. Parameters of the model and ANOVA showing the significance are provided in Appendix 9. Predicted height and dbh had a strong relationship with dbh having a significant effect on predicted height ($R^2 = 0.6055$, $p < .0001$). The residual plots of the relationships between predicted tree height ($\hat{H}_t$) and dbh is shown in Figure 4.8. The residual plots were distributed about the regression line with a maximum residual occurring at +15 and minimum at -10. However, the residuals were highly heteroscedastic.

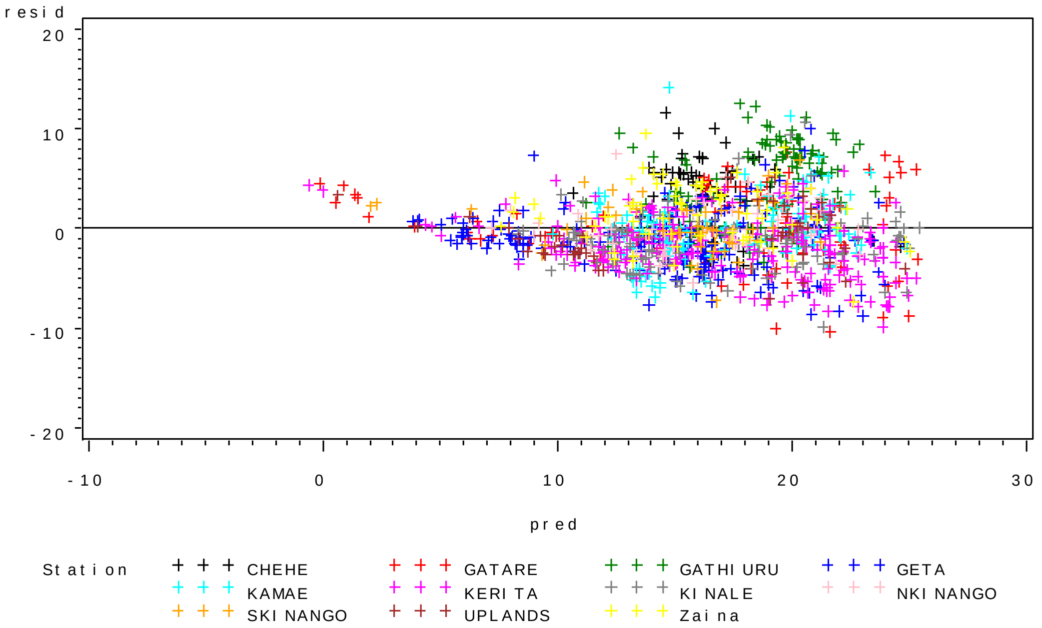

Figure 4.8: Residual plots showing the relationships between predicted tree height ($\hat{H}_t$) and dbh of *C. lusitanica* in forest plantations in the Central region of Kenya

Further analysis of the scatterplot of the residuals, using moments (Appendix 10), normal cumulative plots (Appendix 11) and residual frequency distribution plots (Appendix 12), all indicated that the residuals fairly normally distributed.

The scatter diagram and model fit showing the relationship between DBH and age of *C. lusitanica* in forest plantations in the Central region of Kenya is shown in Figure 4.9.

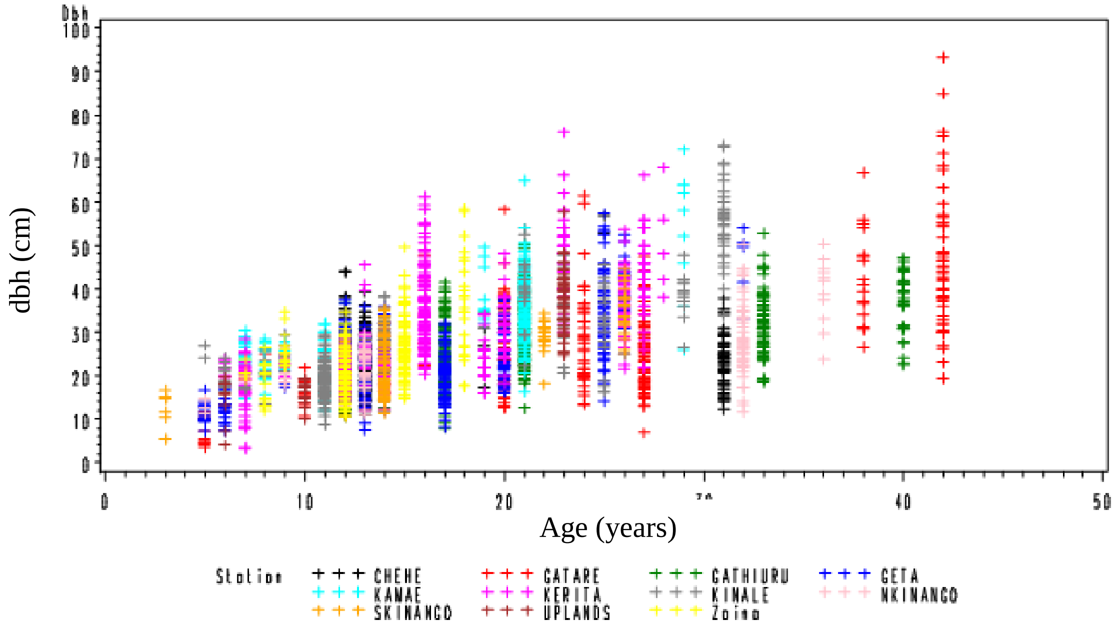

Figure 4.9: Scatterplot showing relationship between DBH and age of *C. lusitanica* in forest plantations in the Central region of Kenya

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

The relationship between DBH and age was fully fitted using the exponential equation:

$dbh = 27.7031(Age)^{-43.836}$……….……………………………………………. Eq. 5

Where, dbh is measured diameter at breast height. The relationship between dbh and Age was strong with age having a significant effect on dbh ($R^2 = 0.8461$, $p < .0001$, Appendix 13). The residual plots between dbh and age are provided in Figure 4.10.

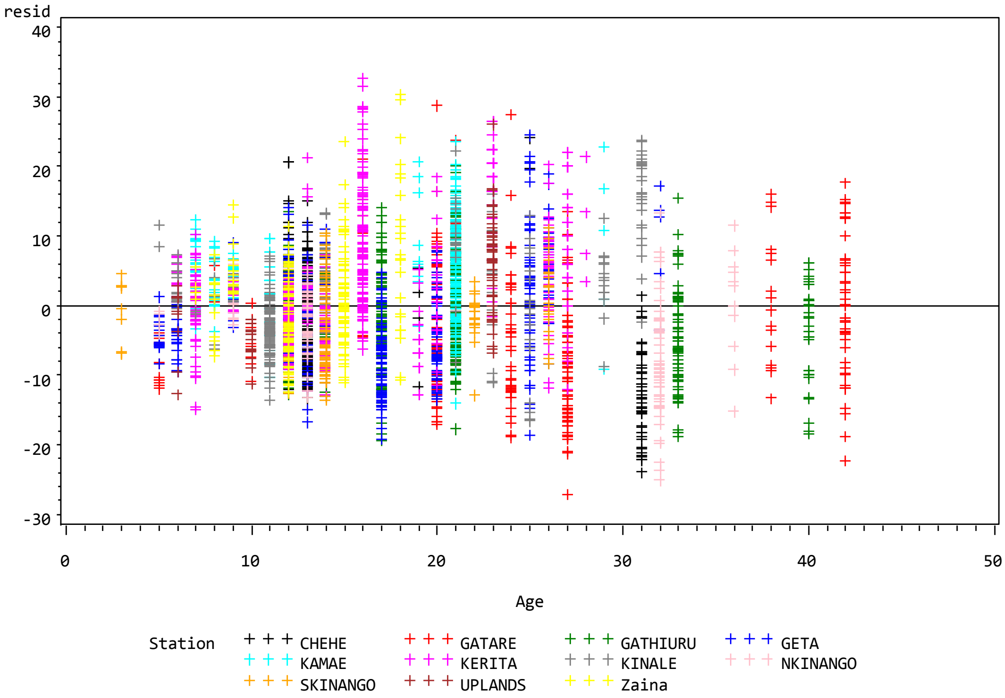

Figure 4.10: Residual plots of the relationships between dbh and age of *C. lusitanica* in forest plantations in the Central region of Kenya

Using equation 5, the predicted dbh (Ďbĥ) was derived from age data of an independent portion of data not used in development of equation 5. The relationship between Ďbĥ and age of *C. lusitanica* in forest plantations in the Central region of Kenya is shown in Figure 4.11.

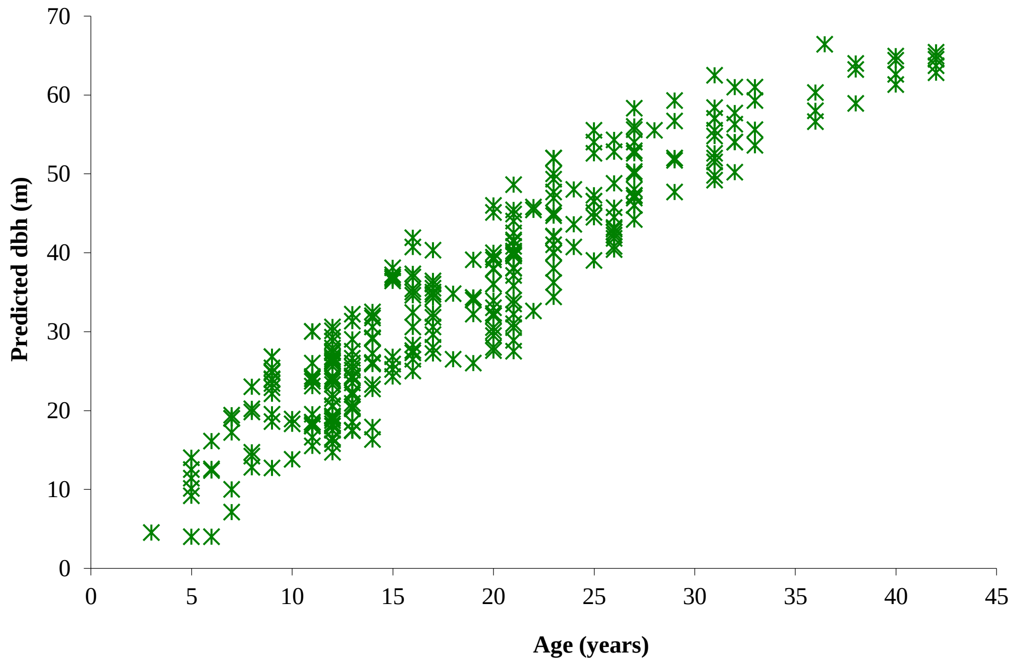

Figure 4.11: Scatter diagram showing the relationship between predicted dbh (Ďbĥ) and age of *C. lusitanica* in forest plantations in the Central region of Kenya

The predicted Ďbĥ based on age data of *C. lusitanica* was used to derive equation below:

Ďbĥ = 7.2894 $(\text{Age})^{\wedge 0.4673}$………………..……………………………………… Eq. 6

Where Ďbĥ is the predicted diameter at breast height. Parameters of the model and illustration of strong relationship between predicted dbh and age ($R^2 = 0.9195$, $p < .0001$) of the model are provided in Appendix 14.

The residual plots between Ďbĥ and age are provided in Figure 4.12. Analysis of the test of normality (Appendix 15), moments (Appendix 16), normal plots (Appendix 17), and frequency plots (Appendix 18) of the residuals from the zero slope are further provided and all indicate that the residuals were normally distributed about the regression line.

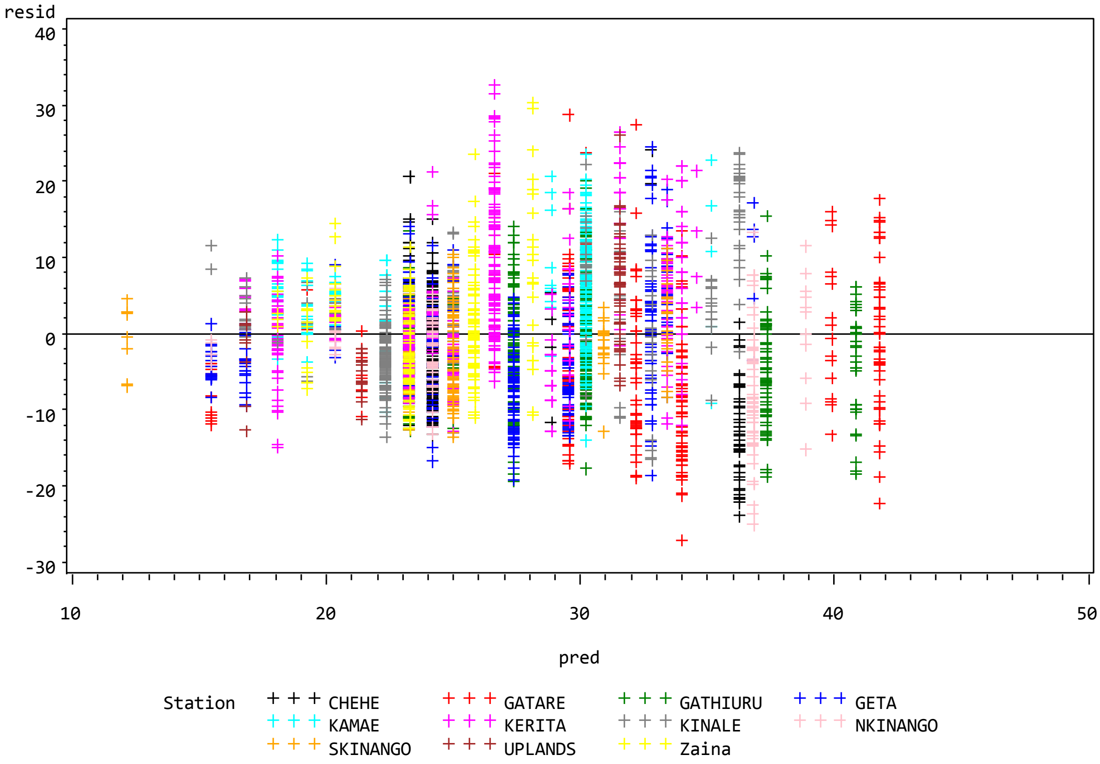

Figure 4.12: Residual plots of the relationships between predicted dbh (Ďbĥ) and age of *C. lusitanica* in forest plantations in the Central region of Kenya

4.1.2 Growth models for *Pinus patula*

The growth models for *P. patula* in Central region of Kenya were also developed. Relationship between tree height and age of *P. patula* in forest plantations in Central Kenya is shown in Figure 4.13.

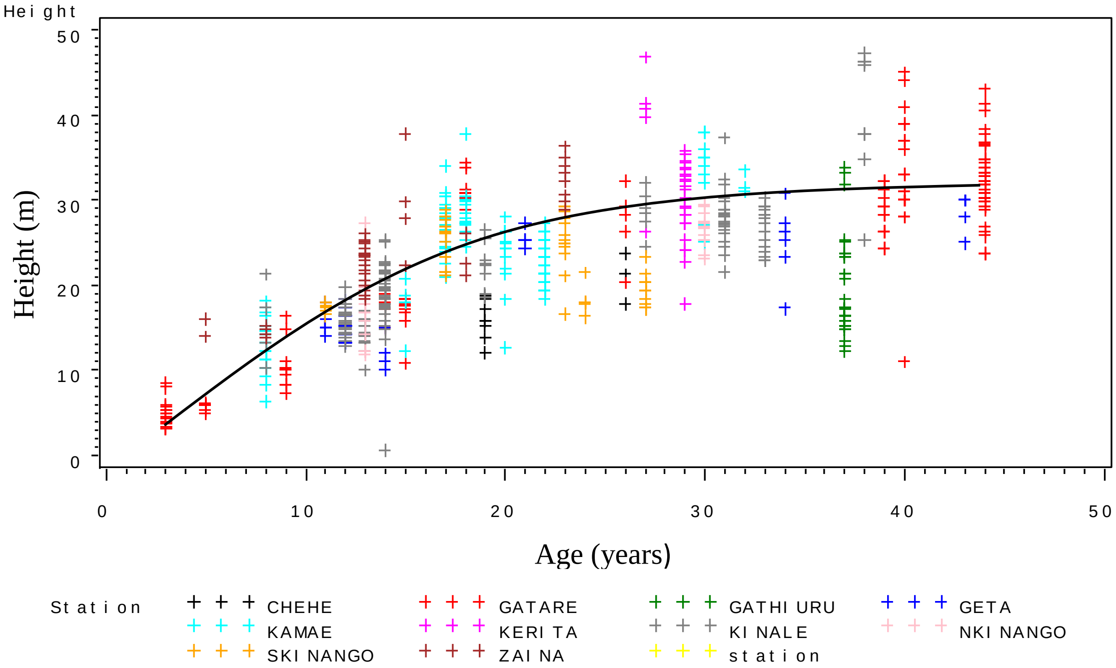

Figure 4.13: Scatter plot and model fit of tree height and age of *P. patula* in forest plantations in the Central region of Kenya

There was an exponential curvelinear relationship between tree height and age. The height initially increased exponentially till the age of 25 years and then levelled off thereafter.

The equation describing the relationship between tree height and age was exponential:

H_t = 12.531(Age)$^{-14.025}$……………………………………………………… Eq. 7

Where, H_t is measured tree height. There was a strong relationship between height and age and age having a significant effect on height (R^2 = 0.6827, p <.0001, Appendix 19). The residual plots between tree height and age are provided in Figure 4.14. Analysis of the slope of the residuals, using normal and frequency plots showed the residuals were normally distributed (Appendix 20).

