MODELING GROWTH AND YIELD OF *GREVILLEA ROBUSTA* GROWN ON FARM BOUNDARIES IN NANDI COUNTY, KENYA.

BY

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DECLARATION

DECLARATION BY THE CANDIDATE

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DEDICATION

I dedicate this work to God who gave me life, health, knowledge and opportunity to produce and accomplish this thesis in His own time. I thank my lovely wife Polyne for the support and encouragement she gave me throughout the span of my studies. I dedicate this work to her for taking care of our two children: Lameck Kiprono Lagat and Linet Chepchirchir Cheruiyot especially when the later was born when I was defending the thesis proposal. My father, Abraham Cheruiyot Randich and my mother, Sarah Tele Randich are acknowledged for the support and motivation to move on.

ABSTRACT

Population pressure has led to changes in land use and livelihood strategies in most highlands of Kenya. This among other factors has contributed to increased integration of fast growing exotic trees species into tree-crop production systems on short rotation for socio-economic benefits. *Grevillea robusta* is one of the exotic species in Kenya planted along farm boundaries for fuel wood and timber production. . It is preferred by most farmers because of its fast growth and yield as well as its suitability to be integrated with crops. This study investigated growth and yield of *G. robusta* grown in line configuration boundary planting and their economic implication in Nandi County. The main objective was to model growth and yield of *G. robusta* grown on farm boundaries. Farmers growing *G. robusta* and knows its ages were identified and growth data (height, diameter at breast height-dbh) collected. A total of 985 *G. robusta* trees of ages ranging from 1-15 years in 39 different locations within the Upper and lower highland agro-ecological zone in Nandi County were measured. Four independent variables: height, dbh, location and spacing were modeled against age. The results showed significant differences among trees height (P=0.0001), basal area calculated from dbh (P=0.0001) and location (P=0.0001). Spacing was not significant (P=0.1993). Height took the form; $Ht = \alpha + \beta * (Age^{\theta})$ while dbh was $Dbh = \alpha + \beta * (Age^{\theta})$ where; *Ht* = tree height, *Dbh* = diameter at breast height (1.3 m), Age = tree age in years and α, β and θ are estimated regression coefficients. The local volume equation; $V = (Dbh)^2 Ht$ was used to model volume because no farmer allowed their trees to be cut, where; *V* = Tree volume, *Dbh* = Tree diameter and *Ht* = Tree height. The study did not find overwhelming evidence (p>0.05) in support of different linear spacing distances. Thus further research, particularly as trees get bigger is recommended so as to advice on thinning for intermediate income. Boundary planting (line spacing) of *G. robusta* is a good system to be adopted in Nandi County.

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LIST OF ABREVIATIONS

BA- Basal Area

Dbh- Diameter at breast height (1.3m above the ground)

EFT-Ecological Field Theory

FAO- Food and Agriculture Organization

FD- Forest Department

G.R- *Grevillea robusta*

Ht- Height

KNBS - Kenya National Bureau of Statistics

KTDA-Kenya Tea Development Agency

LVEMP- Lake Victoria Environmental Management Project

MoE- Ministry of Energy

MRE- Mean Relative Error

NEMA- National Environmental Management Authority

Ppm- Parts per million

SS – Sum of squares

UN- United Nations

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CHAPTER ONE

INTRODUCTION

1.1 Background

The increasing population densities have led to continued subdivision of family land in many areas in Kenya resulting to wood fuel and timber shortages in highland areas. This has increased settlement of people in arid and semi-arid areas leading to increased demand for timber and other tree products in such areas (Okello *et al*., 2001). Rapid degradation of forests to meet household needs for tree products and land for cultivation has negatively impacted on tree resources. The shortage is partly because of reduction in farm lands. Farmers are not encouraged to take forestry as a business through logical analysis of tree growth and yield so as to make good decisions. Growth and yield models of *Grevillea robusta* grown on farm boundaries and easy access to quality forest seeds and seedlings of appropriate species in a given area is lacking.

Nandi County has an area of 2,784 km² and is located at an altitude of 1300-2500 meters above sea level, latitude 0º and 0º 34", longitude 34º 34"- 35º25"E. The temperatures of Nandi County range from a mean annual minimum of 22°C to a mean maximum of 23°C, with annual rainfall amounts of between 1,200 mm and 2,000 mm. The increasing population (about 752,965 in 2009) has continued to experience rapid subdivision of land to small holdings. This has led to a decline in forest cover and if action is not taken, then a serious deficit of tree products will be realized. About ten years ago, Lake Victoria Environmental Management Project (LVEMP) tried to improve the situation by encouraging farmers to plant trees on their farms in small woodlots and boundary planting. The initiative involved seedling production, strengthening the Kenya

Forest Department's extension services (now Kenya Forest Service), capacity building among local farmers in tree establishment and management. According to Matano and Ogweno (2003) over 15.57 million seedlings were planted, of which 85% was on farms and over 80% were *G. robusta* and *Eucalyptus saligna* planted on farms as woodlots, along boundaries and within homesteads. *E. saligna, Cupressus lusitanica and G. robusta* seedlings were preferred because they are fast growing species for fuel wood and timber (Ogweno *et al.*, 2001).

Tree growing cannot succeed if farmers are not encouraged to plant trees for their own benefit. Forestry should therefore provide not only services but financial benefits. This is achieved through economic appraisal to ascertain the benefits from growing trees when compared to other ventures. The analysis requires growth and yield models of the reference tree species. The models should be able to predict trees growth and yield at a given time.

According to the World Rainforest Movement (2011), Kenya's forests are rapidly declining at about 12,000 ha per year. Between 1990 and 2010, Kenya lost 6.5% (about 241,000ha) of its forest cover due to increasing demand for fuel wood, building material and other land uses.

A large section of Kenya is arid and semi-arid. This puts strain on the rest of the land because the economy is natural resource based (U.N. FAO 2005 and 2010; State of the world's forests, 2009,2007,2005,2003,2001)

Boundary planting of trees is a convenient way to increase tree cover because farmers embrace the practice because it does not interfere with agricultural crops and has economic returns from the trees. *G. robusta* as discussed by Imo *et al.* (2001) is a third preferred exotic species in Nandi County after *E. saligna* and *C. lusitanica*. The tree has been adopted as a major agroforestry tree species and is common on small-scale farms significantly contributing to household income (Holding *et al.*, 2006). Most farmers in Nandi County plant *G. robusta* on the boundary of their farms and homestead because of its fast growth and suitability to be integrated with other crops.

Growth and yield of trees varies spatially from plantations, woodlot to edge or boundary plantings calling for spatial modeling approach (Muchiri *et al.*, 2002). Spatial modeling of growth and yield of trees grown on boundary of farms is important for monitoring growth and yield to determine and management decisions by forest owner and the future ecological condition resulting from timber and wood fuel management. It is important to understand growth and yield potential of trees in a given area to optimize management goals. It is a risk for any manager or tree owner to make management decision without consulting output of growth and yield models. Models are also used for formulation of policy concerning forest resources (Meadows and Robinson, 2002). It is a long–term goal of growth and yield modeling to build models of greater accuracy over larger domains of applicability.

1.2 Problem Statement

Farmers in Nandi County grow *E. saligna*, *C. lusitanica* and *G. robusta* as major exotic species. *G. robusta* is third in preference after Eucalyptus and Cypress. However, *G. robusta* is gaining popularity since it takes a short time to mature. It is integrated with other crops on farms and is mostly grown on boundaries. The popularity is also accelerated by an increase in human and domestic livestock populations that has led to reduction in family land-holdings and forest cover. Adequate forest cover is a pre-requisite for sustainable agricultural systems, wildlife management and tourism. Forestry and agriculture is increasingly becoming the pivot of rural economy in Nandi County and effort to alleviate poverty cannot be successful if roles of trees and forests are not fully addressed. Eradication of poverty is closely linked to fight against deforestation. Even the poorest households know the importance of protecting the environment, land and water. However, they are forced to take desperate measures to survive and the weakest point of entry is to encroach into the forest (FAO, 2003; FAO, 2007).

1.3 Justification

The effect of linear spacing, rather than the traditional square or rectangular spacing on growth and yield of *G. robusta* trees grown on farm boundary forms the basis of this research. There is a need to fill this gap because farmers in Nandi County do not have growth and yield models to help them determine and predict growth of *G. robusta* grown on farm boundary.

G. robusta is economically used in Nandi County as shade tree in tea plantations, firewood, timber, apiculture, charcoal, and wood carving. A good growth and Yield prediction model is important to enable accurate predictions of *G. robusta* products but also the outcomes of various management strategies. Spatial modeling of growth and yield of boundary trees will help farmers predict *G. robusta* products over time. This will encourage them to venture in the business of growing trees.

1.4 Objectives of the Study

1.4.1 Main Objective

The main objective of this study was to model growth and yield of *G. robusta* grown on farm boundaries in Nandi County, Kenya.

1.4.2 Specific objectives

1. To develop a height model for *G. robusta* grown in linear spacing on farms;

2. To develop a dbh model for *G. robusta* grown in linear spacing on farms;

3. To develop a volume model for *G. robusta* grown in linear spacing on farms; and

4. To assess the effect of spacing on growth and yield of *G. robusta* in linear spacing on farms.

1.4.3 Hypothesis

H_o: Linear spacing (boundary planting) does not significantly affect height growth of *G. robusta*

H_o: Linear spacing (boundary planting) does not significantly affect diameter growth of *G. robusta*

H_o: Linear spacing (boundary planting) does not significantly affect volume growth of *G. robusta*

H_o: Spacing significantly affects growth and yield of *G. robusta* grown on farm boundaries

CHAPTER TWO

LITERATURE REVIEW

2.1 Tree growing in Kenya

In Kenya, trees are commonly planted in plantations, woodlot, and boundary or in mixtures with agricultural crops. The increasing human population densities, intensive cultivation, repeated subdivision of family lands and rapid decrease in land available for farming are some of the major causes of wood fuel and timber shortages in the highland areas of Kenya (Ngugi and Brabley, 1986). As the human population increases, the size of farm land decreases and this has led to a change of farming methods.

The government of Kenya has been promoting tree planting at farm level with the aim of increasing tree cover to 10% by the year 2030 (Republic of Kenya, 2007). Farmers in Kenya have been successful in cultivating and managing trees in and around their farms. They have been able to increase tree cover, fuel wood supplies and infiltration of rain, provide protection against wind, and reduce runoff (Otengi *et al*., 2000) through boundary planting.

Numerous studies have examined the complementarities and competition between trees and crops (Namirembe, 1999; Lott *et al*., 2000b). However, a gap exist in regards to availability of growth and yield models of line spacing of boundary trees in different agro ecological zones. Although the impact of *G. robusta* on crop growth has been widely examined, there are no studies when grown on farm boundary. Tree growing along farm boundary has some level of competition for sunlight, water and nutrients which are influenced by spacing and weeding. The relationship between trees is usually competitive (Phiri *et al*., 1991). Modeling boundary growth applies the so-called ecological field theory (EFT) presented by Wu (Wu *et al.* 1985) and applied in other studies ((Kuuluvainen and Pukkala (1989); Pukkala (1989) and Miina and Pukkala (2002)) which suggest that the effect of growth resources can be described by equations showing the influence of the competing tree as a function of distance. Effects of spacing and management on growth and yield of trees is determined by equations which predict tree height, DBH, (or basal area) and volume as a function of spacing.

2.1.1 Tree growing in Nandi County

Agriculture is the main economic activity in Nandi County with many households earning from it. This includes; maize and dairy farming, tea-farming and small-scale tree growing. The tree cover in Nandi County has been declining due to population increase that has exerted pressure on land and wood. There is high demand for wood fuel for domestic use, schools, brick burning and in tea factories. Construction and capentry has also increased demand for wood.

LVEMP has been promoting tree planting in Nandi County to improve vegetation cover and provide sustainable supply of wood products.

2.1.2 Dominant Exotic Tree Species in Nandi County

In Nandi County, Eucalyptus species, Cypress and Grevillea are the dominant exotic species. According to Matano and Ogweno (2003), on private tree nurseries in Ndalat the main objective of seedling production in tree nurseries was to generate cash income and the biggest proportion was exotic tree species. The most common were *C. lusitanica, E. saligna, G. robusta* and *Aberia caffra* while those of indigenous species were *Zizigium quineense, Prunus africana, Cordia abyssinica* and *Brachylaena huilensis.* Passion fruits, avocado, guavas and mangos were the most common fruit seedlings in the private nurseries. Farmers had varied preferences for different tree species as discussed by Imo *et al.* (2001). Among the exotic tree species, the most preferred exotic tree species were *E. saligna*, *C. lusitanica* and *G. robusta* Matano and Ogweno (2003).

2.1.3 Wood Energy Demand in Kenya

Woodfuel contribute 70% of the National energy demand in Kenya while about 90% of Kenyan rural households use wood fuel either as firewood or charcoal (Ministry of Energy, 2002). Wood fuel meets over 93% of rural household energy needs whilst charcoal is the dominant fuel in urban households (Theuri, 2002; Kituyi, 2008). Woodfuel, therefore, is not only an important source of energy, but its use relates to public sector interest such as environment, public health, rural development, employment and even foreign exchange (Githiomi, 2010)

Firewood is domestically used for cooking, water heating, house heating, lighting and other home businesses. Households are the most important category in wood energy consumption with an estimated consumption of 6.5 tones per household per year (Mugo, 2001). The second highest consumer of wood fuel are the cottage industries which include brick making, tobacco curing, fish smoking, jaggaries and bakeries. Others include small restaurants/hotels and kiosks and learning institutions. On average, most cottage industries use between 20-30% of the total operation costs on energy which is mainly from wood (Ministry of Energy, 2002). Tea industries are also major fuel wood consumers in rural areas with over 50 small-scale tea factories spread in most Kenyan districts and run by Kenya Tea Development Agency (KTDA). Most of these factories are using wood-fired steam boilers to generate heat in order to reduce cost in tea production other than using furnace oil which is costly.

Table 2.1 was taken from Ministry of Energy (2002) Kamfor report and outlines the major changes in biomass consumption, supply and deficit/balances for the years 2000 to 2020 as far as households and cottage industries are concerned. The sustainable supply is computed using average annual increment. If the total annual wood fuel consumption is higher than the total sustainable supply, then a deficit is created as observed in Table 2.1

Table 2. 1: Projection of biomass consumption/Supply in Kenya.
(Source : MoE report, 2002)

Years	Year 2000	Year 2005	Year 2010	Year 2015	Year 2020
Population	28,686,607	32,694,444	36,810,671	40,941,673	44,981,767
Consumption tonnes/yr	35,119,615	39,896,632	44,599,347	49,164,960	53,416,327
Sustainable supply tonnes/yr	15,024,510	15,488,936	16,634,550	17,984,406	19,559,738
Deficit tonnes/yr	(20,095,105)	(24,407,696)	(27,964,797)	(31,180,555)	(33,856,539)
Deficit (%)	-57.2	-61.2	-62.7	-63.4	-63.4
Deficit (tonnes/person)	-0.701	-0.747	-0.760	-0.762	-0.753

2.2 Farm Forestry

2.2.1 Overview of farm forestry

According to Tengnas (1994), agroforestry, social forestry, community forestry, village forestry and farm forestry are all terms used to describe tree growing that is undertaken mainly outside gazetted forest areas. These terms are often used to describe very similar activities, but in theory they have slightly different meanings.

Agroforestry is a land-use system in which trees or shrubs are grown in association with agricultural crops, pastures or livestock. This integration of trees can either be a spatial arrangement-trees growing in a field at the same time as the crop, or in a time sequence-shrubs grown on a fallow for restoration of soil fertility. The trees are not necessarily planted but instead natural regeneration of trees may be protected, or mature trees may be deliberately left in the fields or pastures and hence described agroforestry as a much wider concept than tree planting; Social forestry is a slightly wider concept as it includes tree growing for ornamental purposes in urban areas and in avenues; Farm forestry can be regarded as almost synonymous to agroforestry, but it may also include large-scale forest production on private farms, an activity that would fall outside the definition of agroforestry; and finally, the term community forestry has been used to stress the involvement of people in tree-growing efforts, although people are, of course, much involved in all agroforestry activity, Tengnas (1994)

G. robusta has been successfully planted on farms because it provides economically viable products, and it can tolerate pollarding and pruning of its roots (Harwood and Booth, 1992). It has the ability to harvest water in the deeper horizons beneath the crop's rooting zone and to develop a cluster of roots that acquire nutrients from the soils deficient of phosphorus (Harwood and Booth, 1992). Dead leaves and twigs serve as manure in the topsoil layer (Raju 1992; Reddy, 1992). *G. robusta* is also easy to propagate and not significantly affected by pests and diseases. There is also the popular belief by farmers and supported by some research (Evan, 1990; Akyeampong *et al.* 1999), that *G. robusta* does not compete much with the agricultural crops and may even enhance yields of some crops. The most likely situation is that, with a given level of wood production, *G. robusta* does not compete as strongly with adjacent crop as the other tree species available to farmers because of its relatively light crown and deep rooting habit. The level of competition may also be regulated because *G. robusta* tolerates heavy stem pruning,

2.2.2 Significance of farm forestry

Farm forestry contributes significantly to tree cover in Kenya. High deficit of wood fuel and timber can be corrected through proper planning and support for farm forestry (Schuren and Snelder, 2008) supported through research on farm forestry systems that are diverse, efficient and easily adapted to the local condition (Adensinu and Chianu, 2002). The government of Kenya has been promoting tree planting at farm level with the aim of increasing tree cover to 10% by the year 2030 (Republic of Kenya, 2007). This initiative has led to successful tree planting programs involving rural communities guided by government extension services and various non-governmental organizations (Githiomi *et al.,* 2011).

Inadequate supply of wood fuel and timber in Kenya has led to overharvesting of trees leading to environmental degradation and loss of biodiversity (Nellie and Githiomi, 2009). The Kenya Forest Service strategic plan 2009 indicates that 10.385 million hectares of land is covered with trees on farmlands with wood stocking of about 9.7 m^3 ha^{-1}. In the year 2000, a comprehensive biomass study showed that the principal source of wood fuel is the farm lands with a production of 84% of the total wood fuel requirement (National Environmental Management Authority, 2004)

According to Ogweno *et al.* (eds 2009), private agricultural lands which includes farmlands supply 200,000 tones of wood per annum (Table 2.2)

Table 2. 2: Supply of wood fuel (in tones per annum) in Kenya in the early 2000. (Source : Ogweno *et al*., eds 2009)

Type	Wood supply – tonnes per annum
Forest reserves	168,000
Private agricultural land	200,000
Range Land, Government And Trust land	5,600,000
National parks and game reserves	Not applicable
Total wood fuel supply	5,968,000

2.2.3 Boundary planting

The main architectural arrangement of trees on farms is woodlot, along boundaries and within homesteads. Tree growing on farm boundaries is a very common practice and are planted in lines (Figure 2.1). The main objective is to demarcate farm boundaries (Tejwani, 1987). About 100% of the farmers surveyed in Kipkaren (Nandi County) practiced boundary planting of trees in linear spacing (Imo *et al*., 2001)

Figure 2. 1: Boundary planting of *Grevillea robusta* in Kapsabet. (Source : Author, 2012)

Boundary plantings increase tree cover, fuel wood supplies, infiltration of rain, protection against wind, and reduce runoff (Otengi *et al.*, 2000). In small-scale farming areas, boundary planting reduces wind speed. Trees on boundaries which are regularly pollarded can also meet most of a family's need for firewood. In addition, other tree products and services are obtained and the boundary is effectively demarcated. People with smaller land parcels have been noted to plant more trees per capita.

Planting trees to mark the boundary of a land parcel owned by a family is very common and has the advantage over other planting patterns because it is easy to establish and manage (Muchiri *et al.*, 2002). If trees are not well managed, there may be negative effects on crops, and if competitive species are planted, root competition may be a problem. Conflicts with neighbours may arise if the sharing arrangements are not well handled (Tengnas, 1994). The choice of planting method depends mainly on the size of the farm, needs and choices of the farm land owner or the environmental conditions favoring growth of trees. According to Matano and Ogweno, (2003), LVEMP's strategy in Nandi County has increased forest cover in Lake Victoria catchment areas and over 80% of seedlings were *G. robusta* and *E. saligna,* planted in farms.