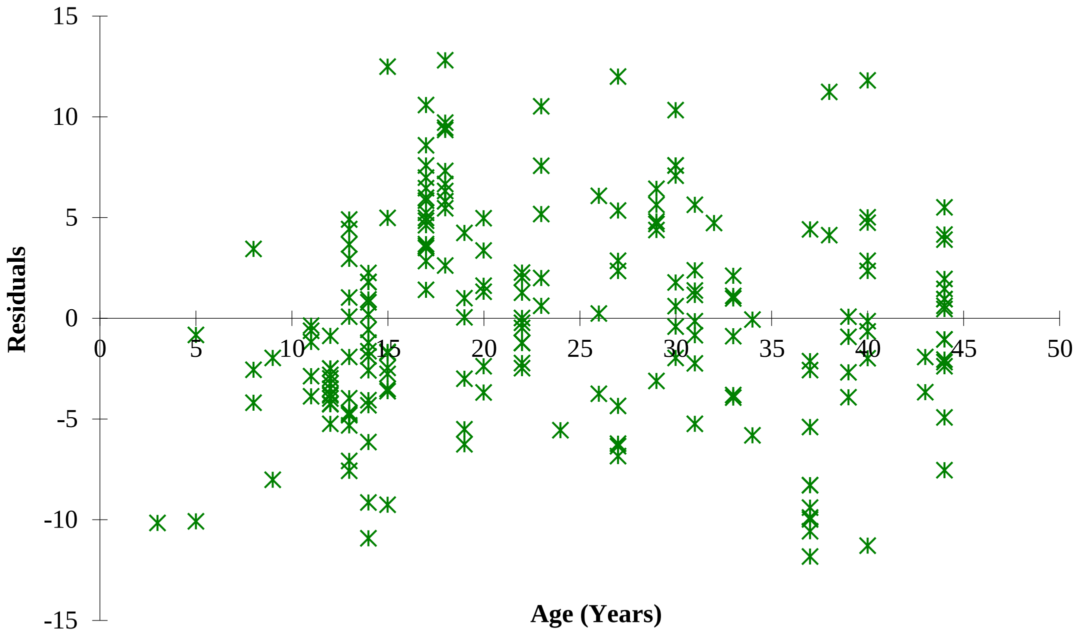

Figure 4.14: Residual scatterplot of tree height and age of *P. patula* in forest plantations in the Central region of Kenya

The equation relating the predicted height (Ĥt) against age of *P. patula* in forest plantations was derived from equation 7 thus:

$\hat{H}_t = 5.2135 + (Age)^{0.479}$…………………………………………………… Eq 8.

Where, $\hat{H}_t$ is predicted tree height. Parameters derived for the model relating the predicted height (Ĥ) and age of *P. patula*, regression and ANOVA showing the model relationship are shown in Appendix 21. The relationship between predicted height and age was very strong with age having a significant effect on predicted height ($R^2 = 0.9848$, $p < .0001$).

The residual plots between predicted tree height (Ĥt) and age are provided in Figure 4.15. Analysis of the slope of the residuals, using normal and Frequency plots showed normal distribution of the residuals (Appendix 22 and 23).

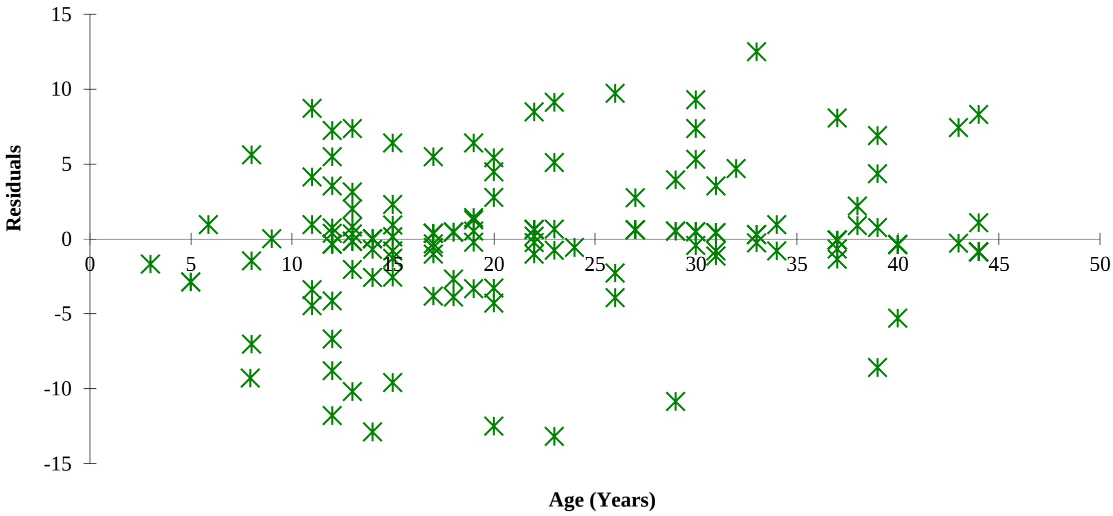

Figure 4.15: Residual scatterplot of predicted tree height ($\hat{H}$) and age of *P. patula* in forest plantations in the Central region of Kenya

Scatterplots showing the relationship between tree height (H_t) and diameter at breast height (dbh) of *P. patula* in forest plantations in the Central region of Kenya is shown in Figure 4.16.

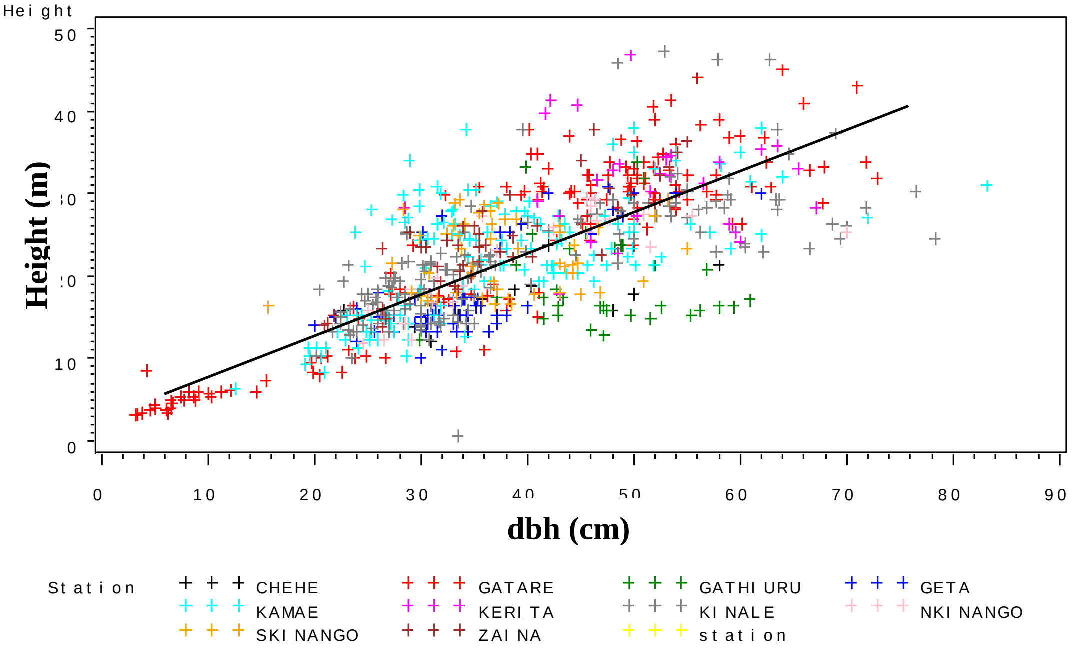

Figure 4.16: Relationship between tree height and dbh of *P. patula* in forest plantations in the Central region of Kenya

The relationship between tree height and dbh showed linear relationship where there was linear increase in height as dbh increased. The equation describing the relationship was:

$H = 5.1238 + 0.4443(dbh)$………………………………………………………… Eq. 9

Where, H_t is measured tree height and dbh is the diameter at breast height.

The estimates, standard error and confidence limits of the model parameters are provided in Appendix 24. The relationship between H_t and Age was fair with dbh having a significant effect on height ($R^2 = 0.5309$, $p < .0001$). The residual plots between tree height and dbh are shown in Figure 4.17. Analysis of the scatter diagram, using normal and Frequency plots of the residuals showed normal distribution, though with some heteroscedasticity (Appendix 25 and 26).

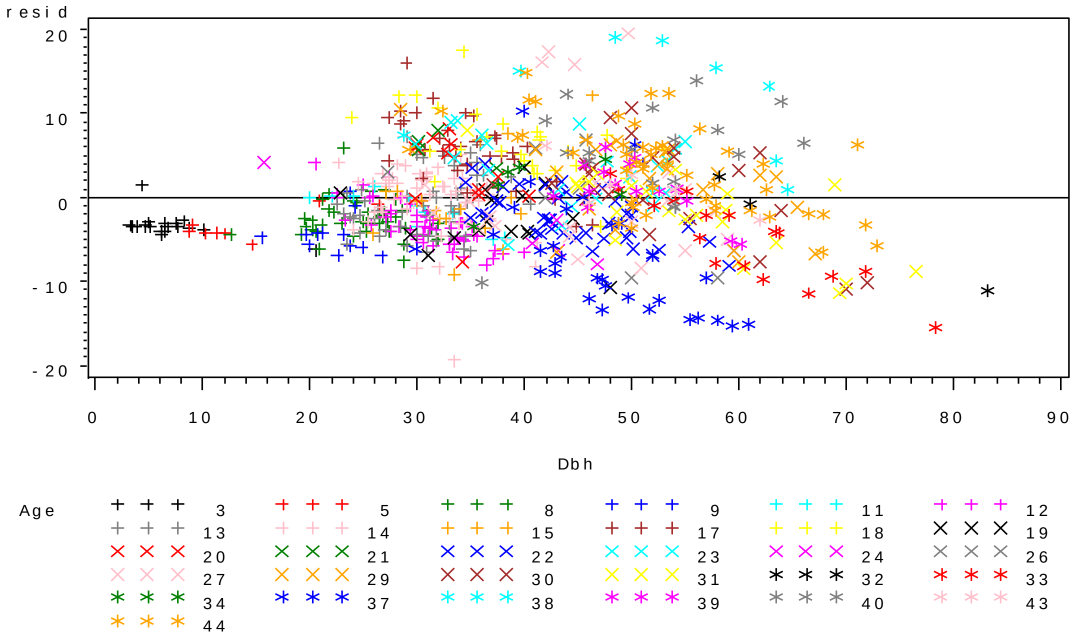

Figure 4.17: Residual plots of the relationships between tree height and dbh of *P. patula* in forest plantations in the Central region of Kenya

Using equation 9, the predicted height ($\hat{H}_t$) was derived from dbh data of an independent portion of data not used in development of equation 9. The relationship between $\hat{H}_t$ and dbh of *P. patula* in forest plantations on the Central region of Kenya is shown in Figure 4.18.

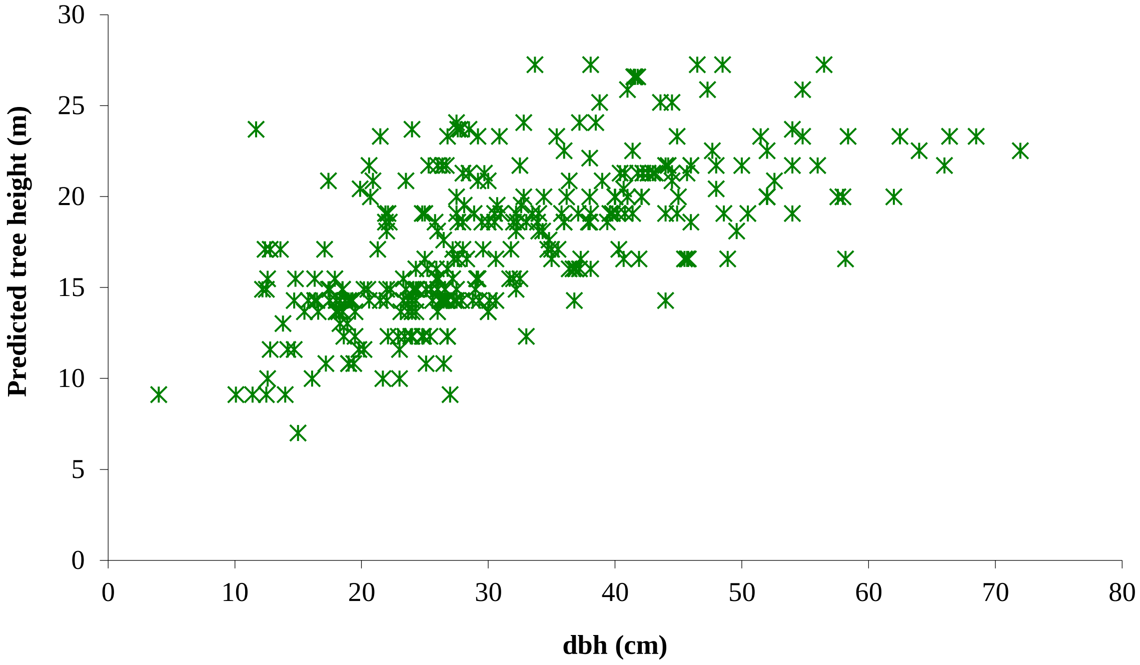

Figure 4.18: Scatter diagram showing the relationship between predicted tree height ($\hat{H}_t$) and dbh of *P. patula* in forest plantations in the Central region of Kenya

The relationship between predicted tree height ($\hat{H}_t$) and dbh of *P. patula* was described using the equation:

$\hat{H}_t = 3.9341 + 0.8453(\text{dbh})$………………………………………………… Eq. 10

Where $\hat{H}_t$ is the predicted height. The relationship between $\hat{H}_t$ and dbh was fair with dbh having a significant effect on predicted height ($R^2 = 0.4927$, $p < .0001$) (Appendix 27).

The residual plots of the relationships between predicted tree height (Ĥt) and dbh is shown in Figure 4.19. The residual plots were distributed about the regression line of the scatterplot with a maximum residual occurring at +16 and minimum at -11.

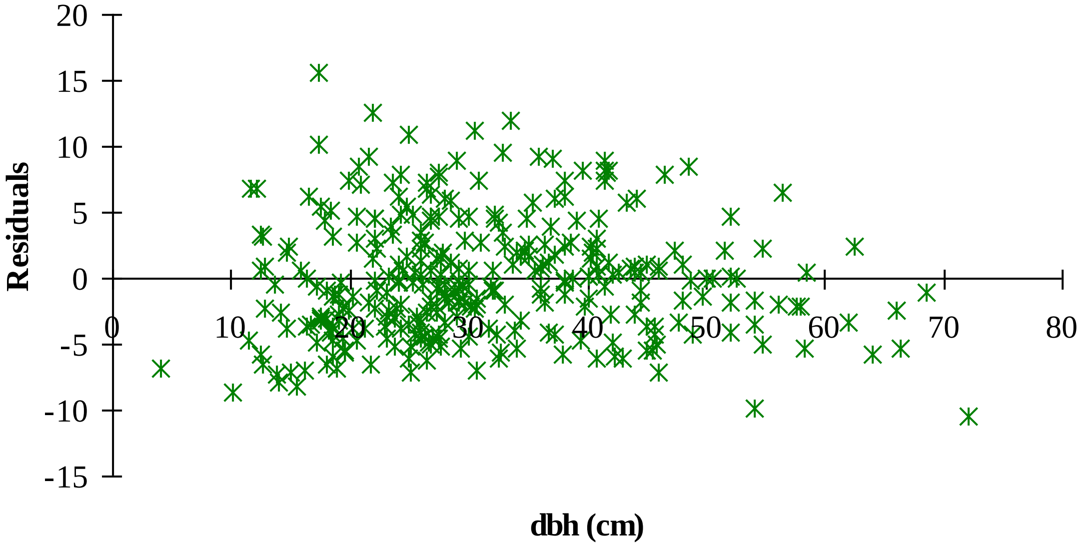

Figure 4.19: Residual plots showing the relationships between predicted tree height ($\hat{H}_t$) and dbh of *P. patula* in forest plantations in the Central region of Kenya

Further analysis of the scatterplot of the residuals, using normal cumulative plots (Appendix 28) and residual frequency distribution plots (Appendix 29), indicated that the residuals were normally distributed.

The scatter diagram and model fit showing the relationship between dbh and age of *P. patula* in forest plantations on the Central region of Kenya is shown in Figure 4.20.

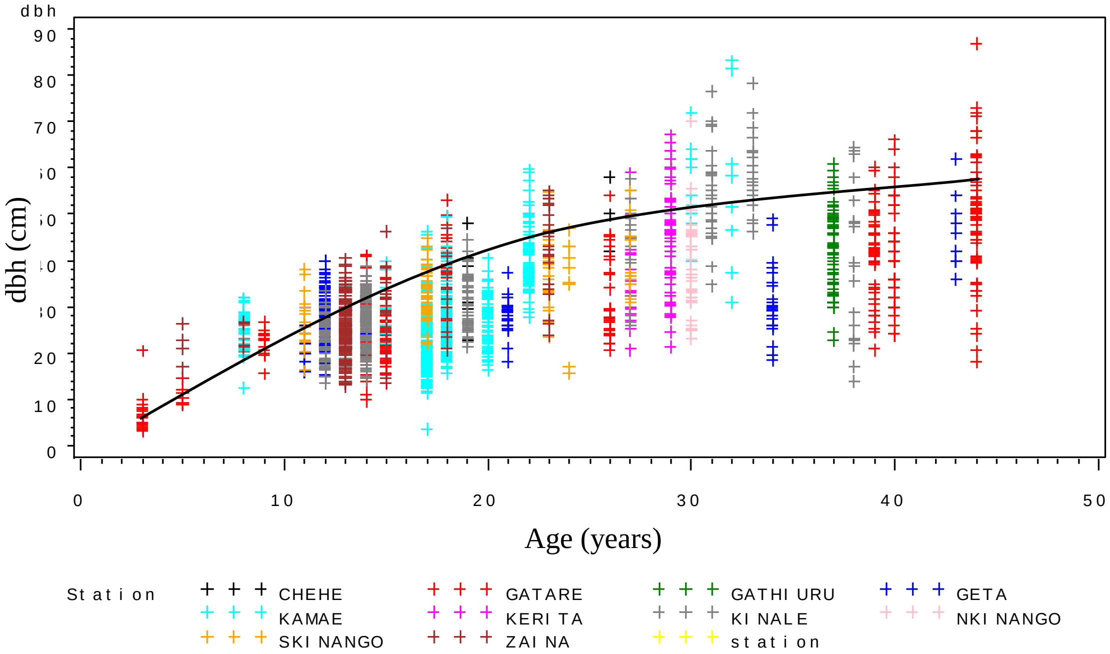

Figure 4.20: Scatterplot showing relationship between dbh and age of *P. patula* in forest plantations in the Central region of Kenya

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 relative to the increase in age. The equation describing the relationship between dbh and age was an exponential equation:

$dbh = 26.8034(Age)^{9.1636}$ ………..………..………………………………….. Eq. 11

Where, dbh is measured diameter at breast height. The relationship between dbh and Age was fair with age having a significant effect on dbh ($R^2 = 0.5310$, $p < .0001$, Appendix 30).