The Government policy to increase the forest cover to 10% by 2030 (Republic of Kenya, 2007) and the legal notice no. 166 of November 2009 on Agricultural Act requires the farmers to maintain 10% of tree cover in agricultural holdings. This intervention strategy is supply oriented as it aims to increase wood fuel supply from farm lands. The major constraint to this strategy is the small pieces of land ownership by farmers and the competition of trees with the agricultural crops (Githiomi *et al.*, 2011) Boundary planting is therefore an appropriate measure to realize this objective.

2.3 Distribution and growth of *Grevillea robusta*

2.3.1 *Grevillea robusta*

Grevillea robusta A. Cunn., (Silky Oak or Silver Oak) is the largest species in the genus *Grevillea*, in the plant family Proteaceae. The name commemorates Charles F. Greville (1749-1809), one of the founders of the Royal Horticultural Society of London. It is a native of eastern coastal Australia, in riverine, subtropical and dry rainforest environments.

Its first introduction outside the natural range was in 1828 by the botanist Alan Cunningham who dispatched seeds to England (Harwood 1989). The species was introduced to Kenya around 1901 and by 1920 it had been widely planted on farms. The earliest time recorded for growing of *Grevillea robusta* was in 1910 (Wimbush, 1945) when the Forest Department recommended inter planting broad-leaved species to avert possible insect and fungal attack on monoculture plantations of cypress which by then was the most widely planted exotic species. Literature indicates that the tree was introduced to Uganda about 1901 and subsequently planted in coffee plantation in 1913 around Entebbe (Tothill, 1940). From the mid-1950s the tree has been favored by farmers because of the economic benefits derived from its use.

2.3.2 Climatic Range and its uses

G. robusta grows well in an altitude of 0-2300 m, Mean annual temperature of 14-23 to 25-31ºC, and a Mean annual rainfall of 600-1700 mm (Orwa *et al.*, 2009). Its uses include provision of poles, posts, firewood, mulch, climatic improvement, erosion control, and demarcation of farm boundaries, shade and various economic benefits. Due to its high ability to decay resulting to reduction of mechanical properties, *G. robusta* is recommended for use in furniture, wall, ceiling, roofing, flooring and selected fencing, where mechanical properties are secondary Mburu *et al* (2008)

G. robusta is one of the most important trees for agro forestry in the tropical highlands of Eastern and Central Africa. It is commonly planted as a boundary tree around the perimeter of small farms in a single row at 2–2.5 m spacing. It is also planted in rows between small fields, and as scattered individuals over crops such as coffee and maize (Spiers and Stewart, 1992).

2.3.3 Tree Management

Growth and yield of crops to a larger extent depends on the management of the trees by the farmer. Thus, choice of good seeds, good nursery regime, pre and post plant managements of the crops contributes a lot to tree growth and yield.

Under favorable climate, soil and moderate weed competition, annual height and diameter increments of *G. robusta* are at least 2 m and 2 cm, respectively (Orwa *et al.*, 2009). Annual height increments of 3 m have been observed at the most favorable sites. A plant density of 800-1200 trees ha^{-1} is recommended for plantations. Control of competing vegetation is required for the first 1-2 years after planting. Seedlings are normally planted at a spacing of 2.5-3 * 3-4 m. For firewood production, rotations of 10-20 years are applied and annual volume increments of 5-15 cubic m ha^{-1} may be expected (Orwa *et al.*, 2009).

According to Farahat *et al.* (2013), spraying the seedlings of *Grevillea robusta* with 100 or 200 ppm ascorbic acid significantly increased plant height, stem diameter, root length, leaves number/plant, fresh and dry weights of shoots and roots compared with untreated plants (control).

2.4. Growth and Yield Modeling

2.4.1 A model

Growth and yield prediction systems, or models, are abstraction, or a simplified representation, of some aspect of reality. According to the famous Oxford Dictionary, a model is defined as a simplified mathematical description of a system or process, used to assist calculations and predictions. It is a simplification of a real situation or phenomena based on mathematical or logical assumptions (Christian, 1975).

The central aim of forest growth modelling is directly related to the longevity of trees and stands. A given treatment regime for forest stands cannot be tested in short-term experiments. Long-term experiments on the other hand take too long, and upon conclusion the treatment model in question is presumably already outdated. The longevity of trees and forest stands forces the researcher to use theoretical and experimentally derived relationships and integrate these into growth models. The long-term consequences of given silvicultural prescription or possible disturbances can be simulated with the model and analyzed at the stand, enterprise, or landscape level. Consequently, with a reliable model, it is not necessary to respond to each new question by establishing new experiments.

2.4.2 Growth and Yield Model

Growth refers to the increase in dimensions of one or more individuals in a forest stand over a given period of time, while a growth model generally refers to a system of equations which can predict the growth and yield of a forest stand under a wide variety of conditions. It may comprise a series of mathematical equations which have numerical values embedded in them and the logic necessary to link these equations in a meaningful way using the computer code required to implement the model on a computer (Vanclay, 1994). There are different types of models in forestry which includes; Empirical growth and yield model, ecological model, process-based and hybrid model. Growth models comprise statistically derived equations describing empirical growth data from experiments or permanent sample plots and needs to be biologically sound (Kirongo, 2000). Empirical growth models are adequate for describing growth for a range of silvicultural practices and site conditions. A growth model may also embrace yield tables and curves, which are analogous to equations, but which have been stated in a tabular or graphical form, rather than a mathematical form. Growth equation predicts the growth of diameter, basal area or volume in units per annum as a function of age and other stand characteristics.

Yield refers to the final dimensions of a forest stand at the end of a certain period. A yield equation would predict the diameter, stand basal area or total volume production attained at a specified age Vanclay (1994)

Growth and yield are related, for while growth is the rate of production, yield is the total production over a given time period. Mathematically, if yield is **Y**, growth is the derivative **dY/dt** (Hyink and Zedaker, 1987) in Figure 2.2.

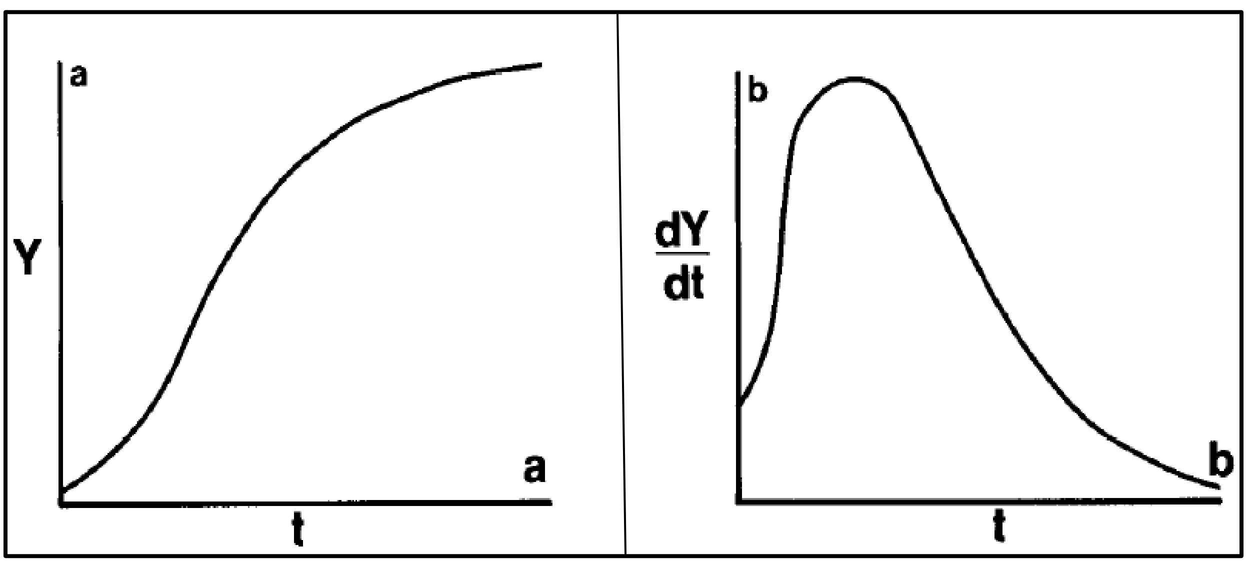


Figure 2. 2: The sigmoidal pattern of yield (a) and its associated growth curve over time (b). (Source : Hyink and Zedaker , 1987)

Although the rates of growth varies widely among different tree species, the general pattern of growth is remarkably consistent characterized by “S” or sigmoid shape as shown in the figure 2.2a. When plotted as a derivative (Figure 2.2b), the pattern of tree growth becomes more apparent. All the dimensions including height, diameter, basal area, volume and weight, when plotted over an appropriate measure of time will exhibit the sigmoid shape (Hyink and Zedaker, 1987).

A tree model enables reasonable predictions to be made about tree growth and development. Growth modeling is an essential prerequisite for evaluating the consequences of a particular management action on the future management of a forest resource. An individual tree model is appropriate when the relevant size attributes of a tree and the attributes and coordinates of its immediate neighbors are available Klaus *et al.* (2001)

2.4.3 Modeling growth and yield in Kenya

Tree growth and yield models have been developed for predicting growth and yield of stands over the years using both individual and stand level approaches. In Kenya, growth and yield has been modeled for cypress and pines (Mathu and Philips, 1979). *G. robusta* yield has not been modeled despite the species being dominant in central highlands. However, information of both bole and branch wood is needed because *G. robusta* has its socio-economic benefits to farmers (Kamweti and Hanna, 1987).

G. robusta is randomly planted on the farms and it is better to think in terms of yield per tree. A yield per hectare can only be estimated by an assumption of the number of trees on farms. A figure of between 100 and 200 trees per hectare has been mentioned as providing a possible optimum yield (Poulsen, 1983).

2.4.4 Spatial Modeling Approach

The spatial distribution of trees (Muchiri *et al.*, 2002) varies from rather uniform to extremely aggregated patterns, calling for spatial modeling approach. The use of tree individual models for forest planning and forecasting is considered unrealistic alternative, but it has been shown, however, that these models are capable of producing more realistic predictions of tree growth than simple distribution models and that they can be used to explain variation in growth resulting from variations in forest structure (Pukkala, 1989). Further development of these important tools is thus essential, not only for mixed, uneven-aged forest, but also for plantation forests with regular spatial distribution which can often be reconstructed without difficulty.