The frequency distribution plots of residuals dbh and age are provided in Figure 4.21. Analysis of the scatter diagram, using normal and Frequency plots showed the residuals were normally distributed with a mean of zero.

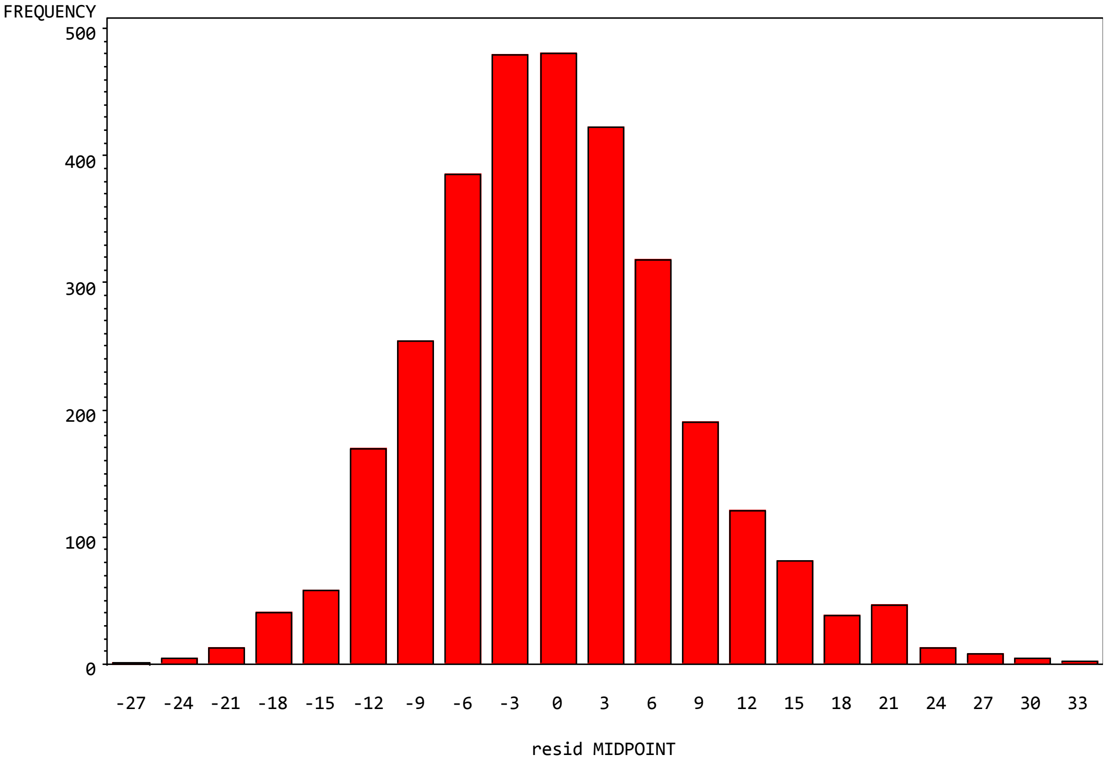

Figure 4.21: Frequency distribution plots of the relationships between dbh and age of *P. patula* in forest plantations in the Central region of Kenya

Using equation 11, the predicted dbh (Ďbĥ) was derived from age data of an independent portion of data not used in development of equation 11. The relationship between Ďbĥ and age of *P. patula* in forest plantations on the Central region of Kenya is shown in Figure 4.22.

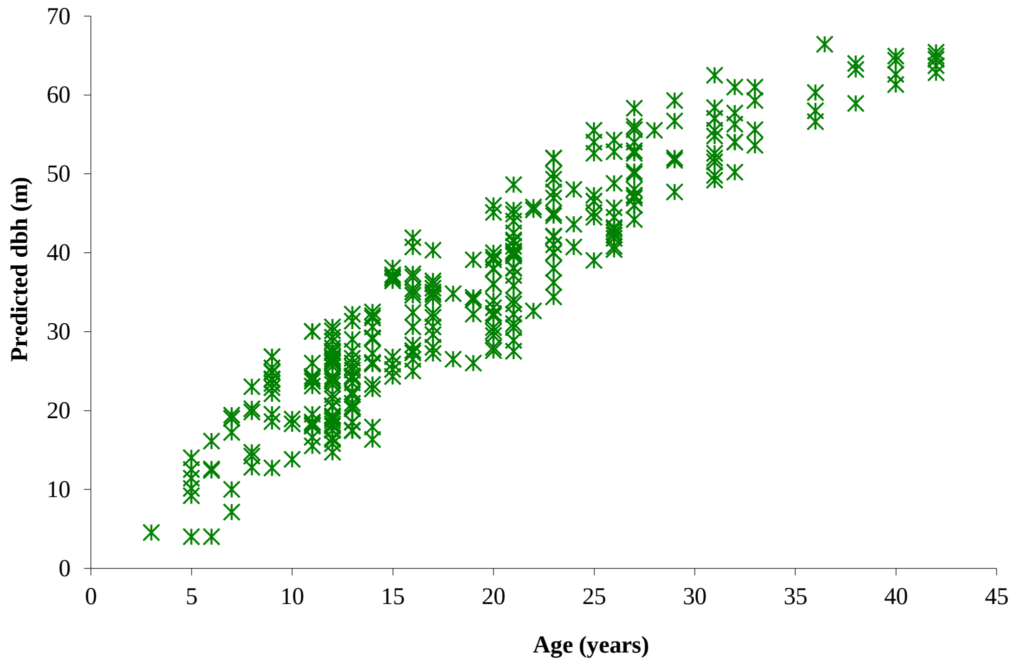

Figure 4.22: Scatter diagram showing the relationship between predicted dbh (Ďbĥ) and age of *P. patula* in forest plantations in the Central region of Kenya

The predicted Ďbĥ based on age data of *P. patula* was used to derive the following equation:

$\check{D}b\hat{h} = 7.2894(\text{Age})^{0.4673}$……………….…………………………………… Eq. 12.

Where Ďbĥ is the predicted diameter at breast height. The relationship between predicted dbh and age was fair with age having a significant effect on predicted dbh ($R^2 = 0.5544$, $F_{1,686} = 853.46$, $p < .0001$, Appendix 31). The residual plots between Ďbĥ and age are provided in Figure 4.23. Analysis of the scatter diagram, using moments, normal plots, and frequency plots showed the residual plots were normally distributed with a mean of zero (Appendix 32 and 33).

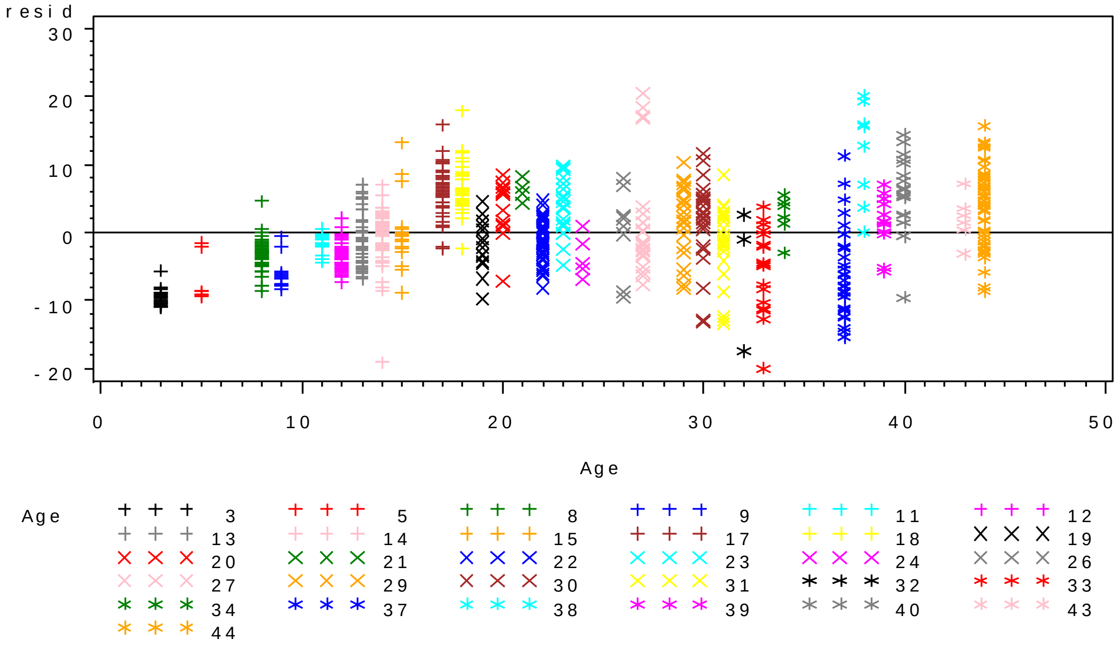

Figure 4.23: Residual plots of the relationships between predicted dbh (Ďbĥ) and age of *P. patula* in forest plantations in the Central region of Kenya

4.2 Yield models for *Cupressus lusitanica* and *Pinus patula* use in forest plantations in Central regions of Kenya

4.2.1 Yield models for *Cupressus lusitanica*

The relationship between volume measured by Smalian formula (measured volume) and dbh for *Cupressus lusitanica* is shown in Figure 4.24. The relationship between the measured volume and dbh was fully fitted with third order differential equation of cubic function. At dbh lower than 0.2 m measured volume increased at slower rate, followed by an exponential increase in measured volume between dbh 0.2 to 0.45m and then a plateau thereafter.

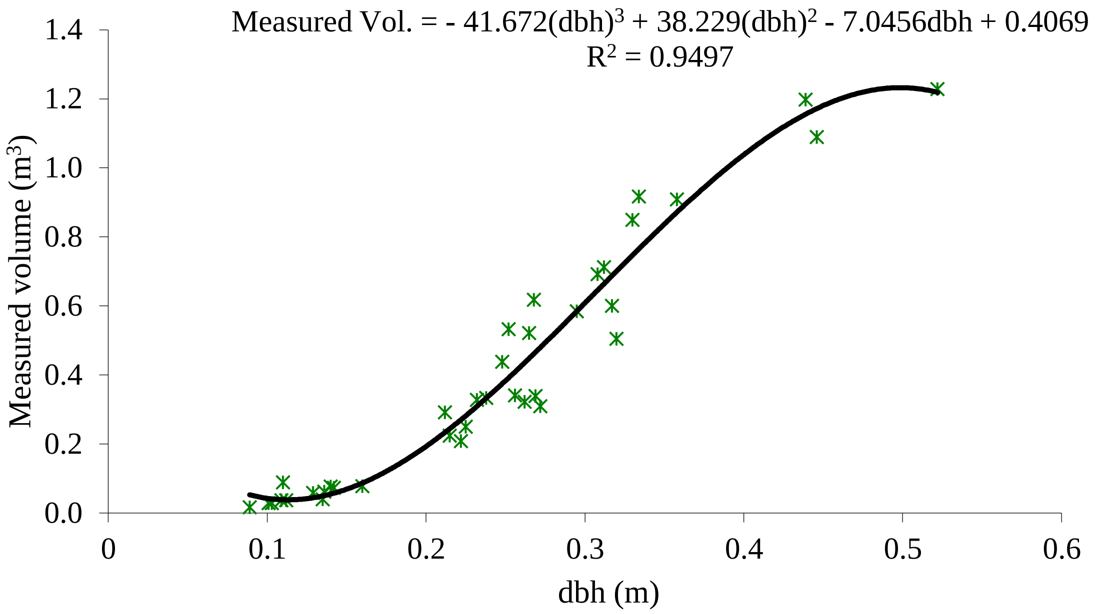

Figure 4.24: Relationship between measured volume and dbh for *Cupressus lusitanica* in forest plantations in the Central region of Kenya

The residual plot depicting the measured volume and dbh of *C. lusitanica* is shown in Figure 4.25. The relationship between volume and dbh was strong with dbh having a significant effect on volume (Multiple R = 0.9396, *p* <.0001; Appendix 34).

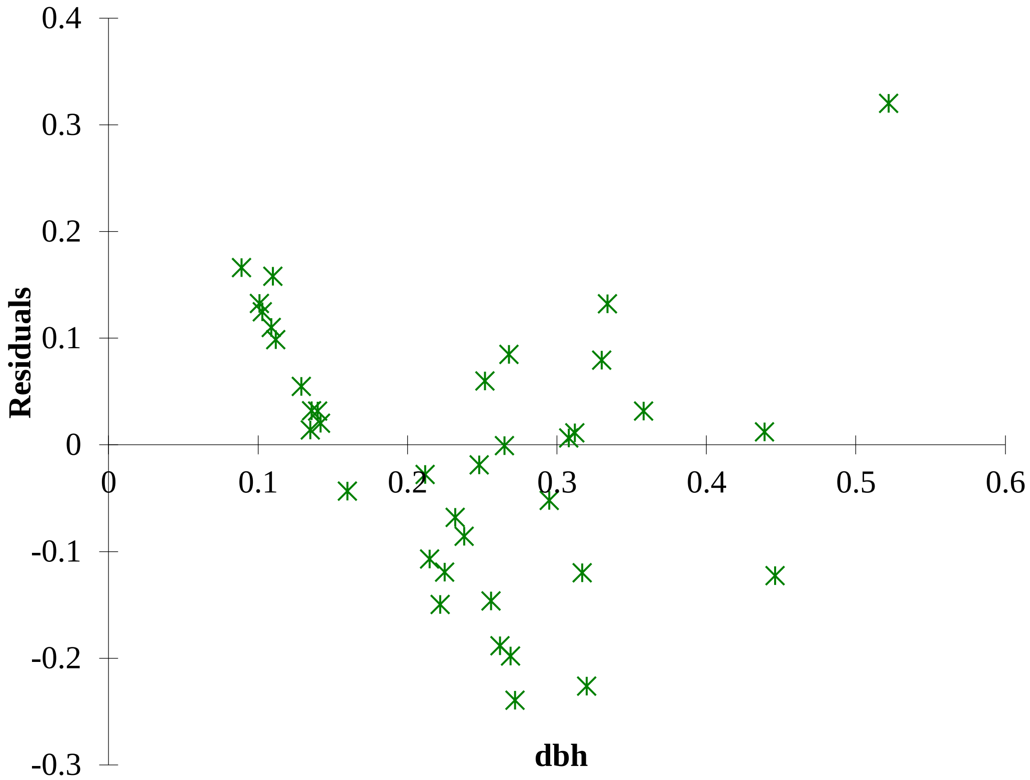

Figure 4.25: Residual plots for measured volume and dbh for *C. lusitanica* in forest plantations in the Central region of Kenya

The relationship between measured volume and height of the *Cupressus lusitanica* is shown in Figure 4.26. The relationship between the measured volume and height was fully fitted with third order differential equation.

The residual plot depicting the measured volume and height of *C. lusitanica* is shown in Figure 4.27. The residuals were, to a large extent, evenly distributed within the slope of the regression line and did not show any significant deviation from the regression line, though there were two incidences of possible outliers. The relationship between volume and height was strong with height having a significant effect on measured volume (Multiple R = 0.8154, *p* <.0001; Appendix 35).