2.4.5 Importance of growth and yield models

Every model has a unique characteristics and no one model is applicable in all situations. Differences among models stem from differences in the databases used to calibrate them and differences in model development. Growth models can provide a means for determining the carbon sequestration potential of on-farm tree planting (Ogweno and Mugabe, 2008)

Models aid researchers to understand the process of tree growth (Goulding, 1975) in response to environmental influences. They provide reliable method for forecasting future yields and for exploring impacts of various management and silvicultural options (Kirongo, 2000)

A model should provide information that is sufficiently accurate and detailed to suit the intended purpose. Flexibility to accommodate a range of stand conditions and management options may be an important quality. Some applications which may require growth models include site evaluation, testing hypotheses of growth, estimating expected yields, examining variability of yield, exploring silvicultural options. Site characteristics play a major role in tree growth and yield.

2.5 Determinants of tree growth and yield

The site differences may be due to soil factors such as fertility and drainage, climate factors such as temperature and rainfall patterns, topography factors such as elevation and aspect and other factors which include management and quality of seeds. Meaningful growth and yield forecasts require site differences which must be accurate as any bias may propagate through growth, mortality and recruitment functions to affect all modelling results.

In a study carried out to investigate the performance of *G. robusta* on various environmental conditions in Rwanda, analyses of variance demonstrated that fertile soil, intercropping and cultivation between trees considerably improved growth performance of *G. robusta*. Growth was negatively correlated with altitude with stands above 2300 m above sea level showing poor growth (Kalinganire, 1995)

2.5.1 Topography

Many trees in high altitudes grow more slowly than trees at lower elevations. This happens because in addition to thin air and cold temperatures, the soil has fewer nutrients, and there is less protection from high winds and storms which generally combines to create a hostile environment that is not conducive to some types of trees achieving full growth. These trees are unable to grow to full height because high altitude affects hydraulic pressure. Pressure is lower at higher altitudes and limits ill-adapted plants' ability to channel water through their vascular system. The result for these trees is slower and less robust (Coomes, 2006)

Height growth of most tree species is associated with topographic variables such as elevation and aspect. Incorporation of topographic details for each site will enhance a reasonable analysis of growth and yield estimates. Climatic variables can only give a general indication of site productivity because they do not account for any local variation in site like topography and management. Topographic details can easily be obtained from topographic maps or air photos. In areas of marked relief, topographic effects may be the dominant force controlling site productivity.

2.5.2 Tree spacing

Spacing is referred to as the distance between trees planted either in a rectangular, square or in a line form. According to a study done by Kirongo *et al.* (2012) on the Effect of Spacing and Genotype on Height and Diameter Growth of Four Eucalyptus Under Short Rotation, tree growth was significantly influenced by spacing and genotype with the best spacing being 2.4-by-1.0 m. Relative growth rates of height and dbh increased with distance between trees but decreased with age. The result from this study further showed the importance of species-site-matching using improved germplasm and planting trees at the correct spacing for optimal growth.

Spacing trials have traditionally been carried out to determine practical spacing for commercial tree crops to reduce intra-specific competition, optimize growth and get quick returns (Kirongo *et al.*, 2012). Good rainfall and crop husbandry alone does not ensure good growth. Individual trees will still need sufficient growing space to ensure optimum growth (Auld *et al.*, 1987, Evans, 1982)

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

The study was carried out in Nandi County which is located in the Rift Valley. It borders Uasin Gishu County to the North, Kakamega and Vihiga Counties to the West, Kisumu County to the South, Kericho County to the South-East and Baringo to the North-East, latitude of 0º and 34'', longitude of 34º 34''- 35º 25E with an altitude of 1300-2500 m. Nandi County (Figure 3) has an area of 2, 884.2 km² and a population of 752,965 which amounts to a population density of 261 people per km² (Kenya National Bureau of Statistics, 2009 report). This study was carried out in Kenya's lower highland (LH) and upper midland (UM) agro-ecological zones in Nandi County. Lower highlands Zone (LH) consist of LH0 (Forest Zone), LH1 (Tea-Dairy Zone), LH2 (Wheat/Maize-Pyrethrum Zone) and LH3 (Wheat/Maize-Barley Zone) while UM Zone consist of UM1 (Tea-Coffee Zone), UM2 (Coffee Zone), UM3 (Marginal Coffee Zone or (coffee-) Maize Zone) and UM4 (Sunflower-Maize Zone) (Figure 3) according to Jaetzold and Schmidt (1983). The average temperature of Nandi County is 18-25°C. Precipitation is very high and varies from 1,200 mm to 2000 mm, annually, (Jaetzold and Schmidt, 1983). The month of March marks the onsets of rains which continue to November with no clear-cut distinction between the long and short rains.

The area is generally an agricultural zone and major crops are tea, maize, wheat and multipurpose trees and shrubs. Its Agro-Ecological zones are shown in Figure 3.1. The key used is as stated above.

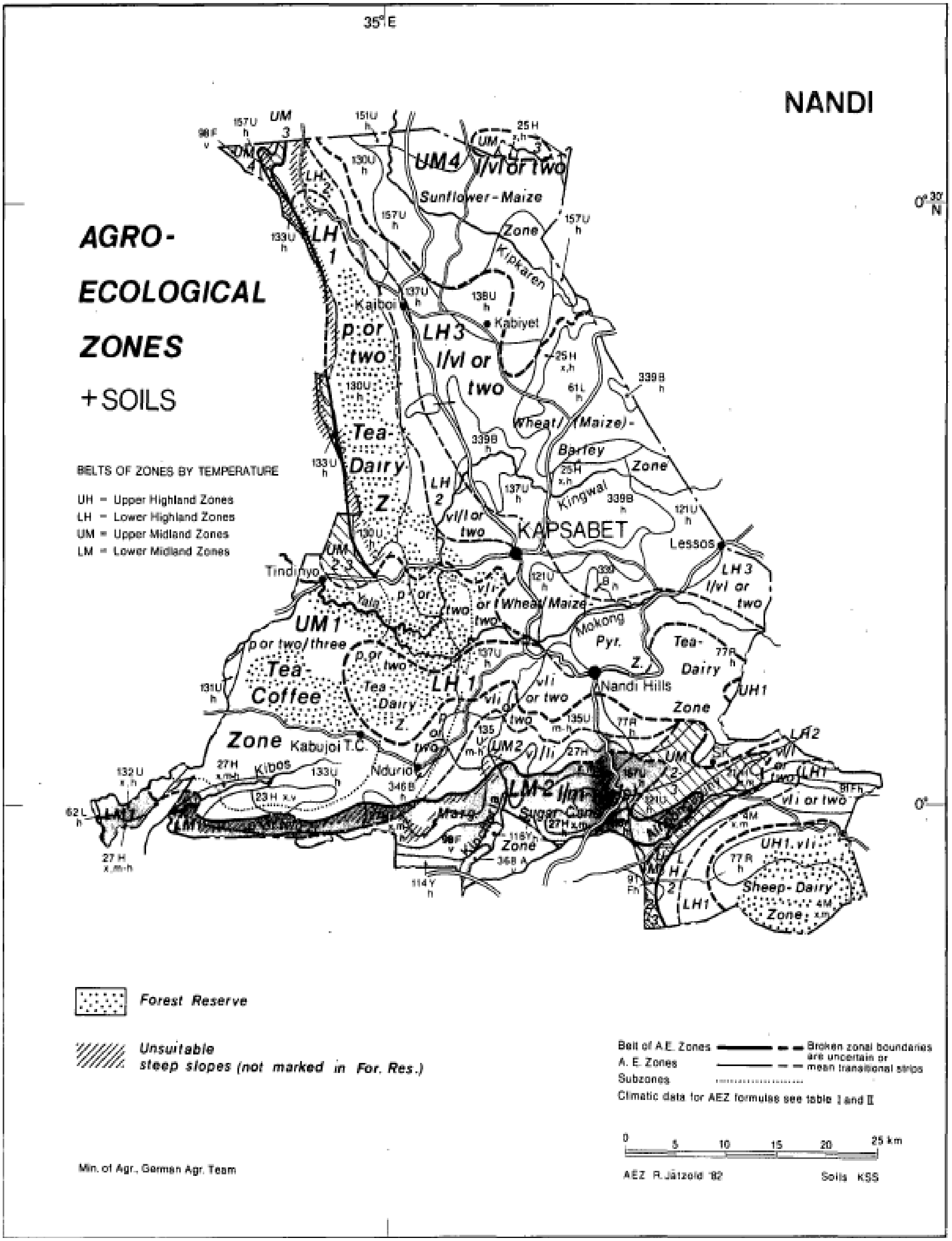


Figure 3. 1: Nandi County Agro-Ecological Zones. (Source : Jaetzold and Schmidt, 1983)

3.2 Materials

Tree height measurements were done with Suunto Clinometer, tape measure, height pole, and diameter by diameter tape.

3.3. Experimental Design

This study investigated growth and yield of *G. robusta* trees grown in line configuration boundary planting and their economic implication in Nandi County. A purposive sampling of farmers growing *G. robusta* who knew its age was identified and growth data (height, diameter at breast height – dbh) collected from willing farmers. A total of 985 trees of *G. robusta* of ages from 1-15 years in 39 different locations (not all points were shown in figure) within the upper midland and lower highland agro-ecological zone in Nandi County were measured. Five independent variables were height, diameter at breast height (dbh), location, spacing and age. Basal area (BA) was calculated and age was given by the farmers.

A topographic and agro-ecological zone map (Figures 3.1 and 3.2) were used to identify farming areas. Accessible and unequal sized sample plots were randomly and proportionately selected along the agro-ecological gradients. In each sample plot, complete enumeration of trees was done and information on the year of planting was obtained from the farmers' record for calculation of tree age.