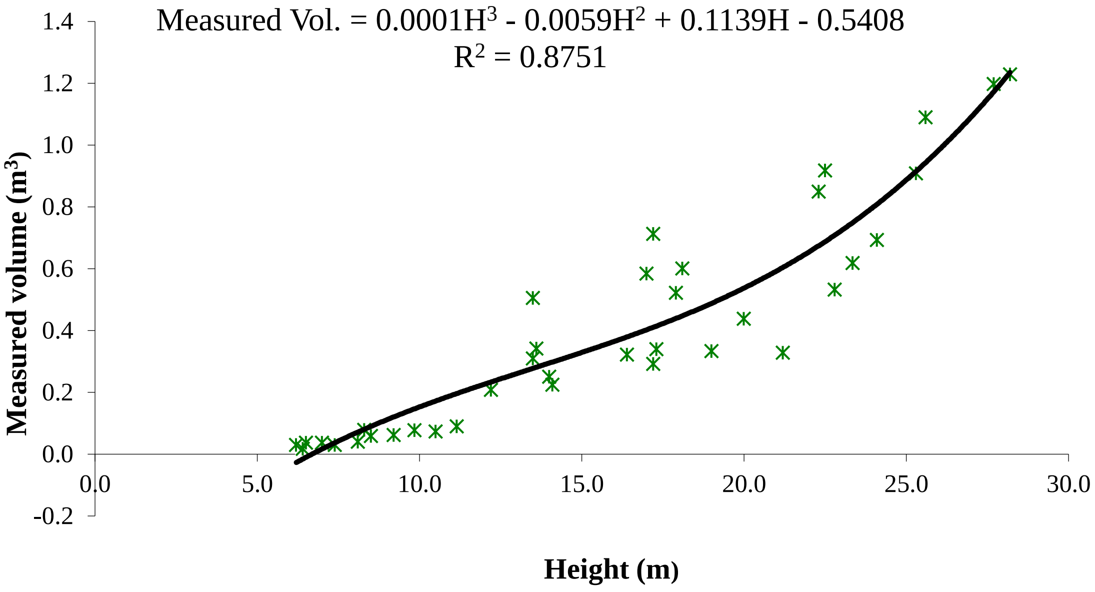

Figure 4.26: Relationship between measured volume and height of *Cupressus lusitanica* in forest plantations in the Central region of Kenya

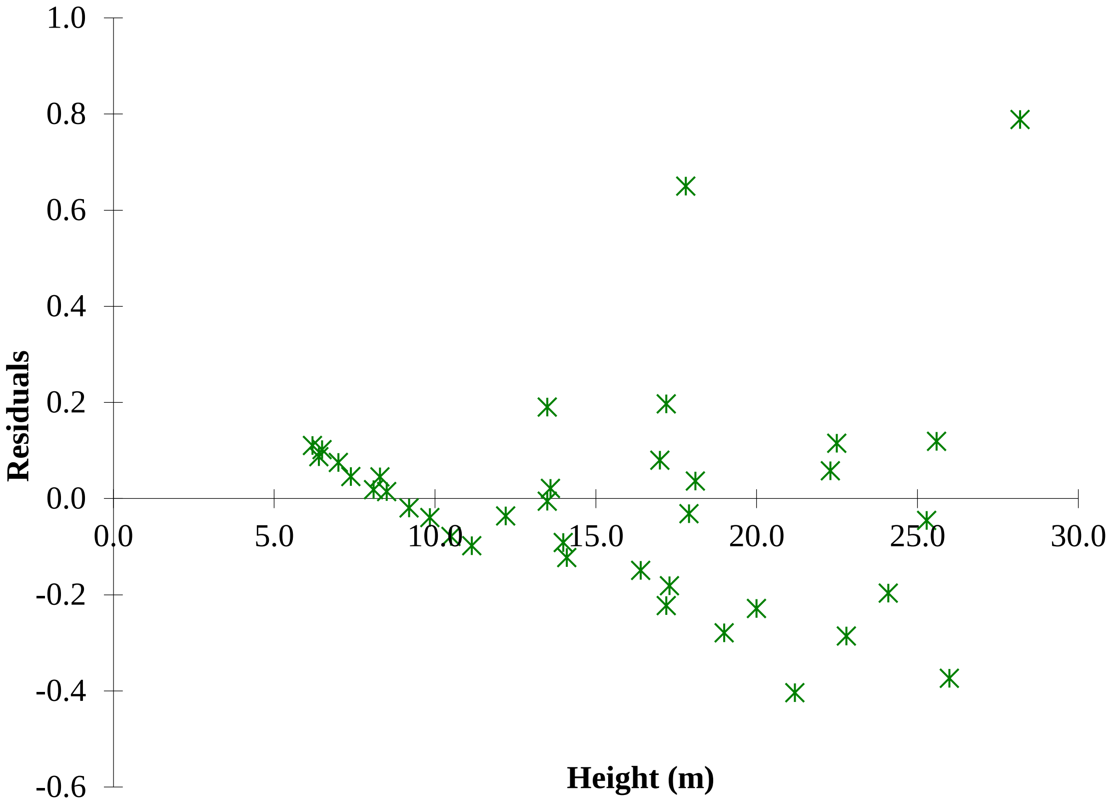

Figure 4.27: Residual plots for measured volume and height for *C. lusitanica* in forest plantations in the Central region of Kenya

The equation describing the measured volume, height and dbh was developed for *Cupressus lusitanica* as: $V = -0.1247 + 0.02233(dbh)^2 - 0.0233H + 0.0012H^2$…Eq. 13

Then equation 13 was used to predict the volume given H and dbh. The relationship between predicted volume ($\tilde{V}$) and measured volume (V) for *C. lusitanica* is shown in Figure 4.28. The relationship showed a high goodness of fit ($R^2 = 0.9561$, RMSE = 0.0873).

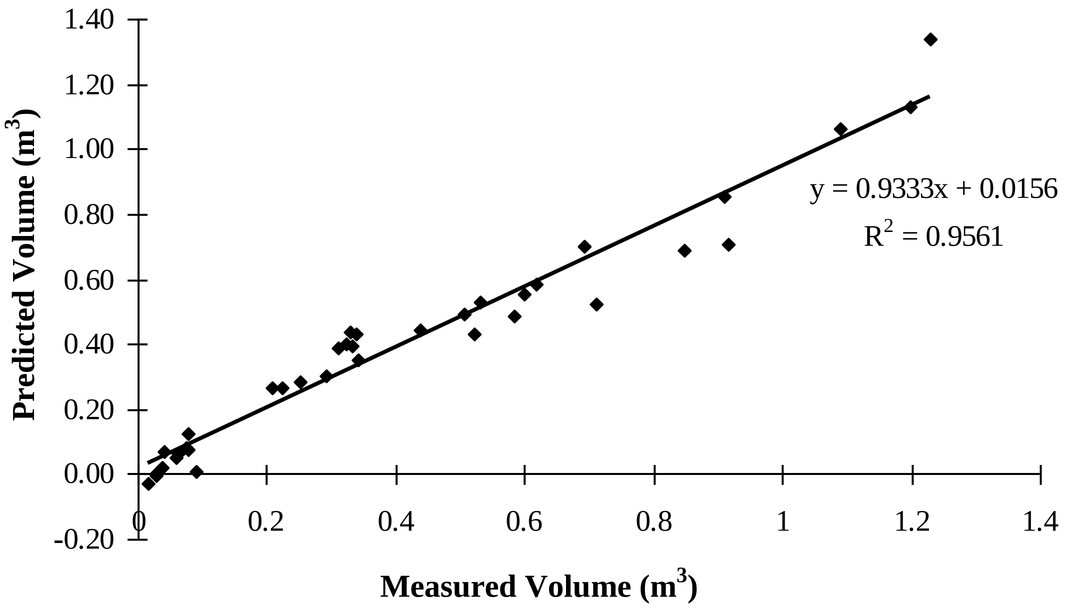

Figure 4.28: Relationship between predicted volume ($\tilde{V}$) against measured (V) volume of *Cupressus lusitanica* in forest plantations in the Central region of Kenya

4.2.2 Yield models for *Pinus patula*

The relationship between measured volume and dbh for *Pinus patula* is shown in Figure 4.29. The relationship between the measured volume and dbh was fully fitted with third order differential equation. The residual plots for measured volume and dbh of *P. patula* is shown in Figure 4.30.

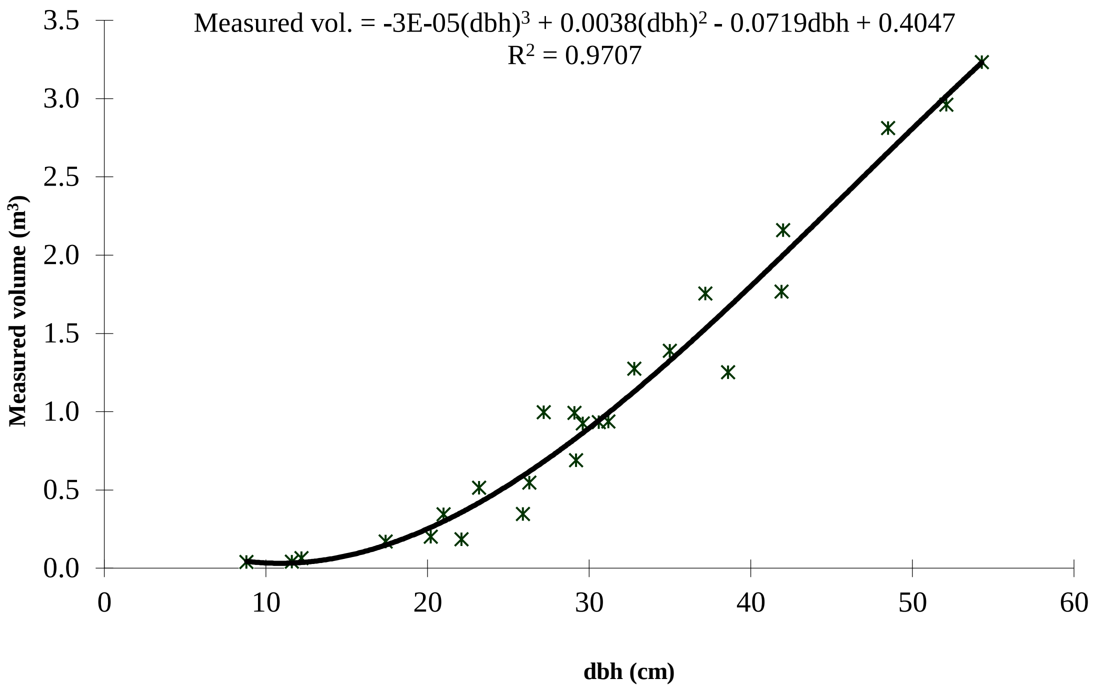

Figure 4.29: Relationship between measured volume and dbh for *Pinus patula* in forest plantations in the Central region of Kenya

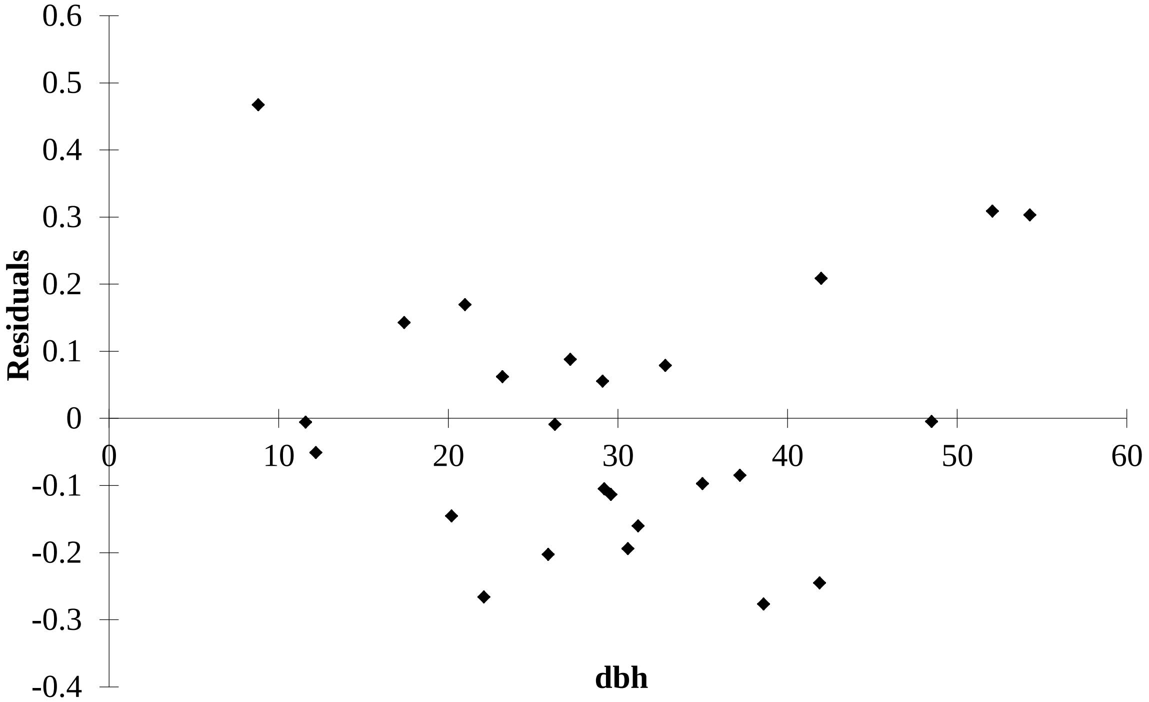

Figure 4.30: Residuals for measured volume and dbh of *Pinus patula* in forest plantations in the Central region of Kenya

The relationship between measured volume and height of the *P. patula* is shown in Figure 4.31. The relationship between the measured volume and dbh was fully fitted with third order differential equation of cubic function. The residual plots for measured volume and height of *P. patula* is shown in Figure 4.32

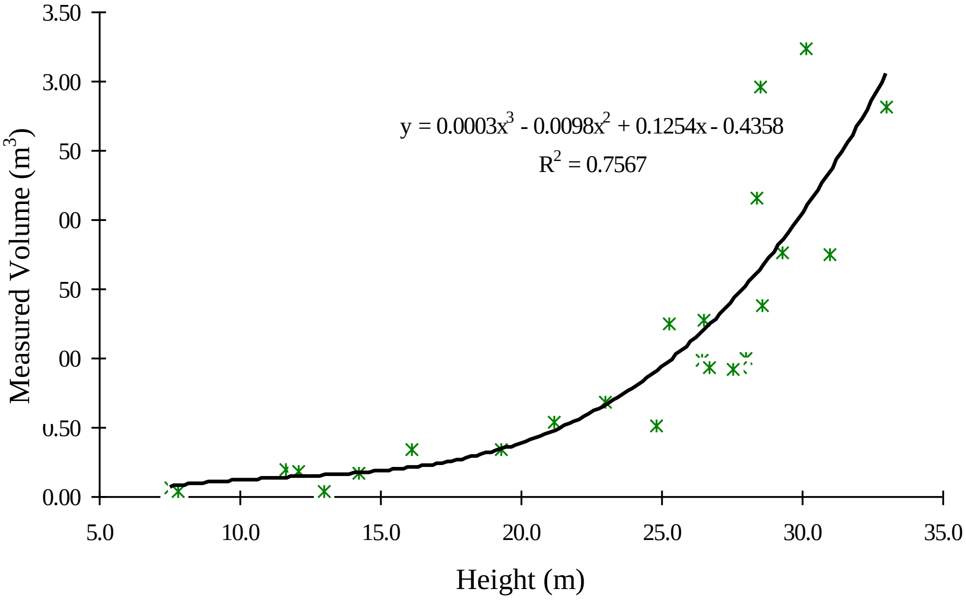

Figure 4.31: Relationship between measured volume and height of the *Pinus patula* in forest plantations in the Central region of Kenya

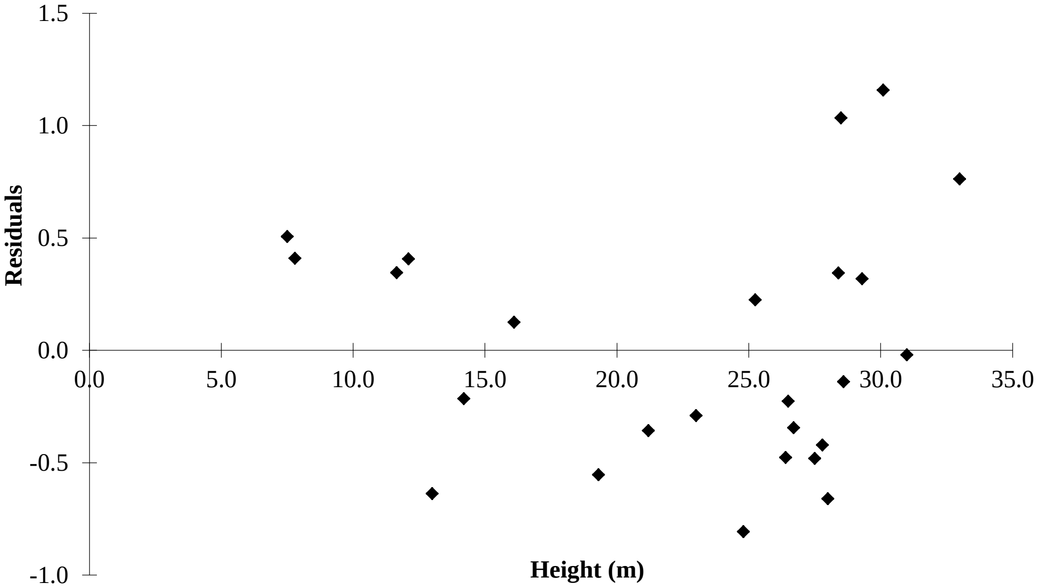

Figure 4.32: Residuals for measured volume and height of *P. patula* in forest plantations in the Central region of Kenya

The equation describing the measured volume, height and dbh was developed for *P. patula* as: $\tilde{V} = 0.1994 + 0.0685dbh - 0.1525H + 0.0039H^2$…………………… Eq 14.

Equation 14 was used to predict the volume given H and dbh. The relationship between predicted volume ($\tilde{V}$) and measured volume (V) of *P. patula* is shown in Figure 4.33.

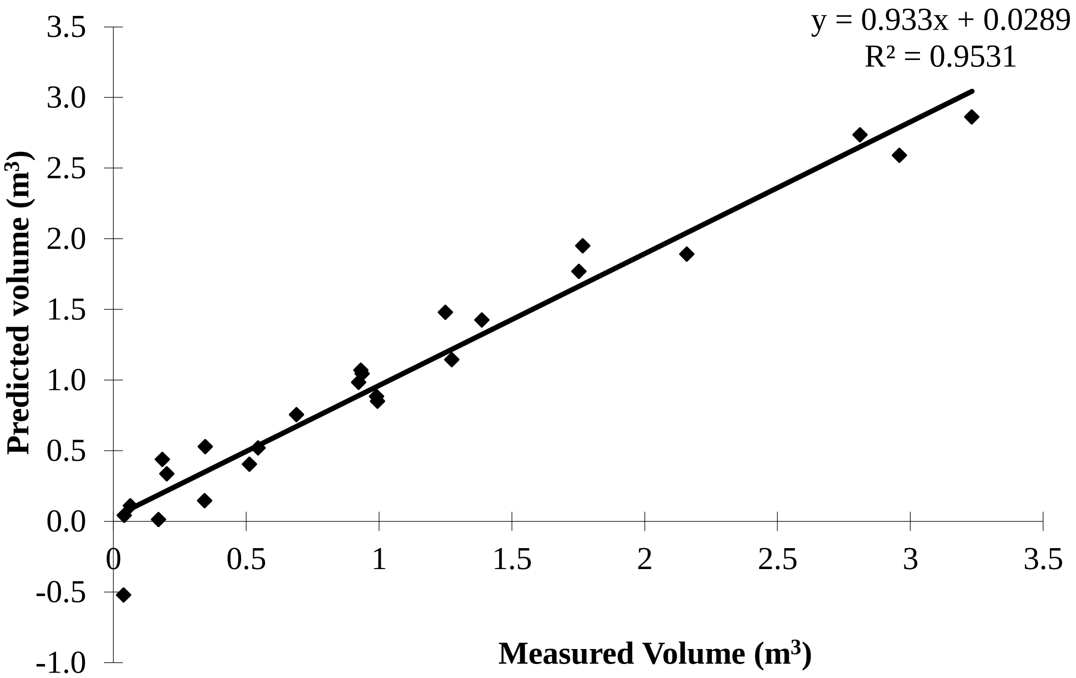

Figure 4.33: Relationship between predicted volume and measured volume of *Pinus patula* in the Central Region of Kenya

There was a high goodness of fit ($R^2 = 0.9531$, RMSE = 0.0902)

The residual plot of the measured volume and predicted volume of *Pinus patula* is shown in Figure 4.34. The residuals were homoscedastic with a mean of zero.

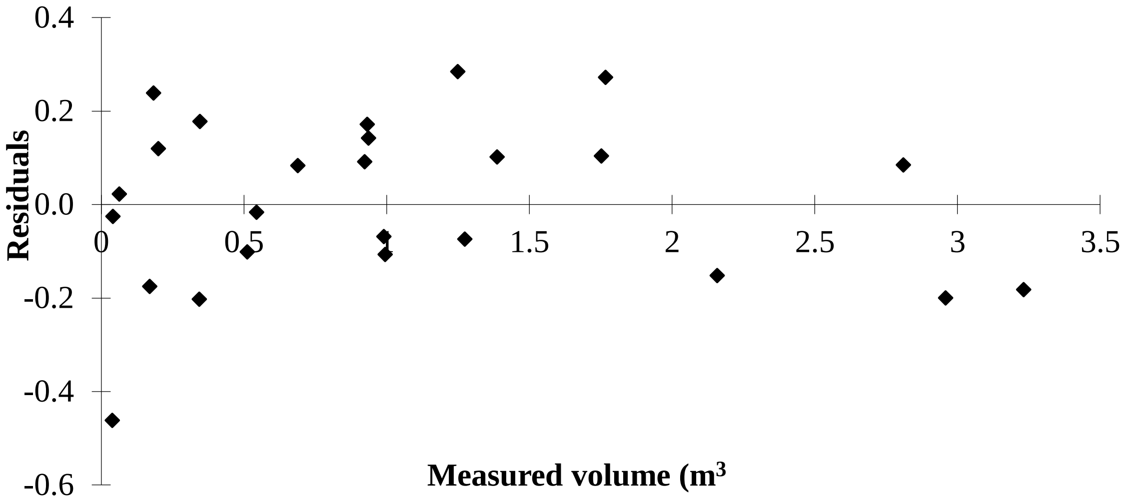

Figure 4.34: Residuals for the predicted volume (Ṽ) and measured volume (V) of *Pinus patula* in Central Region of Kenya

4.3 Comparisons of developed yield models and conventional models used by KFS in forest management in Kenya

4.3.1 *Cupressus lusitanica* model

The KFS model developed in 1975 was: $\tilde{V} = 0.013152 - 0.00005069(dbh)^2 + 0.0001769(dbh)H + 0.00002895(dbh)^2H$

The relationship between the measured volume and volume derived from the KFS model for *Cupressus lusitanica* is shown in Figure 4.35. The relationship between the measured volume and volume derived from the KFS model showed the model had a low goodness of fit (Multiple R = 0.6077; RMSE = 0.5065). At lower measured volume below 0.2 m^3 and higher volumes (> 1 m^3), the KFS model overestimated the volume. However, for measured volume between 0.2 to 0.9 m^3, the KFS model underestimated the volume of the tree.

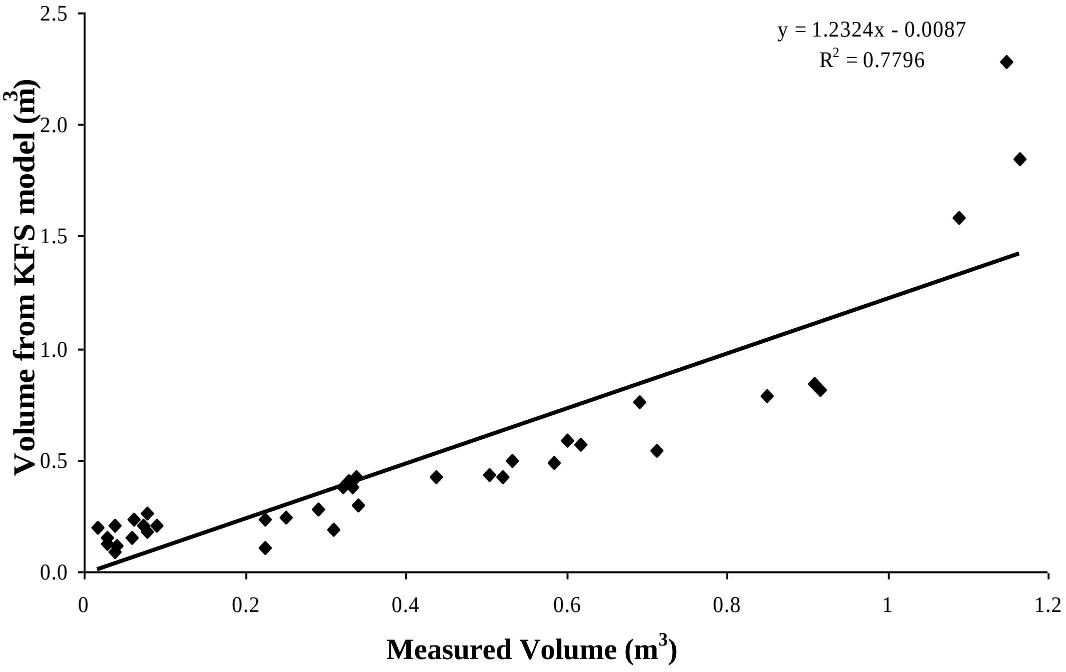

Figure 4.35: Relationship between the measured volume and volume by KFS model for *Cupressus lusitanica*

The residual plot of the measured volume and predicted volume based on KFS model for *Cupressus lusitanica* is shown in Figure 4.36. The residuals were not homoscedastic. At low (below 0.2m^3) and high (above 0.9m^3) measured volumes the residuals were positive while at measured volume between 0.2 and 0.9 m^3 the residuals were negative.

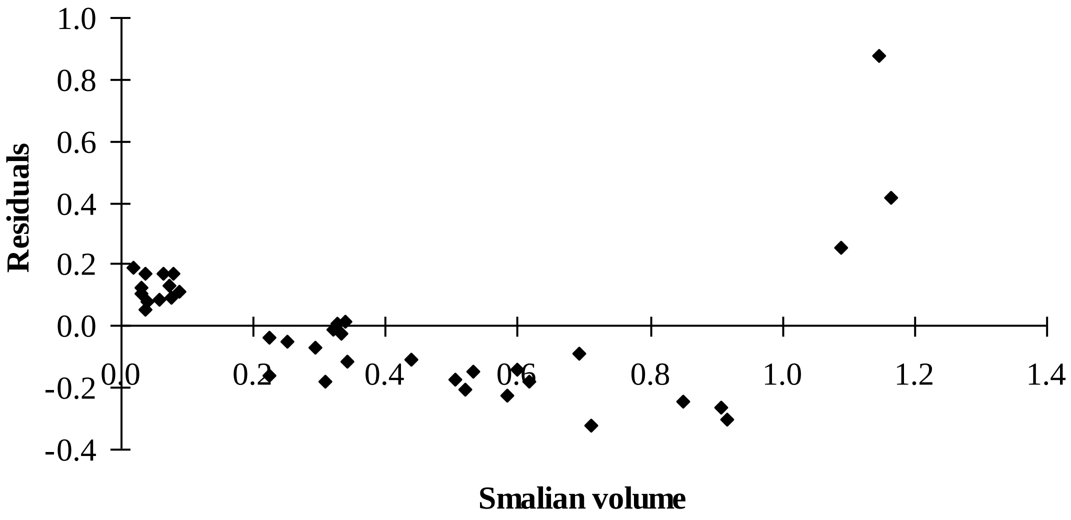

Figure 4.36: Residual plots for relationship between the measured volume and KFS model derived volume for *Cupressus lusitanica*

The model developed for *Cupressus lusitanica* in this study was: $\tilde{V} = -0.1247 + 0.02233(dbh)^2 - 0.0233H + 0.0012H^2$ (Equation 13).

The relationship between the volume predicted by the new model and measured volume showed a high goodness of fit ($R^2 = 0.9561$, RMSE = 0.0873) as shown in figure 4.28 and the residuals were homoscedastic and normally distributed.

4.3.1 *Pinus patula* model

The KFS model developed in 1975 was:

$V = -0.00041 - 0.0000571(dbh)^2 + 0.0001352(dbh)H + 0.00003313(dbh)^2H$

The relationship between the measured volume and volume derived from the KFS model for *P. patula* is shown in Figure 4.37. The relationship between the measured volume and volume derived from KFS model showed a low model fit (Multiple R = 0.6185; RMSE = 0.4648). At lower volume below 0.7 m^3 and higher volumes > 2.7

m^3, the KFS model overestimated the volumes. However, at volume between 0.7 to 2.4 m3, the KFS model underestimated the volume of the tree.

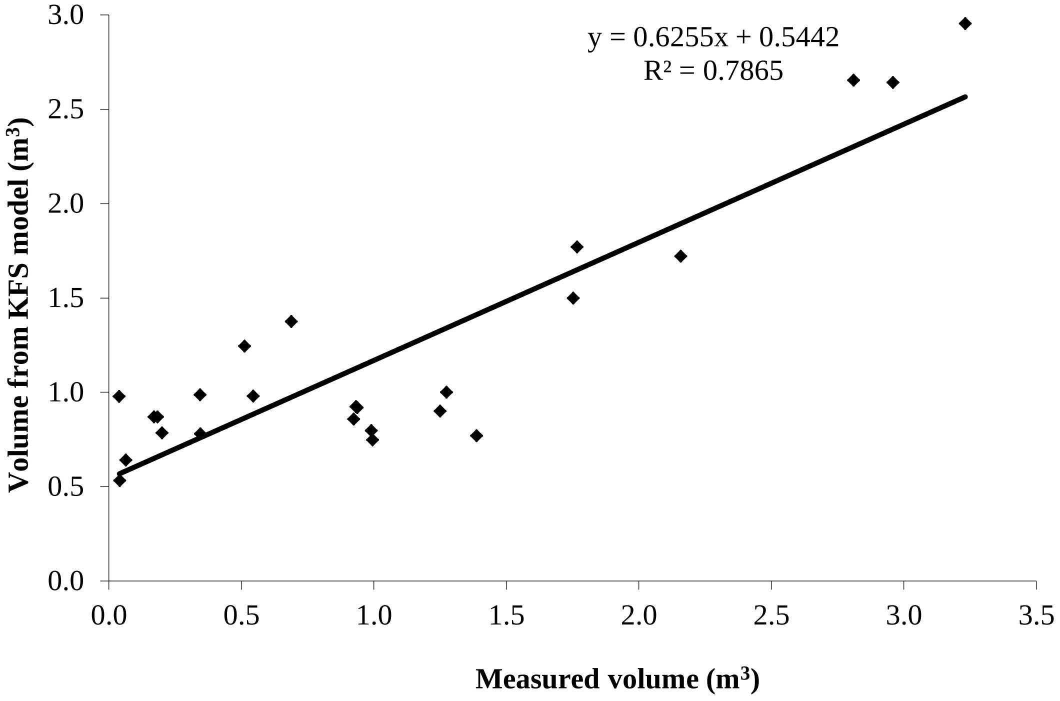

Figure 4.37: Relationship between the measured volume with volume derived from KFS model for *Pinus patula* in the Central region of Kenya

The residual plot of the measured volume and volume predicted by KFS model for *Pinus patula* based on is shown in Figure 4.38. The slope of the residuals was significantly different from zero (Appendix 38), however at low and high measured volumes the residuals were positive while at measured volume between 0.7 and 2.4 m^3 the residuals were negative.

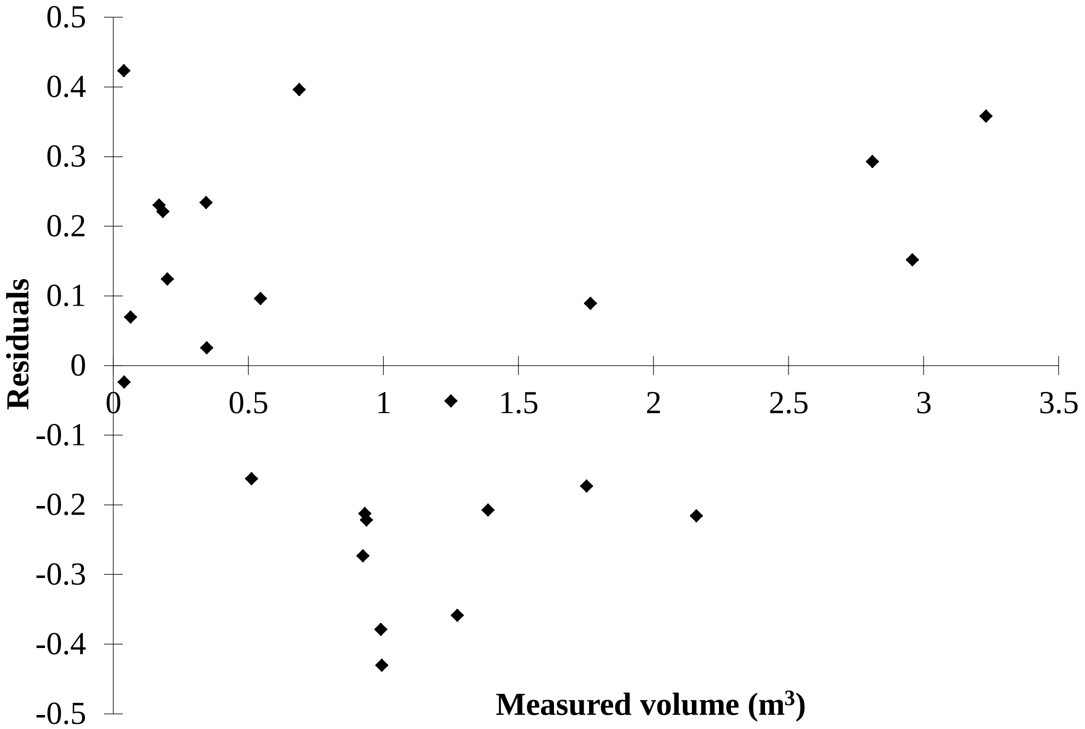

Figure 4.38: Residual plots for relationship between the new model and KFS model for *Pinus patula.*

On the other hand, the model developed for *Pinus patula* during this study was: Ṽ = 0.1994 + 0.0685(dbh) - 0.1525H + 0.0039H^2 (Equation 14). The relationship between volume predicted by the new model and the measured volume had a high goodness of fit (R^2 = 0.9531, RMSE = 0.0902) as shown in figure 4.33. The residual plots were homoscedastic and normally distributed as shown in figure 4.34

CHAPTER FIVE

DISCUSSION

5.1 Growth models for *Cupressus lusitanica and Pinus patula* use in forest plantations on the Central region of Kenya

Plantations provide timber for economic purposes and therefore there is a constant need to establish methods of estimating the forest resources. In this study, the growth models of two main forest plantation tree species in Kenya (*Cupressus lusitanica* and *Pinus patula*, 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 using 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, while for *P. patula* the height increased exponentially till the age of 25 years and then levelled off thereafter, 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 estimating initial conditions may have a greater effect on overall precision than contributions from the growth model.

The equation describing the growth of *C. lusistanica* and *P. patula* was therefore established to be exponential. The *C. lusistanica* equation was $H_t = 8.0599(\text{Age})^{-5.1127}$ while that of *P. patula* was of the form $H_t = 12.531(\text{Age})^{-14.025}$. The equations suggest that *P. patula* has higher absolute b coefficient than *C. lusistanica*. The b coefficient represents the slope or the growth rate of the trees and hence based on slopes, *P. patula* exhibit higher growth coefficient that *C. lusistanica* and could explain higher growth rate than that of *C. lusitanica*. These equations take 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 for the two species. The equation relating predicted tree height ($\hat{H}_t$) and age of *C. lusitanica* was exponential of the form, $\hat{H}_t = 3.9646 \times Age^{0.5157}$, while for the *P. patula* it took the form $\hat{H}_t = 5.2135 + Age^{0.792}$. These results suggest that growth of *P. patula* is not dependent only on age, but other components may be important. Therefore, determination of the height of *P. patula* requires knowledge of the other parameters other than age alone (for example, dbh), which agrees with other studies on this species (Domec and Gartner, 2003; Stephens and Gill, 2005).

The tree height and dbh showed exponential relationship for *C. lusitanica* where there is linear increase in height as dbh increase upto 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). On the other hand, relationship between tree height and dbh *P. patula* showed sigmoid relationship where there is slow linear increase in height as dbh increase upto a dbh of 30 cm, then a phase of rapid increase in dbh upto 45 cm and then after which there is no subsequent increase in height in tandem with increase in dbh in agreement with Scott and Lesch, (1997).

The equation describing height and dbh was $H_t = -10.4673 + 6.5433(dbh)^{0.2776}$ in *C. lusitanica* while in *P. patula* the equation Ht = 5.1238 + 0.443(dbh). The equation relating predicted tree height ($\hat{H}_t$) and dbh of *C. lusitanica* was described using the equation: $\hat{H}_t = -12.5346 + 7.5589(dbh)^{0.3942}$. The equation relating predicted tree height ($\hat{H}_t$) and dbh of *P. patula* was described using the equation $\hat{H}_t = 5.1238 + 0.4443(dbh)$.

The relationship between dbh and age of the *C. lusitanica* showed exponential relationship where there is linear increase in dbh as age increases up to age of 28 years, after which there was no subsequent increase in dbh relative to the increase in age. The relationship between dbh and age in *P. patula* showed exponential relationship where there is linear increase in dbh as age increases up to age of 30 years, after which there was no subsequent increase in dbh relative to the increase in age. This is agreement with other studies (Kush, 2004; Scott and Lesch, 1997).