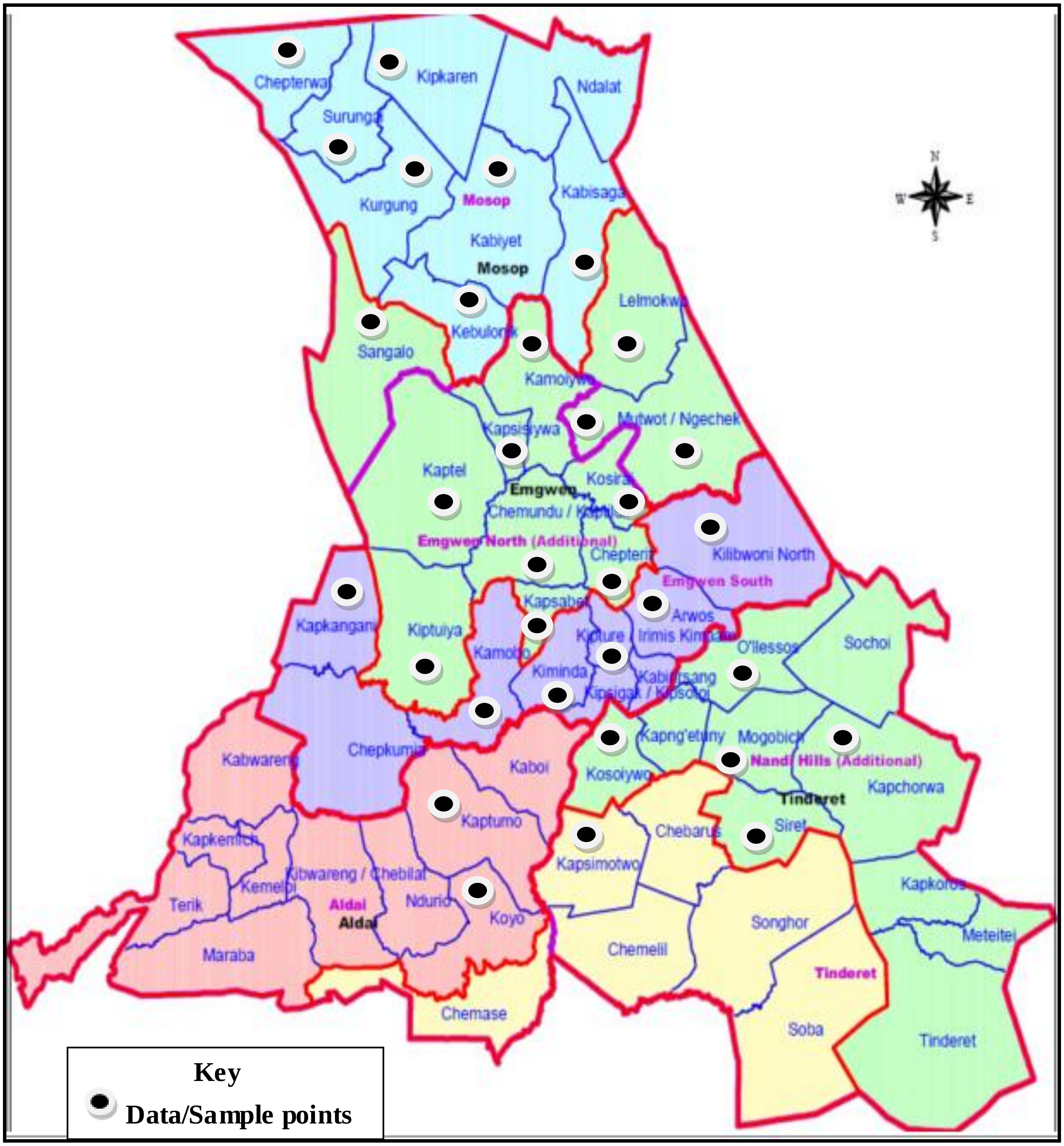


Figure 3. 2: A map of some administrative Locations in Nandi County.
(Source : KNBS, 2009, Kenya Population & Housing Census)

3.4 Tree measurements

A height pole was used to measure the height of trees which were below 15m and those above this height were measured using a Suunto Clinometer. The height of trees obtained from the height pole was read directly while the height obtained from a Suunto Clinometer was calculated by taking: $\%\ of\ total\ tree \frac{height}{100} * the\ distance\ \ between\ the\ observer\ and\ the\ tree$

Tree diameter was measured using a diameter tape at 1.3 m above the ground (Figure 3.3) generally known as diameter at breast height (dbh).

Figure 3. 3: Diameter at breast height (dbh) measurement. (Source : Author, 2012)

3.5 Data analysis

The data collected from 985 trees of various ages and locations (farms) were analyzed using SAS/STATS (2006) to identify the best growth and yield models (Height model, Dbh model and Volume model). Modelling tree growth and yield and further analysis on the effect of spacing on tree growth and yield were done in two steps.

Reid and Stephen, (2001) in farm forest line used the following formula to calculate tree basal area; *Basal area* = $\left(\frac{Ddh}{200}\right)^2 * 3.14$ and standing tree volume was calculated from dbh and total tree height as follows:

$$Tree\ volume(m^3) = Tree\ basal\ area\ (m^2) * Tree\frac{height\,(m)}{3}$$

$$V = \left(\frac{dbh}{200}\right)^2 * 3.142 * \frac{ht}{3}$$

The equation took the general form of exponential growth during the early phases of growth as characterized in young plantations (Mbelase, 2012) where:

Ht, Dbh ≈ f (Age, Spacing, Location + ϵ)

Volume was analyzed as a function of Basal area, Height, Spacing, Age and Location.

Volume ≈ f (Basal area, Height, Spacing, Age, Location + ϵ)

This study adopted mathematical equations of the general form;

$$Y_{ijk} = \mu + L_i + S_j + (LS)_{ij} + \epsilon_{ijk}$$

Where;

Y_{ijk} = Tree height and Dbh at a given age.

μ = Mean tree height and Dbh about which observations are assumed to vary.

L_i = Location effect.

S_j = Spacing effect.

$(LS)_{ij}$ = Interaction effect between location and spacing.

ϵ_{ijk} = Random error.

3.6 Analyzing the effect of location and spacing

The effect of location and spacing was analyzed by fitting a regression equation using a forward approach method using SAS/STAT (2006) to understand the most significant variable influencing volume.

CHAPTER FOUR

RESULTS

4.1 Height Model of *Grevillea robusta* in Nandi County

4.1.1 Height growth of *Grevillea robusta* in Nandi County

Height increment for *G. robusta* per age from 1 - 15 years in Nandi County increased in size over time. The different colors and symbols in Figure 4.1 describe observations in each of the 39 locations.

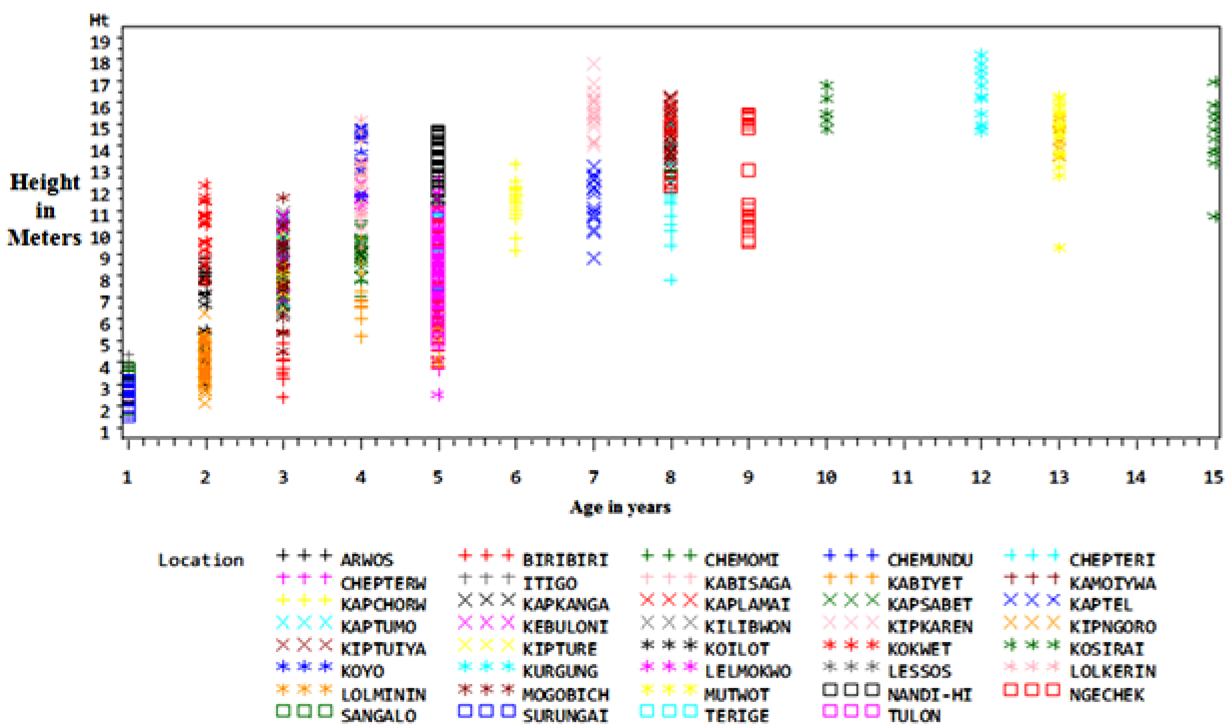


Figure 4. 1: Plot of *Grevillea robusta* mean height by age in Nandi County

4.1.2 Height Model

Height was modeled using the exponential equation, $Ht = \alpha + \beta * (Age^{\theta})$ where;

Ht = tree height,

α, β and θ = estimated regression coefficients

Age = age of the tree in years.

ANOVA showed that there was a significant increase in tree height with age ($F_{2,982} = 845.83$, $P < 0.0001$). Table 4.1 shows the results of fitting height equations to the data. Parameter estimates a, b and c of the height model is given representing estimated regression coefficients α, β and θ respectively.

Table 4. 1: Parameter estimates of fitting height equations to the data

Parameter	**Estimate**	**Approx Std Error**	**Approximate 95% Confidence**	
			Lower Limit	Upper Limit
a	-22.1003	11.2263	-44.1310	-0.0696
b	25.0071	11.0676	3.2880	46.7263
c	0.1566	0.0573	0.0441	0.2690

The choice of the model was based on the model significance, normal plots and acceptable trends of residuals shown in Table 4.2.

Table 4. 2: Moments of height Model

Moments			
N	985	Sum Weights	985
Mean	9.91458E-7	Sum Observations	0.00097659
Std Deviation	2.43340528	Variance	5.92146128
Skewness	-0.0096132	Kurtosis	-0.2523989

The Kolmogorov-Smirnov test for normality was chosen among the three other tests which includes; Shapiro-Wilk, Cramer-Von Mises and Anderson-Darling tests because of its p-value (P=0.0134) less than 0.05.

Residual by predicted plots showed acceptable trends of normality as illustrated in Figures 4.2, 4.3 and 4.4. The data as shown in Figure 4.2 are symmetrically distributed.