The equation describing the relationship between dbh and age of *C. lusitanica* was fully fitted using an exponential equation of the model: $\text{dbh} = 27.7031(\text{Age})^{43.836}$. Using the above equation, we were able to predict dbh (Ďbĥ) from age data. The predicted Ďbĥ based on age data of *C. lusitanica* was used to derive an equation of the form: $\check{D}b\hat{h} = 7.2894(\text{Age})^{0.4673}$. Equation for Ďbĥ based on age data of *P. patula* was the same as that of *C. lusitanica*. However, the *F* value for *C. lusitanica* was higher than that of *P. patula*. The confidence intervals at 95% confidence limit for coefficients of the *C lusitanica* equation were narrower than those of *P. patula.* Though the two model fits were significant, the fit for the *C. lusitanica* model was better, based on the foregoing.

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. This then emphasizes the usefulness of the above growth models. The models presented in this study are simple and they can easily be used for forest management decisions.

5.2 *Cupressus lusitanica* and *Pinus patula* yield models for use in forest plantations in Central regions of 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 measured volume and dbh as well as measured volume and height of the tree. The study was able develop the relationship with high model fit as has been reported in other studies elsewhere (Pereira *et al.*, 2017a, 2017b).

The equation describing the measured volume, height and dbh was developed for *Cupressus lusitanica* as $V = -\ 0.1247 + 0.02233(dbh)^2 - 0.0233H + 0.0012H^2$, which was subsequently used to predict the volume given H and dbh with a full model fit. At the same time, the relationship between measured volume and height of the *P. patula* was described using a third order differential equation of cubic function. The equation describing the measured volume, height and dbh was developed for *P. patula* as $\tilde{V} = 0.1994 + 0.0685(dbh) - 0.1525H + 0.0039H^2$. The derived equation was capable of predicting the volume given H and dbh. 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: 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). These errors could be reduced by ensuring adequate and appropriate data for model calibration (Breidenbach *et al*, 2014; and use of appropriate algorithms to improve on prediction, respectively.

5.3 Comparisons of developed and conventional models used in KFS management in Kenya

The model developed for *Cupressus lusitanica* during this study was:

$\tilde{V} = - 0.1247 + 0.02233(dbh)^2 - 0.0233H + 0.0012H^2$, while the KFS model developed in 1975 was: $\tilde{V} = 0.013152 - 0.00005069(dbh)^2 + 0.0001769(dbh)H + 0.00002895(dbh)^2H$

The relationship between the measured volume and volume predicted by the new model was linear with a high goodness of fit (($R^2 = 0.9561$, RMSE = 0.0873). this showed a high predictive power. On the other hand, the relationship between the measured volume and volume derived from the KFS model showed significant linear relationships, albeit with weak linear regression trends and low goodness of fit (Multiple R = 0.6077; RMSE = 0.5065). At lower measured volume below 0.2 m^3 and higher volumes (above 1 m^3), the KFS model overestimated the volume. However, for measured volume between 0.2 to 0.9 m^3, the KFS model underestimated the volume of the tree.

From the foregoing, the volumes of small trees below $0.2m^3$ and very large trees (over $1m^3$ are overestimated by the KFS model. This has an implication since timber merchants trading with KFS are disadvantaged when they purchase trees in these volume brackets. On the other hand, KFS is losing out when trees between 0.2 to $0.9m^3$ are sold.

The model developed for *Pinus patula* during this study was: $\tilde{V} = 0.1994 + 0.0685dbh - 0.1525H + 0.0039H^2$, while the KFS model developed in 1975 was: $V = -0.00041 - 0.0000571(dbh)^2 + 0.0001352(dbh)H + 0.00003313(dbh)^2H$. The relationship between the measured volume and volume predicted by the new model was linear with a high goodness of fit ($R^2 = 0.9531$, RMSE = 0.0902). This showed a high predictive power. On the other hand, the relationship between the measured volume and volume derived from the KFS model showed significant linear relationships, albeit with weak linear regression trends and low goodness of fit (Multiple R = 0.6185; RMSE = 0.4648). At lower volume below 0.7 m^3 and higher volumes > 2.7 m^3, the KFS model overestimated the volumes. However, volume between 0.7 to 2.4 m^3, the KFS model underestimated the volume of the tree.

Timber merchants purchasing trees from KFS are losing out when *P patula* trees less than 0.7m^3 as well as those above 2.7m^3 were traded. On the other hand, KFS was losing out financially when trees between 0.7 and 2.4m^3 were sold since this volume range is underestimated by the KFS model.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The study developed a set of growth models on height against age, height against dbh as well as the dhb versus age for *C. lusitanica* and *P. patula*. Tree height and age showed exponential relationship of the form $H_t = b(Age)^c$ for C. lusitanica and $H_t = b + Age^c$ for *P.patula*. For both species, height and dbh relationship was developed using models of the form $H_t = a + b(dbh)^c$ and dbh was related to the age by equation of the form $dbh = a(Age)^b$. The height and dbh for both species followed a linear trend of the form $H_t = a + b(dbh)$. These results suggest that the models developed, and parameters were species specific suggesting that each species had its own set of models

The relationship between the volume measured by smalian formula and dbh and height of *C. lusitanica* and *P. patula* was developed using third order differential equation. At dbh lower than 0.2 m, the volume increased at slower rate, followed by an exponential increase in the volume between dbh 0.2 to 0.45m and then a plateau thereafter. Using dbh and height, the volume equation was developed for *Cupressus lusitanica* as $V = - 0.1247 + 0.02233(dbh)^2 - 0.0233H + 0.0012H^2$ and for *P. patula* as $\tilde{V} = 0.1994 + 0.0685dbh - 0.1525H + 0.0039H^2$. The predicted volume of the two tree species showed high model fit with measured volume during validation of the model.

It was established that the new models developed had better fit with the measured volume while KFS models overestimated trees with low volumes below 0.2 m^3 and high volume above 1 m^3 while underestimating volume between 0.2 to 0.8 m^3 in case of *C. lusitanica*. Meanwhile for *P. patula,* the new model showed better fit with measured volume. The KFS overestimated volume below 0.7 m^3 and high volumes above 2.7 m^3, while underestimating volumes between 0.7 to 2.4 m^3. These discrepancies have an effect on cost of saw-logs since the KFS models are used to calculate stumpage rates from state forest plantations.

6.2 Recommendations

6.2.1 Recommendations for management

There is little point in developing a growth model unless it is used. Although model development may have some implications for forest management, the greatest benefit will accrue if forest managers use the model to investigate forest management alternatives. It is therefore recommended that the models developed in this study are integrated into forest management systems and used to explore alternative forest management practices since they have been shown to perform better than the models currently in use by KFS.

All models have been described as imperfect; at best they are a simplification of complex processes. So, validation should be concerned with the inferences that may be drawn from a model rather than its "correctness”. Therefore, this study recommends that the developed models should further be validated using new data to determine their applicability beyond time of collection and to test for their validity. This validation should consider use of higher number of trees for destructive sampling than was used in this study.

6.2.2 Recommendations for further research

Further research is recommended on the effect of forest management practices on the models, which should involve rigorously controlled setup that will evaluate directly if the forest management practices can modify the models for prediction of growth and yields.

Further research is recommended to investigate the application of the developed models to other forest areas where these two species are grown.

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APPENDICES

Appendix 1: ANOVA showing the model relationship between height and age of *C. lusitanica* in plantations of the Central Region of Kenya

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2890.125	2890.125	361.1428	2.76E-54
Residual	317	2536.862	8.002721		
Total	318	5426.987			

Appendix 2: Parameters derived for the model relating the predicted tree height and age of *C. lusitanica* and ANOVA showing the model relationship.

Parameter	Estimate	Std	Lower 95% Confidence	Upper 95% Confidence
B	3.9646	0.1635	3.6438	4.2854
C	0.5157	0.0137	0.4888	0.5425

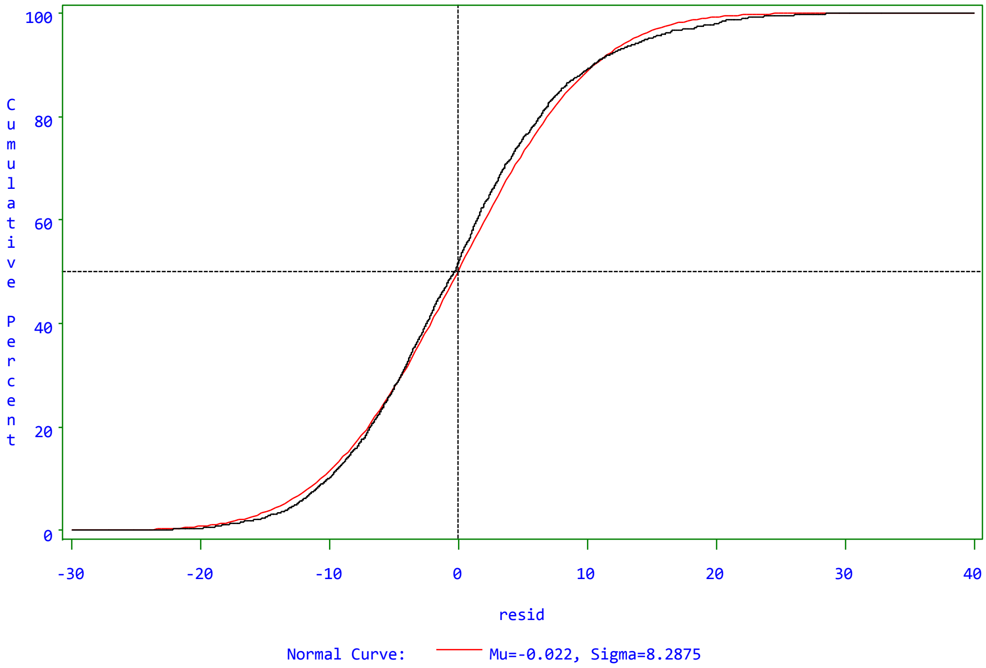
ANOVA table

Source of	Total sums of	df	Mean sums of	F	P
Model	341942	2	170971	11759.2	<.0001
Error	16807.4	1156	14.5393		
Uncorrected	358749	1158			

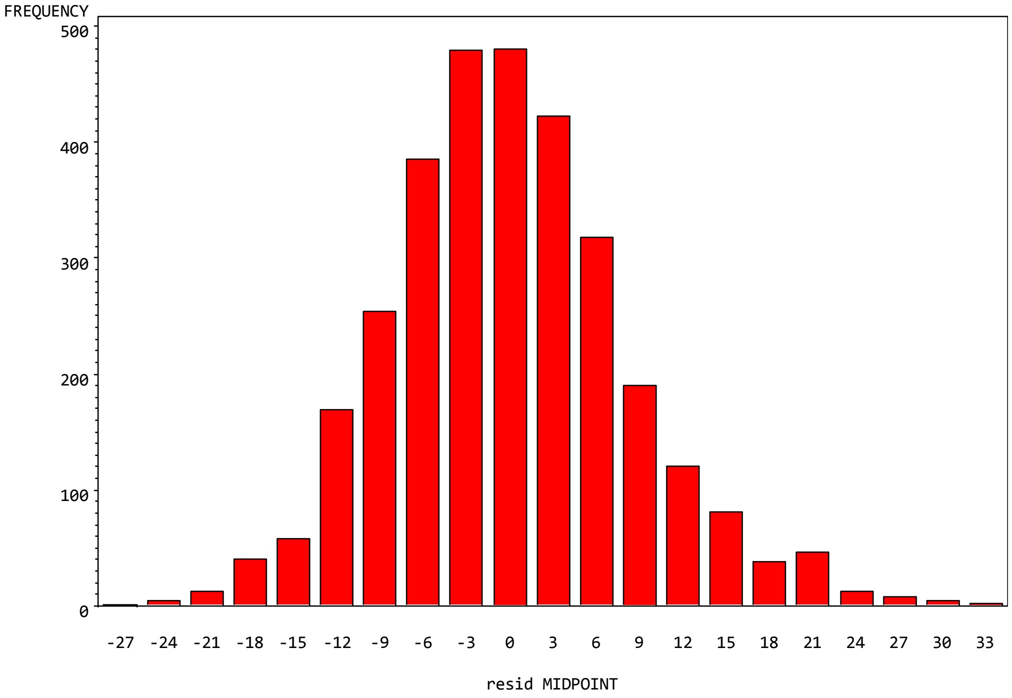
Appendix 3: Moments of the residual of model relationship between predicted height and age of *C. lusitanica* in Central Region of Kenya

Variable	Residual
N	1158
Mean	-0.0324417
Sum Observations	-37.567465
Std Deviation	3.81125743
Variance	14.5256832
Std Error Mean	0.11199896
Skewness	0.42075465
Kurtosis	0.46320409
Uncorrected SS	16807.4343
Corrected SS	16806.2155
Coeff Variation	-11748.027

Appendix 4: Normal cumulative curve for relationship between predicted height and age of *C. lusitanica* in Central Region of Kenya



Appendix 5: Frequency distribution plots of predicted height and age of *C. lusitanica* in Central Region of Kenya



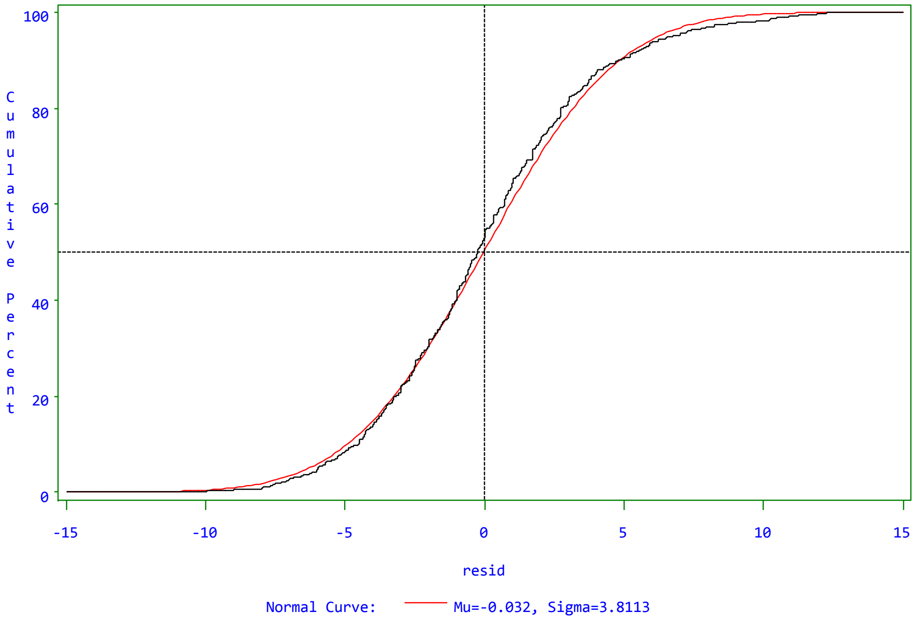
Appendix 6: Parameters derived for the model relating the tree height and dbh of *C. lusitanica* and ANOVA showing the model relationship

Parameter	Estimate	Std Error	Lower 95% Confidence Limits	Upper 95% Confidence Limits
a	-10.4673	3.1124	-13.4324	-8.8477
b	6.5433	2.6743	5.4522	8.7437
c	0.2776	0.0434	0.1221	0.3453

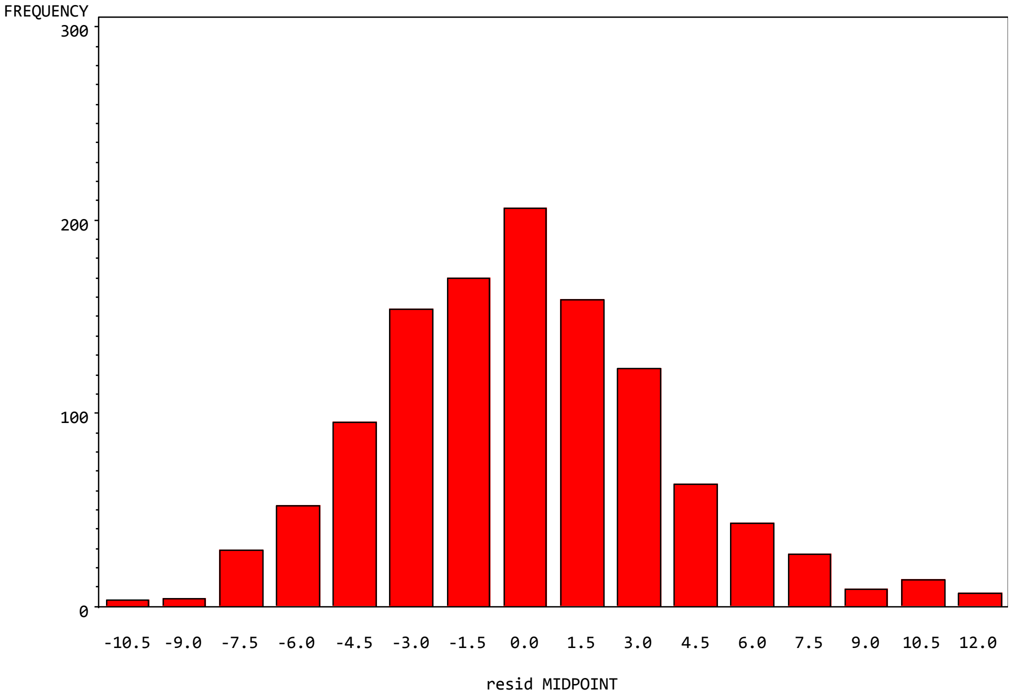
ANOVA table

Source of variation	Total sums of squares	df	Mean sums of squares	F	P
Model	241942	2	120971	9444.094	<.0001
Error	14807.4	1156	12.80917		
Uncorrected	358749	1158			

Appendix 7: Normal plots showing the relationship between height and dbh of the trees in Central Region of Kenya



Appendix 8: Frequency plots of residuals depicting the relationship between Height and dbh of the trees in Central Region of Kenya



Appendix 9: Parameters derived for the model relating the predicted tree height and dbh of *C. lusitanica* and ANOVA showing the model relationship

Parameter	Estimate	Std Error	Lower 95% Confidence	Upper 95% Confidence
a	-12.5346	4.9371	-22.2214	-2.8477
b	7.55589	3.1522	1.3742	13.7437
c	0.3842	0.0719	0.2531	0.5353