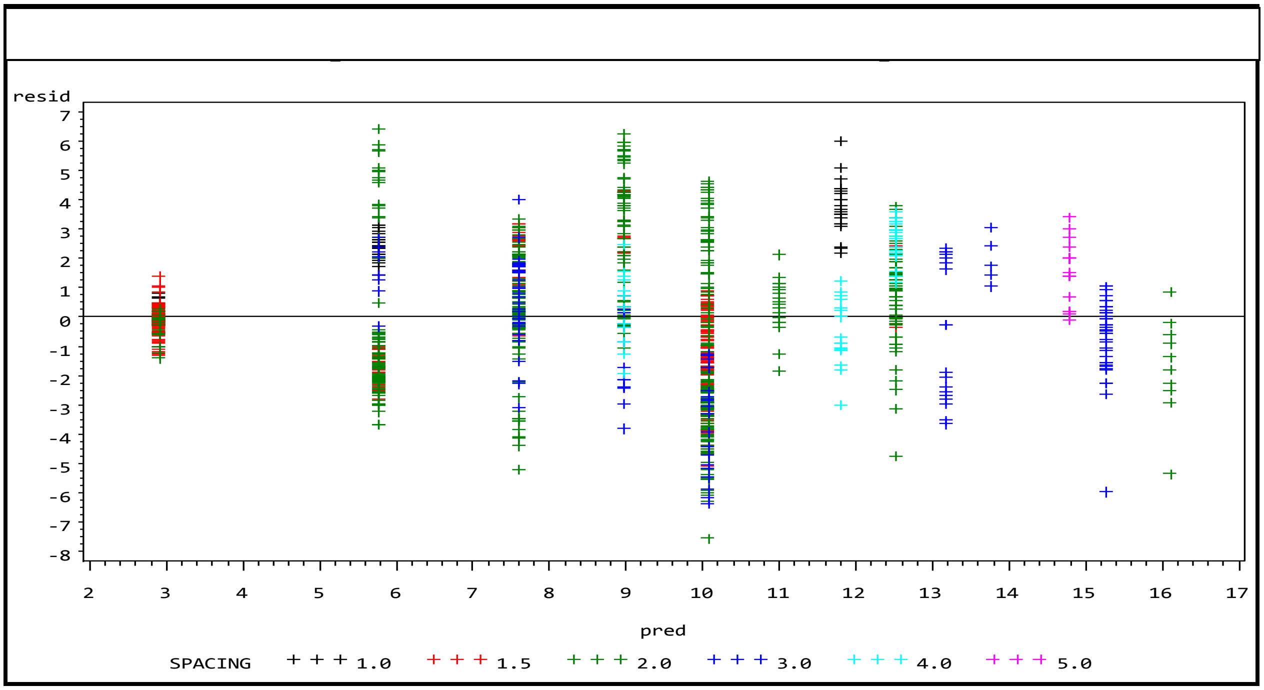


Figure 4. 2: Predicted Verses Residual for *G. robusta* height model in Nandi County

The data as shown in Figure 4.3 fits the normal curve.

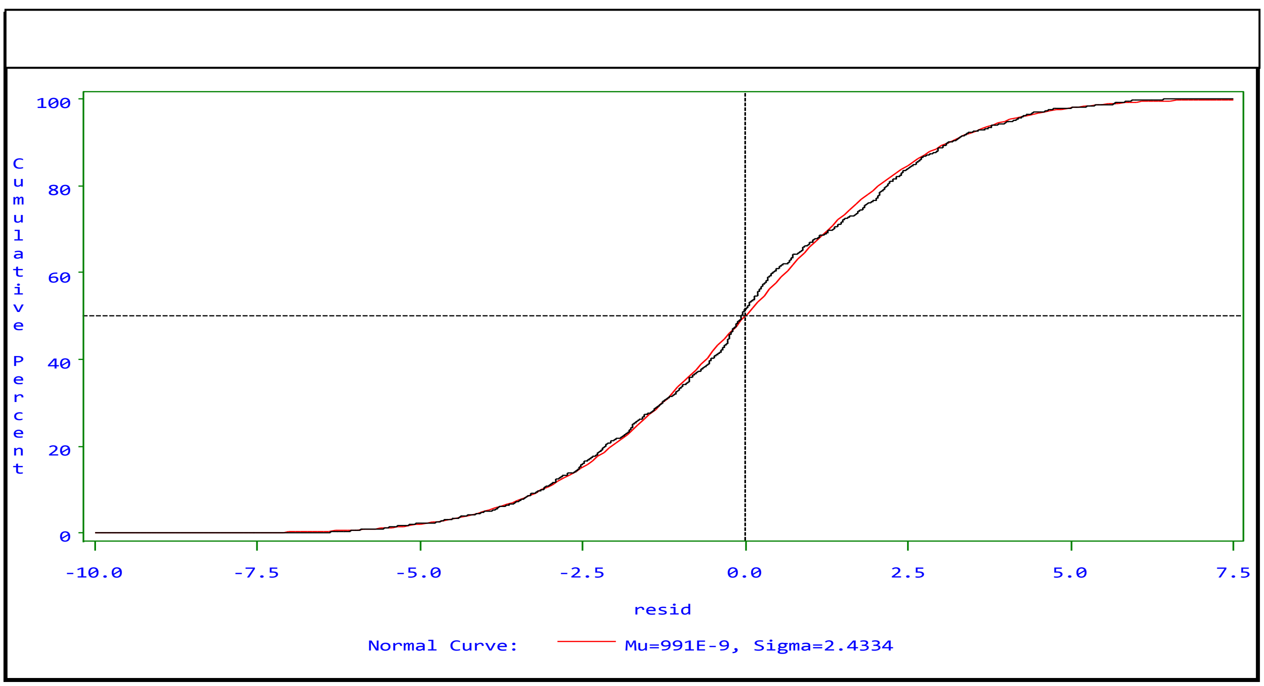


Figure 4. 3: Normal Height Curve

The frequency distribution of residuals (Figure 4.4) is acceptable though with slight disparity.

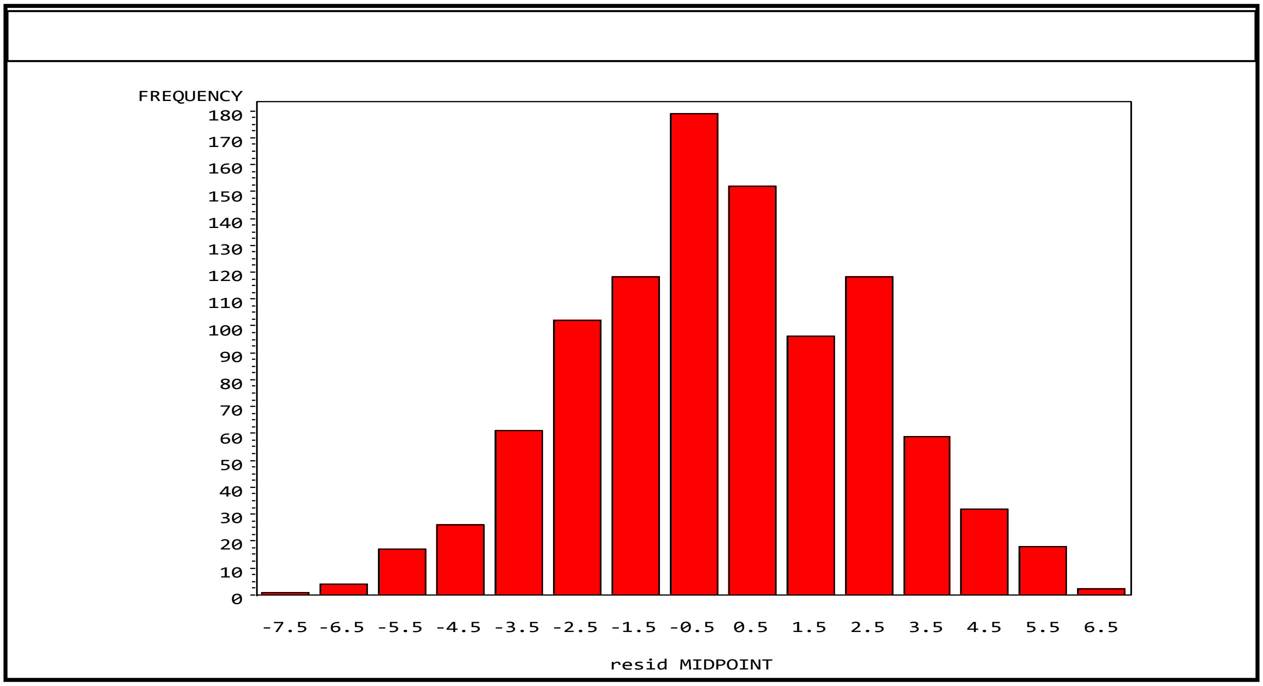


Figure 4. 4: Frequency distribution of residuals for height model for *G.robusta* in Nandi County

4.1.3 Height growth trajectory

The regression coefficients developed from the height model were used to plot height growth curve with age (Figure 4.5) using Microsoft Excel (2007) to show the resultant growth trajectory of *Grevillea robusta* trees in Nandi County. This represents reliable outputs as compared to observations made in the field.