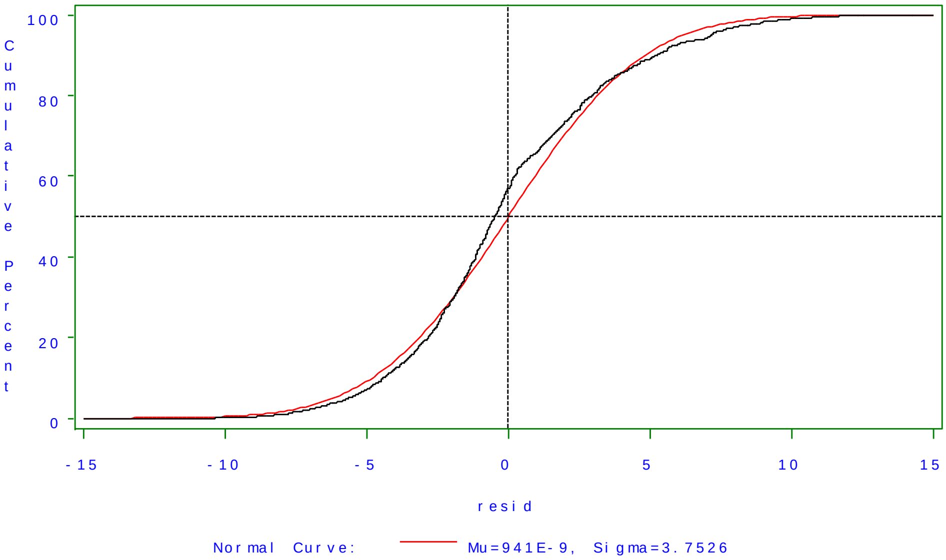
ANOVA table

Source of variation	Total sums of squares	df	Mean sums of squares	F	P
Model	25009.1	2	12504.5	886.4612	<.0001
Error	16292.6	1155	14.1062		
Uncorrected	41301.7	1157			

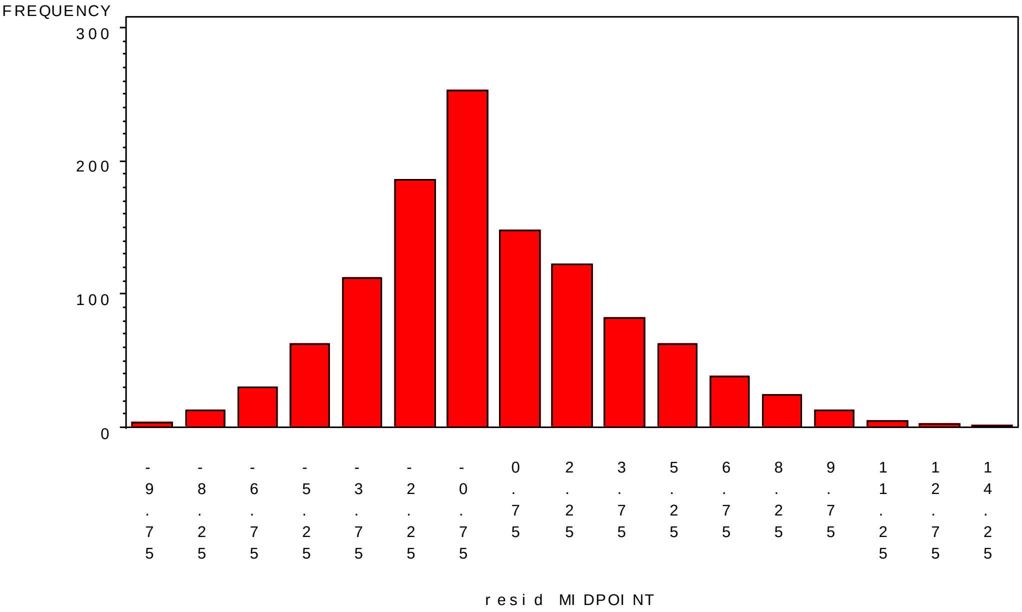
Appendix 10: Moments of the residuals of the relationship between predicted height and dbh of *C. lusitanica*.

Variable	Residual
N	1158
Mean	9.41217E-7
Sum Observations	0.00108993
Std Deviation	3.75256997
Variance	14.0817814
Std Error Mean	0.48639047
Skewness	0.4863904
Kurtosis	0.4296748
Uncorrected SS	16292.6211
Corrected SS	16292.6211
Coeff Variation	398693327

Appendix 11: Normal cumulative plots of height (Ĥ) and dbh of *C. lusitanica*.



Appendix 12: Residual frequency distribution plots of predicted height (Ĥ) and dbh of *C. lusitanica*.



Appendix 13: ANOVA Results showing relationship between dbh and age of *C. lusitanica*

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	55708.42	55708.42	1743.207	7.1E-131
Residual	317	10130.51	31.95743		
Total	318	65838.92			

Appendix 14: Parameters derived for the model relating the predicted diameter at breast height (Ďbĥ) and age of *C. lusitanica* and ANOVA showing the model relationship

Parameter	Estimate	Std Error	Lower 95% Confidence	Upper 95% Confidence
b	7.2894	0.2721	6.7560	7.8229
c	0.4673	0.0125	0.4429	0.4917

ANOVA table

Source of variation	Total sums of squares	df	Mean sums of squares	F	P
Model	2449888	2	1224944	17828.9	<.0001
Error	214568	3123	68.7056		
Uncorrected	2664456	3125			

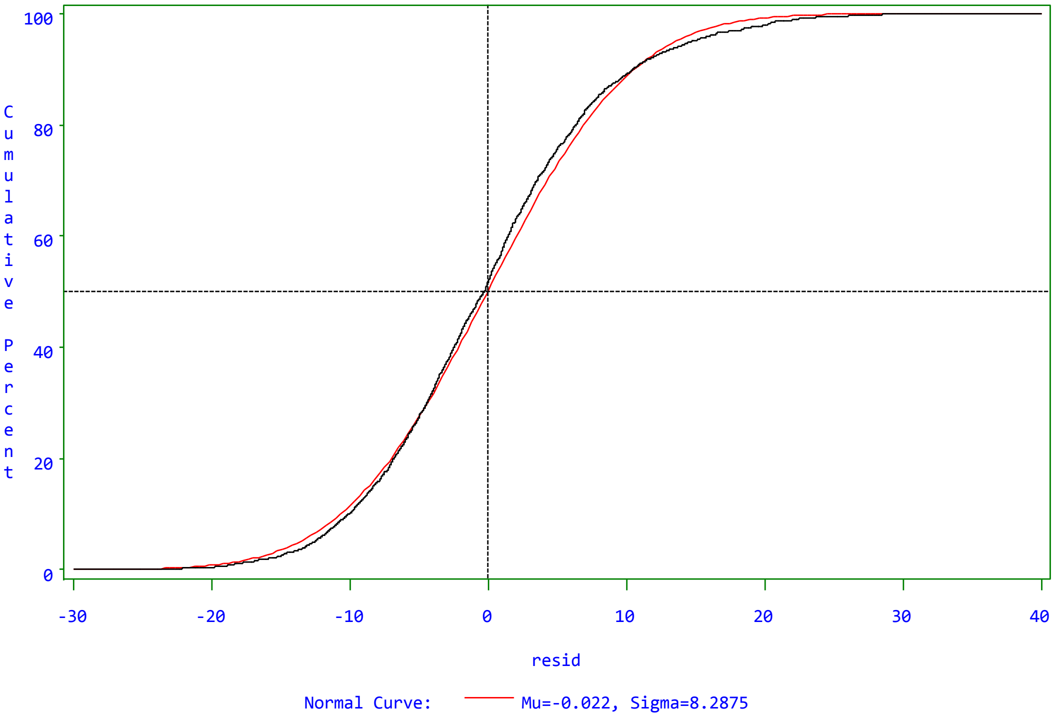
Appendix 15: Tests for Normality for the relationships between Ďbĥ and age of *C. lusitanica* in forest plantations on the Central region of Kenya

Test	Statistics	*P*-value
Kolmogorov-Smirnov	D 0.03532	Pr > D <0.0100
Cramer-von Mises	W-Sq 1.016847	Pr > W-Sq <0.0050
Anderson-Darling	A-Sq 6.908963	Pr > A-Sq <0.0050

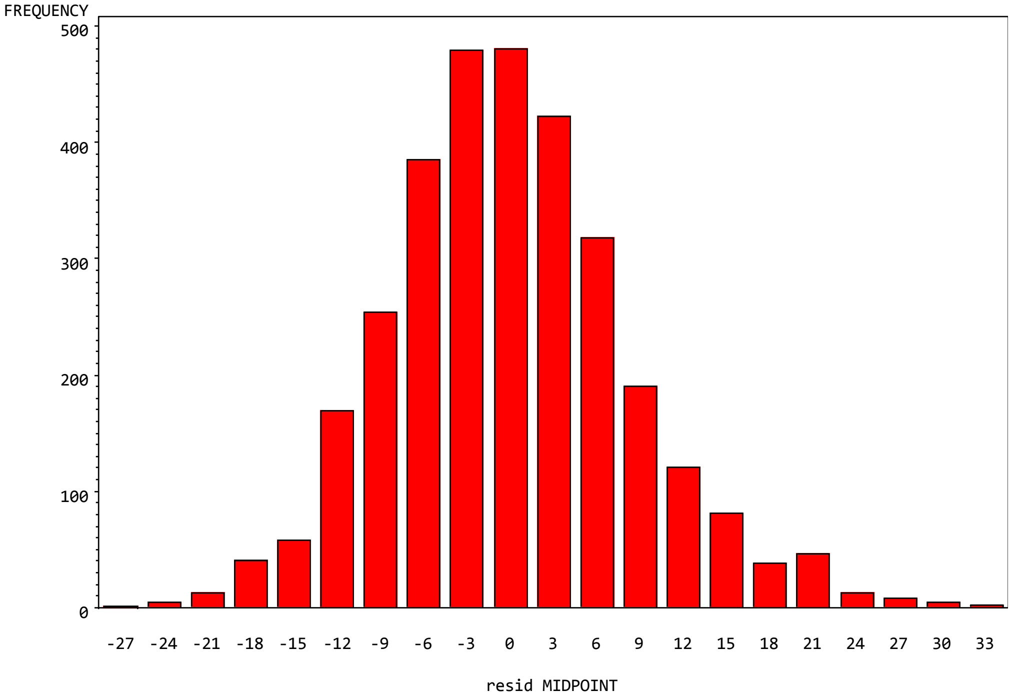
Appendix 16: Moments for the relationships between the residuals of Ďbĥ and age of *C. lusitanica* in forest plantations on the Central region of Kenya

N	3125
Mean	-0.02183
Sum Observations	-68.2460
Std Deviation	8.287530
Variance	68.6831
Skewness	0.38729
Kurtosis	0.5383
Uncorrected SS	214567.698
Corrected SS	214566.208
Coeff Variation	-37948.792
Std Error Mean	0.14825186

Appendix 17: Normal plots the relationships between the residuals of Ďbĥ and age of *C. lusitanica* in forest plantations on the Central region of Kenya



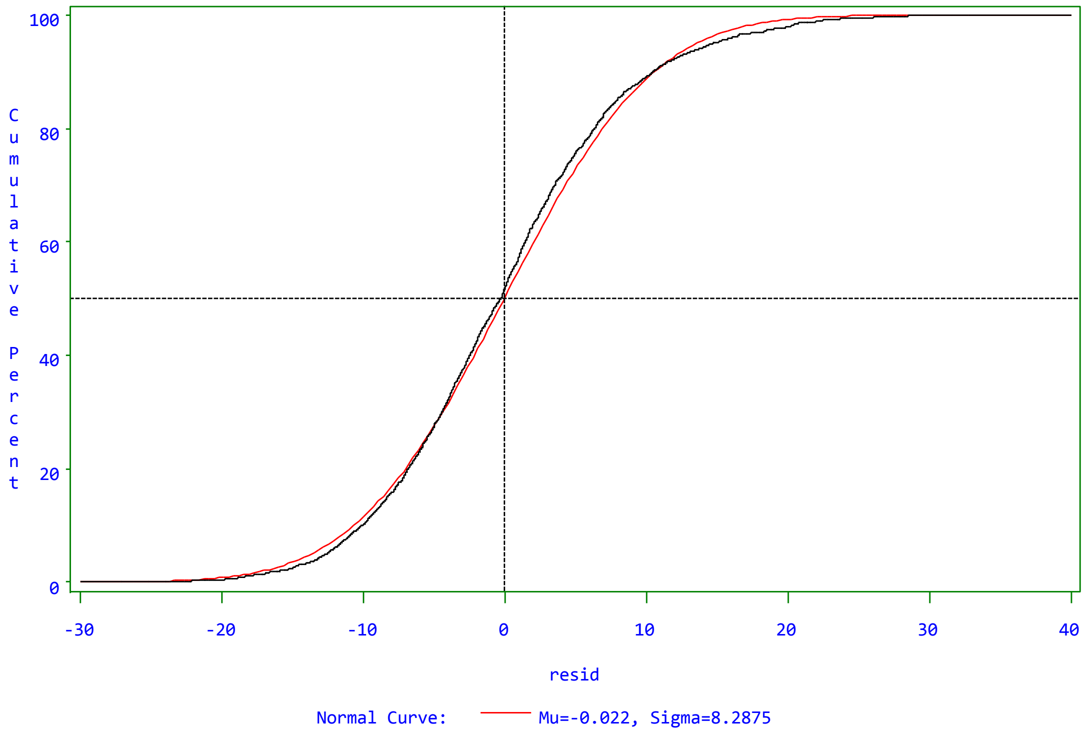
Appendix 18: Probability plots the relationships between the residuals of Ďbĥ and age of *C. lusitanica* in forest plantations on the Central region of Kenya



Appendix 19: Summary of ANOVA outputs for the relationship between Height and age of *P. patula* in Central Region of Kenya

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6910.716	6910.716	441.0462	5.37E-53
Residual	205	3212.128	15.66892		
Total	206	10122.84			

Appendix 20: Normal plots the relationships between the residuals of tree height and age of *P. patula* in forest plantations on the Central region of Kenya



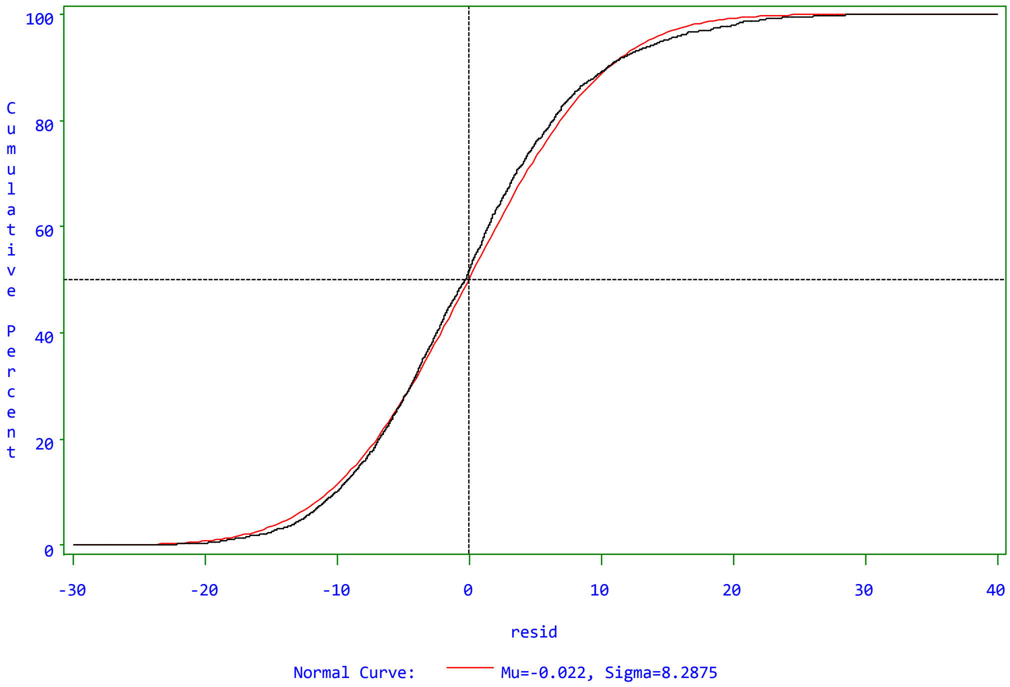
Appendix 21: Parameters derived for the model relating the predicted height ($\hat{H}$) and age of *P. patula*, regression and ANOVA showing the model relationship

Parameter	Estimate	Std Error	Lower 95% Confidence	Upper 95% Confidence
b	5.2135	0.2513	4.8742	5.6496
c	0.4793	0.0234	0.4529	0.4997

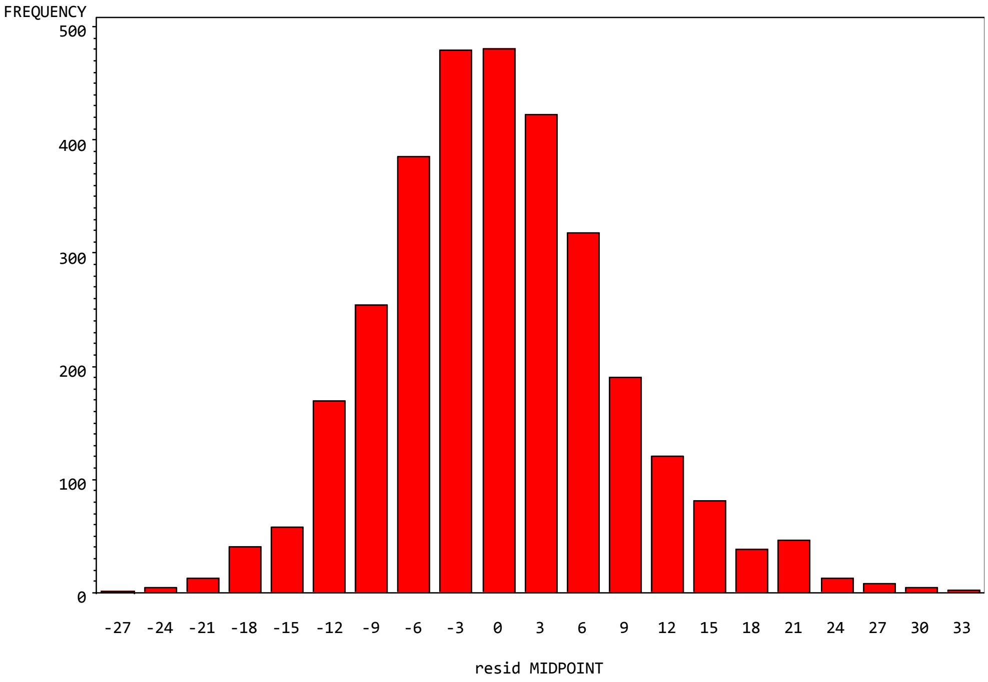
ANOVA table

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	5710.386	5710.386	13301.38	0.0000
Residual	205	88.00812	0.4293		
Total	206	5798.394			

Appendix 22: Normal plots of predicted tree height (Ĥ) and age of *P. patula* in forest plantations on the Central region of Kenya



Appendix 23: Probability plots of predicted tree height (Ĥ) and age of *P. patula* in forest plantations on the Central region of Kenya



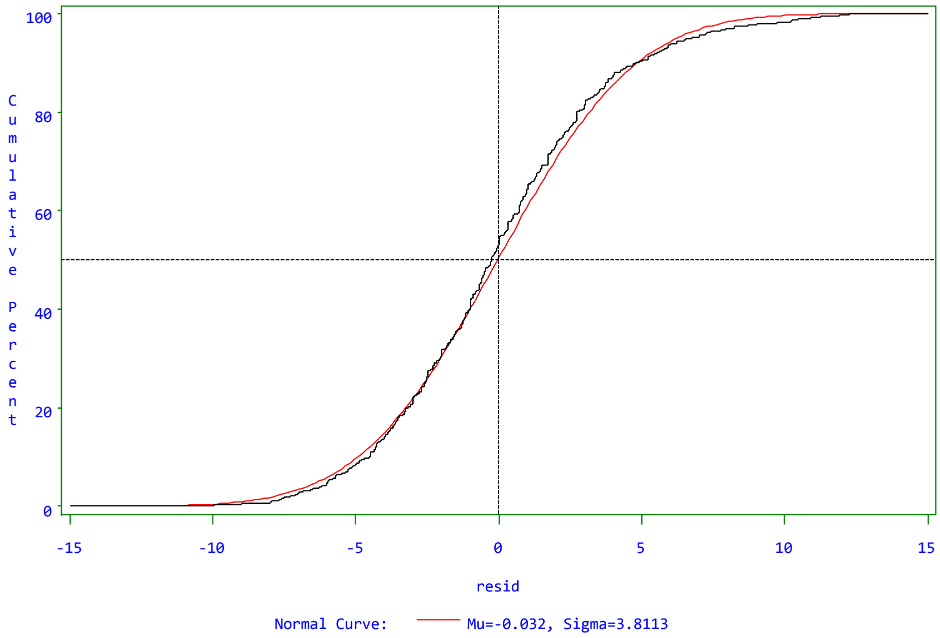
Appendix 24: Parameters derived for the model relating the height (H_t) and diameter at breast height (dbh) of *P patula* and ANOVA showing the model relationship

Parameter	Estimate	Std Error	Lower 95% Confidence	Upper 95% Confidence
b	5.1238	0.6631	3.8217	6.4258
c	0.4443	0.0159	0.4130	0.4756

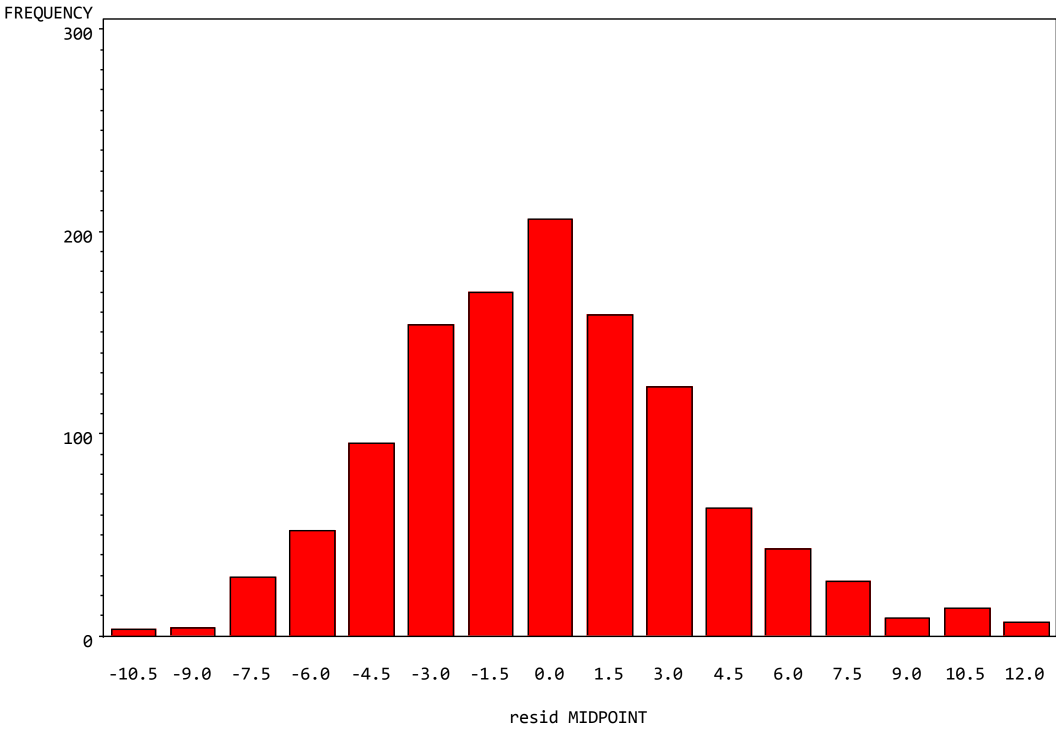
ANOVA table

Source of variation	Total sums of squares	df	Mean sums of squares	F	P
Model	24643.6	1	24643.6	776.52	<.0001
Error	21770.9	686	31.7360		
Uncorrected	46414.5	687			

Appendix 25: Normal plots showing the relationship between Height and dbh of *P. patula* in Central Region of Kenya



Appendix 26: Frequency plots of residuals depicting the relationship between Height and dbh of *Pinus patula* in Central Region of Kenya



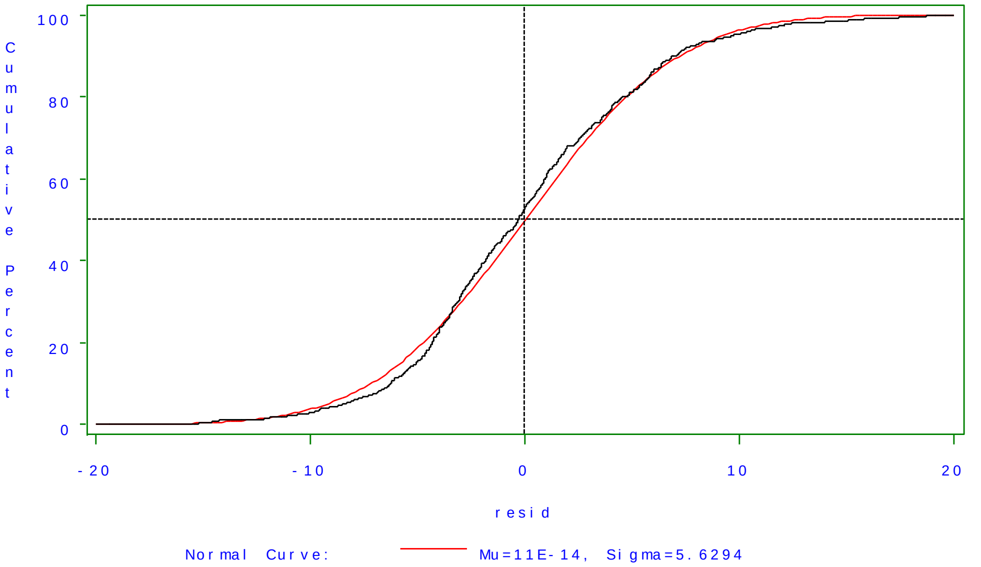
Appendix 27: Summary regression and ANOVA outputs for the relationship between predicted height and dbh of *P. pinus* in Central Region of Kenya

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.7019596
R Square	0.4927473
Adjusted R Square	0.4902729
Standard Error	3.7388033
Observations	207

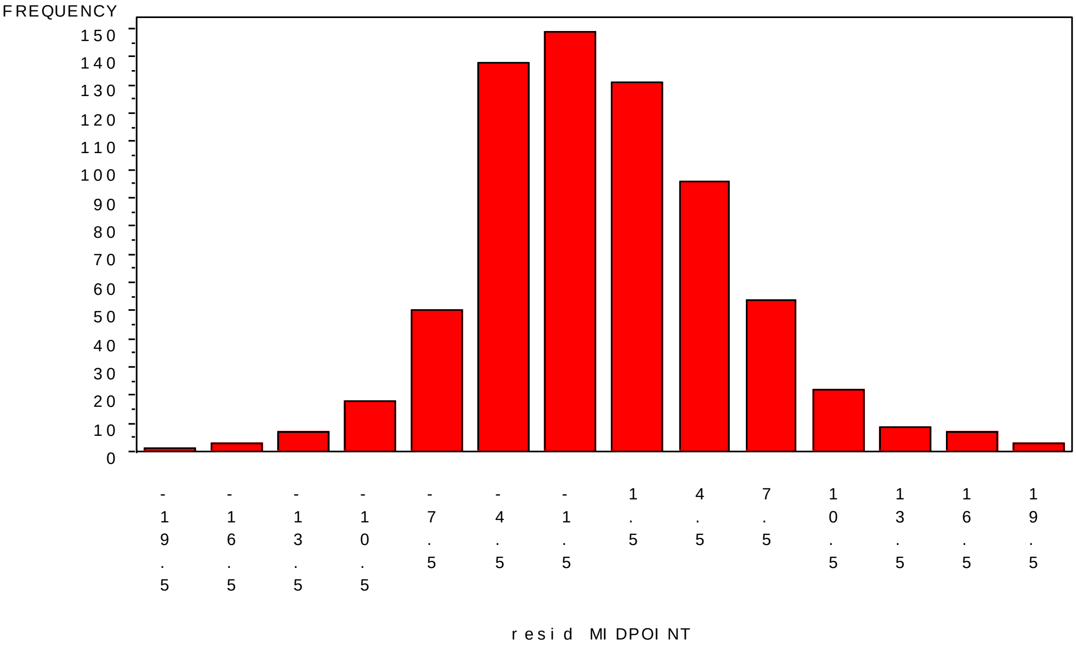
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2783.6779	2783.6779	199.1378	0.0000
Residual	205	2865.623281	13.9786		
Total	206	5649.3011			

Appendix 28: Normal cumulative plots of predicted tree height ($\hat{H}_t$) and dbh of *P. patula* in forest plantations on the Central region of Kenya



Appendix 29: Residual frequency distribution plots of predicted tree height ($\hat{H}_t$) and dbh of *P. patula* in forest plantations in the Central region of Kenya



Appendix 30: Parameters derived for the model relating the diameter at breast height (dbh) and age of *P.patula* and ANOVA showing the model relationship

Parameter	Estimate	Std Error	Lower 95% Confidence	Upper 95% Confidence
b	26.8034	0.1228	23.8217	30.1158
c	9.1636	0.0324	7.4130	11.4753

ANOVA table

Source of variation	Total sums of squares	df	Mean sums of squares	F	P
Model	24636.6	1	24636.6	776.83	<.0001
Error	21755.9	686	31.7141		
Uncorrected	46392.5	687			

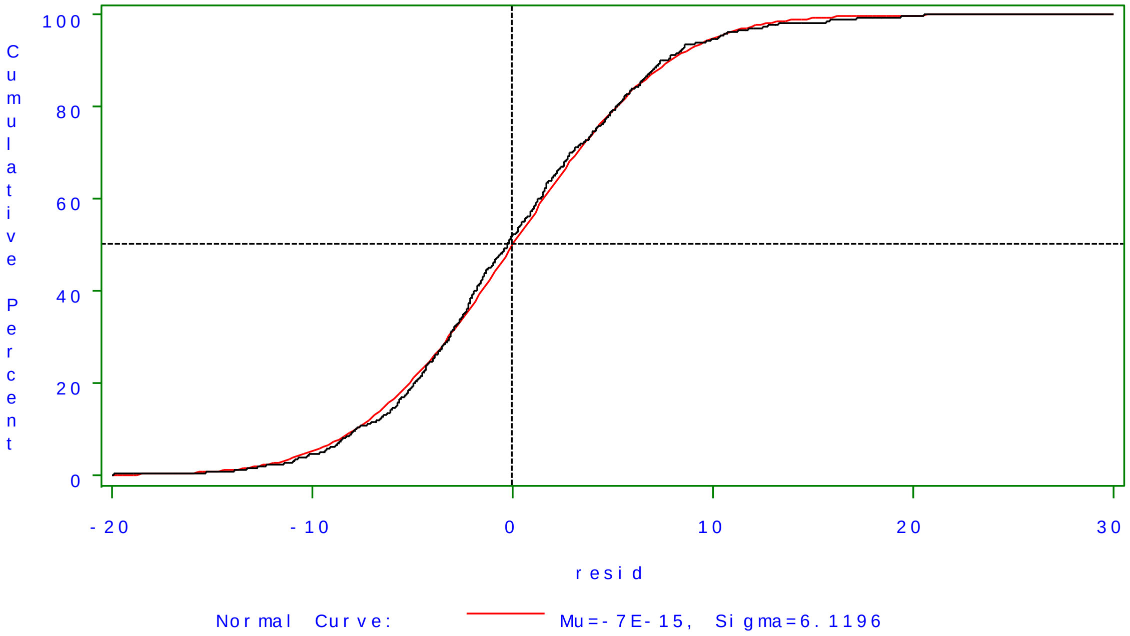
Appendix 31: Parameters derived for the model relating the predicted diameter at breast height (Ďbĥ) and age of *P. patula* and ANOVA showing the model relationship

Parameter	Estimate	Std Error	Lower 95% Confidence	Upper 95% Confidence
b	7.2894	0.2342	5.0114	9.4352
c	0.4673	0.1447	0.4122	0.5422

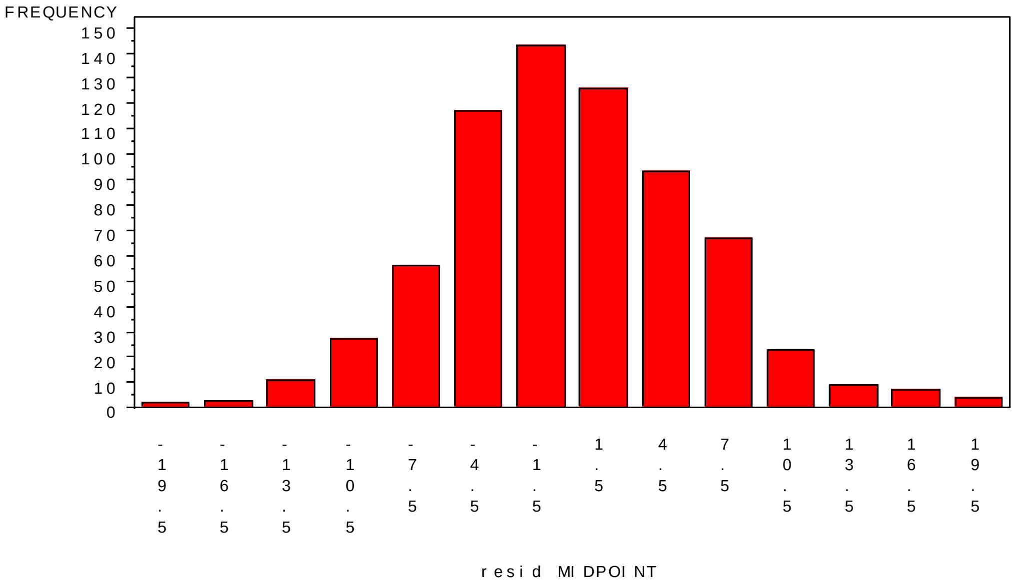
ANOVA table

Source of variation	Total sums of squares	df	Mean sums of squares	F	P
Model	25432.8	1	25432.8	853.46	<.0001
Error	20442.6	686	29.7997		
Uncorrected	45875.4	687			

Appendix 32: Normal plot of Ďbĥ and age of *P. patula* in forest plantations in the Central region of Kenya



Appendix 33: Cumulative percent curve for residuals of Ďbĥ and age of *P. patula* in forest plantations on the Central region of Kenya



Appendix 34: ANOVA showing the model relationship between measured volume and dbh of *Cupressus lusitanica*

Regression Statistics	
Multiple R	0.9396
R Square	0.8830
Adjusted R Square	0.8796
Standard Error	0.1474
Observations	37

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	5.7445	5.7445	264.1935	6.9911E-18
Residual	35	0.76102	0.0217		
Total	36	6.5055			

Appendix 35: ANOVA showing the model relationship between measured volume and height of *Cupressus lusitanica*

Regression Statistics	
Multiple R	0.81528
R Square	0.6646
Adjusted R Square	0.6551
Standard Error	0.2496
Observations	37

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	4.3241	4.3241	69.3799	8.0379E-10
Residual	35	2.1813	0.0623		
Total	36	6.5055			

Appendix 36: ANOVA showing the model relationship between smalian volume and volume derived from the KFS model for *Pinus patula*

Regression Statistics	
Multiple R	0.9230
R Square	0.8519
Adjusted R Square	0.8454
Standard Error	0.2590
Observations	25

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	8.8804	8.8804	132.3335	5.11E-11
Residual	23	1.5434	0.0671		
Total	24	10.423			