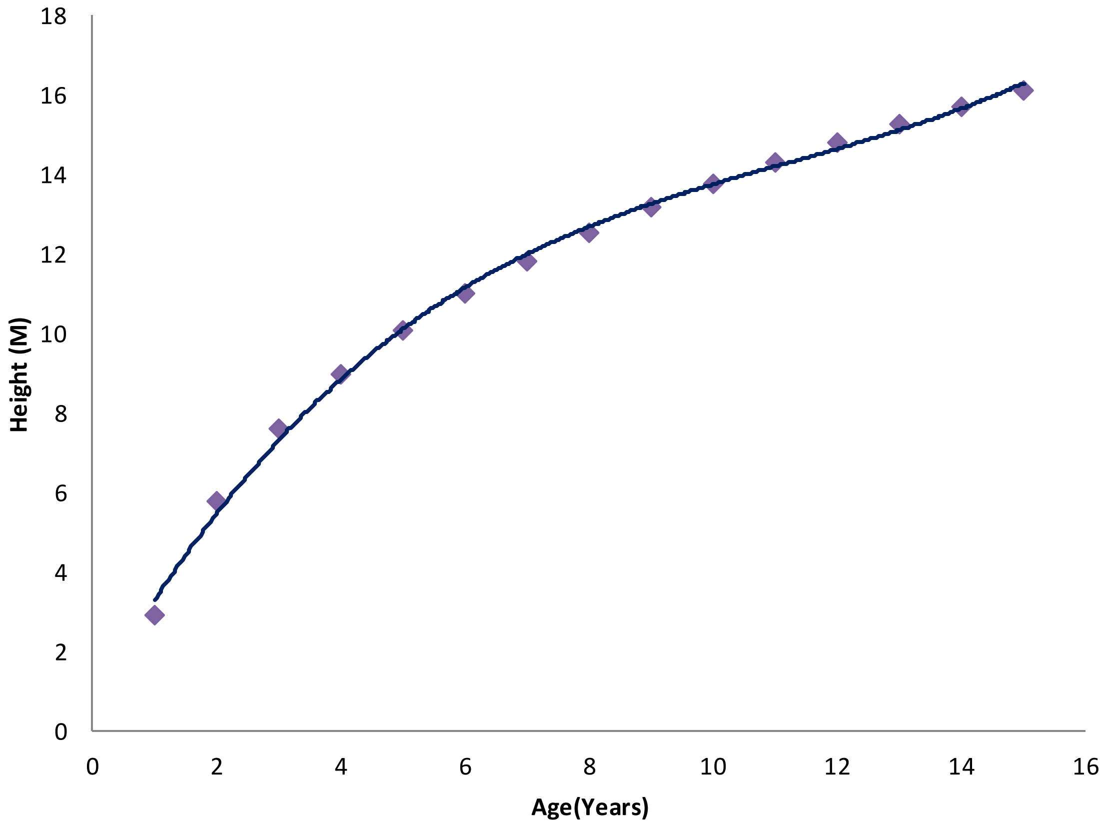


Figure 4. 5: Height growth trajectory for *Grevillea robusta* in Nandi County

4.2 Dbh Model of *Grevillea robusta* in Nandi County

4.2.1 Dbh growth of *Grevillea robusta* in Nandi County

The scattergram of dbh with age of *G. robusta* in the 39 locations (Figure 4.6) indicates that trees dbh increased with age. The different symbols and colors describe dbh measurements in different locations.

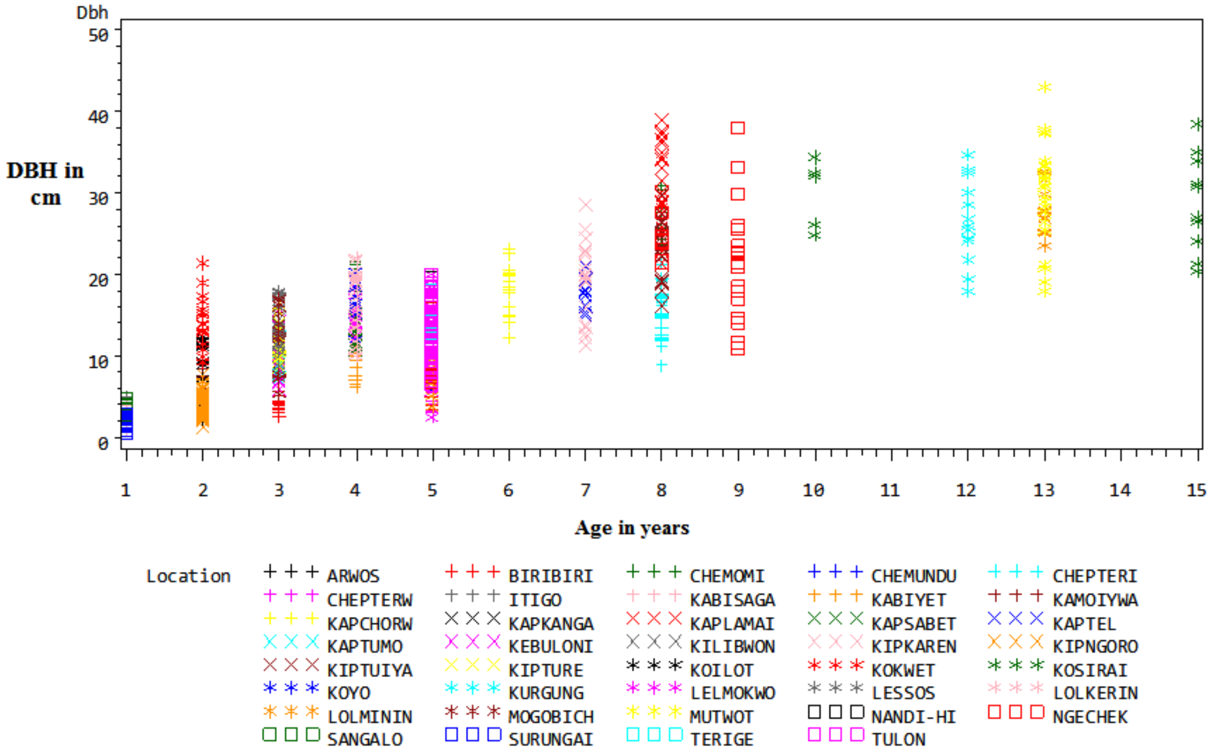


Figure 4. 6: Plot of mean dbh by age of *Grevillea robusta* in Nandi County.

4.2.2 Dbh Model

The model $Dbh = \alpha + \beta * (Age^{\theta})$ was fitted to *G. robusta* data in Nandi County where;

Dbh = diameter at breast height (at 1.3 m above the ground),

α, β and θ = estimated regression coefficients

Age = age of the tree in years.

ANOVA showed that there was a significant increase in tree dbh with age ($F_{2,982} = 1027.41$, $P < 0.0001$). Tables 4.3 and 4.4 statistically illustrate this result. Table 4.3 shows the results of fitting dbh equations to the data. Parameter estimates a, b and c of the dbh model is given representing estimated regression coefficients α, β and θ respectively.

Table 4. 3: Parameter Estimates from the fitting of Dbh Model for *Grevillea robusta* data in Nandi County

Parameter	Estimate	Approx Std Err	Approximate 95% Confidence Limits	
			Lower Limit	Upper Limit
a	-4.4506	1.6148	-7.6195	-1.2817
b	7.2629	1.2840	4.7432	9.7826
c	0.5971	0.0541	0.4909	0.703

Table 4.4 Shows the output of standardized descriptive statistics (moment), which gives an idea of the distribution of data within the variable age. The mean of 1.90416E-6, Skewness of 0.26041075 and Kurtosis of 0.84400578 indicates a good model fit to the data.

Table 4. 4: Moments for dbh

Moments			
N	985	Sum Weights	985
Mean	1.90416E-6	Sum Observations	0.0018756
Std Deviation	4.62608166	Variance	21.4006315
Skewness	0.26041075	Kurtosis	0.84400578

The test for normality was also done using Kolmogorov-Smirnov test because of its significant p value as in height. The normality test indicates its significance since its P value ($P< 0.0100$) is less than 0.05.

Residual by predicted plots showed acceptable trends of normality as those for height as illustrated in Figures 4.7, 4.8 and 4.9. The data as shown in Figure 4.7 are symmetrically distributed.

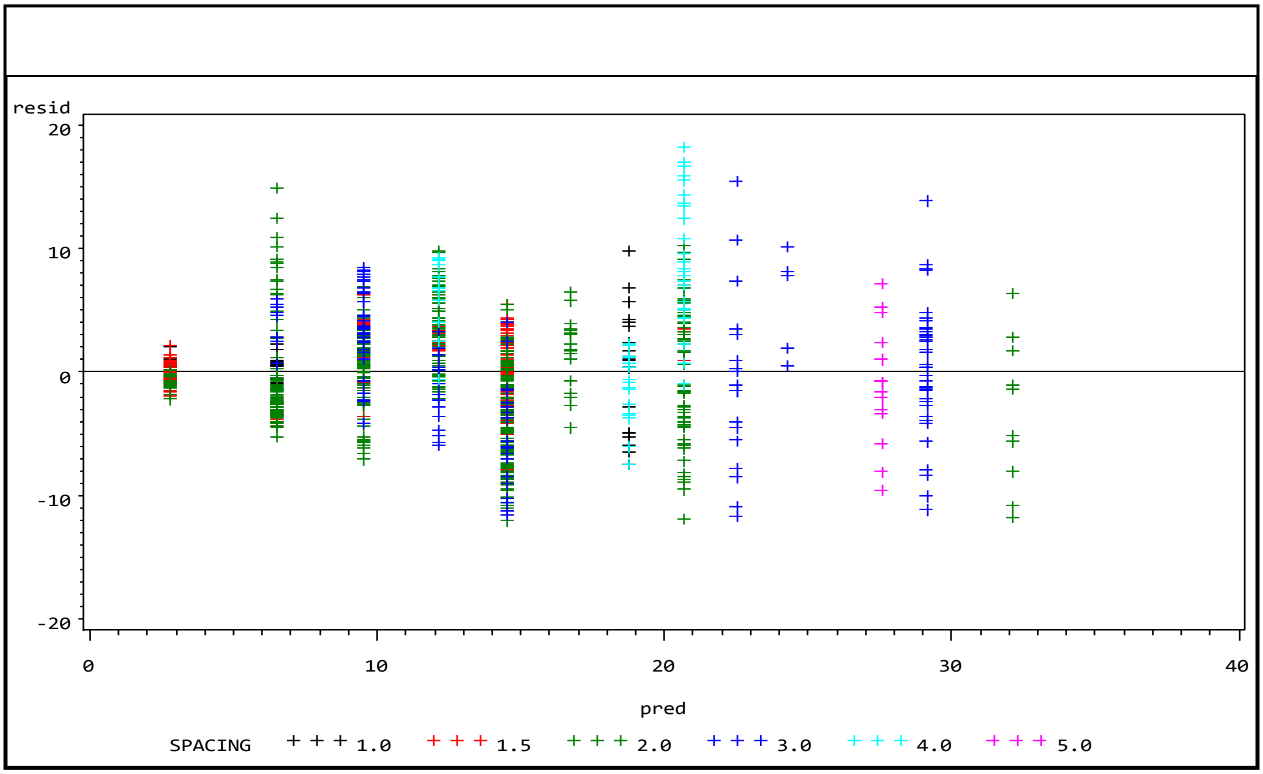


Figure 4. 7: Predicted Verses Residuals for dbh of *G. robusta* in Nandi County.

The data as shown in Figure 4.8 fits the normal curve.

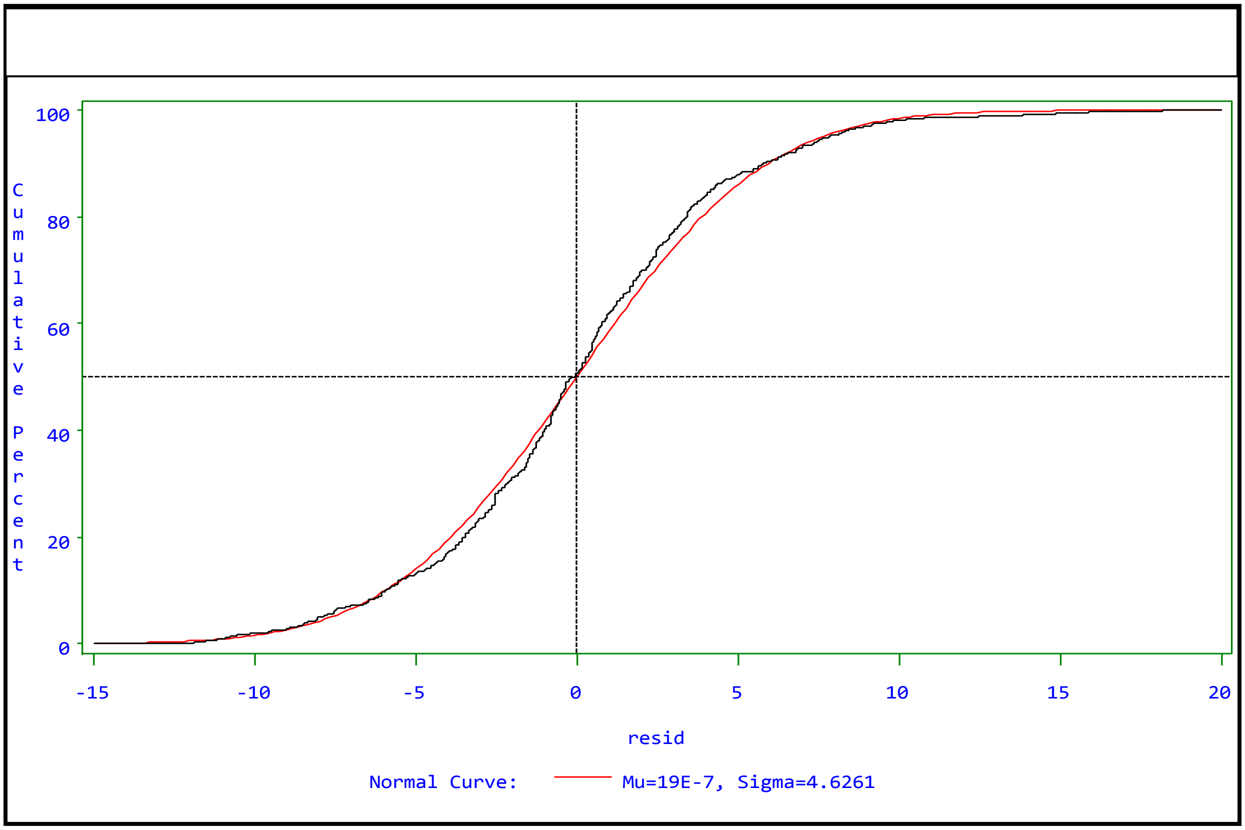


Figure 4. 8: Normal Curve for *G.robusta* dbh model in Nandi County

The frequency distribution of residuals (Figure 4.9) is acceptable though with slight disparity.

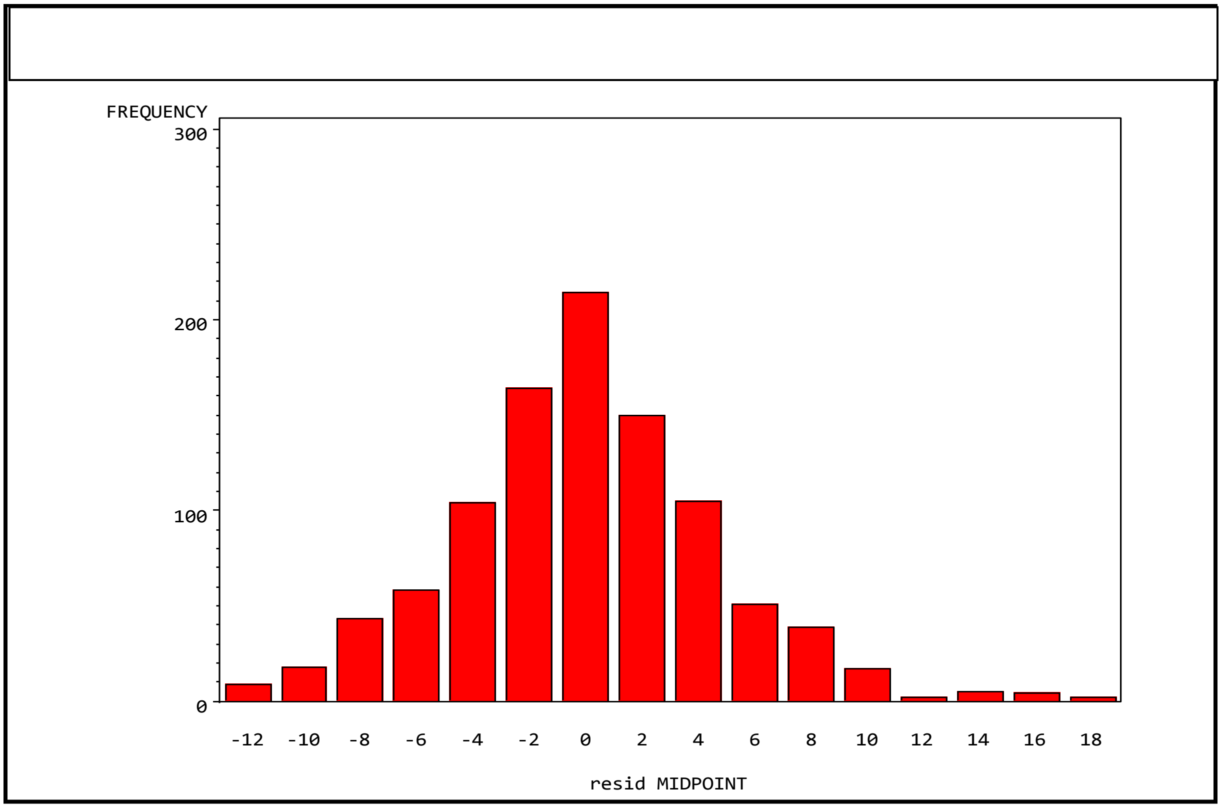


Figure 4. 9: A graph of frequency distribution of residuals for *G. robusta* dbh in Nandi County

4.2.3 Dbh growth Trajectory

The regression coefficients developed from the dbh model was used to plot a growth curve (Figure 4.10) using Microsoft Excel (2007) to show the resultant increase in dbh trajectory of *G. robusta* trees in Nandi County.

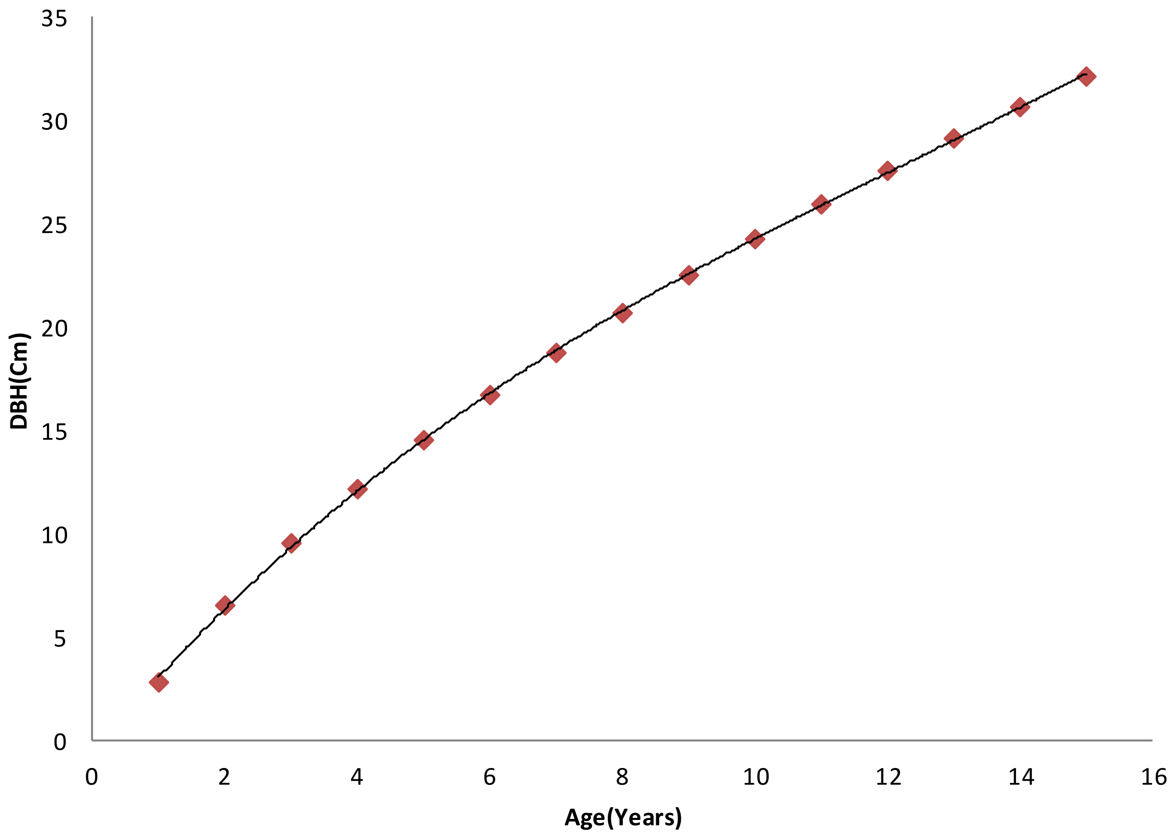


Figure 4. 10: Dbh growth trajectory for *Grevillea robusta* trees in Nandi County

4.3 Volume Model of *Grevillea robusta* in Nandi County

Tree volume increased with age, as expected (Figure 4.11) and there were variations. The effects of management were evident from the scatter plot (see for example figure 4.11 ages 9 and 13).

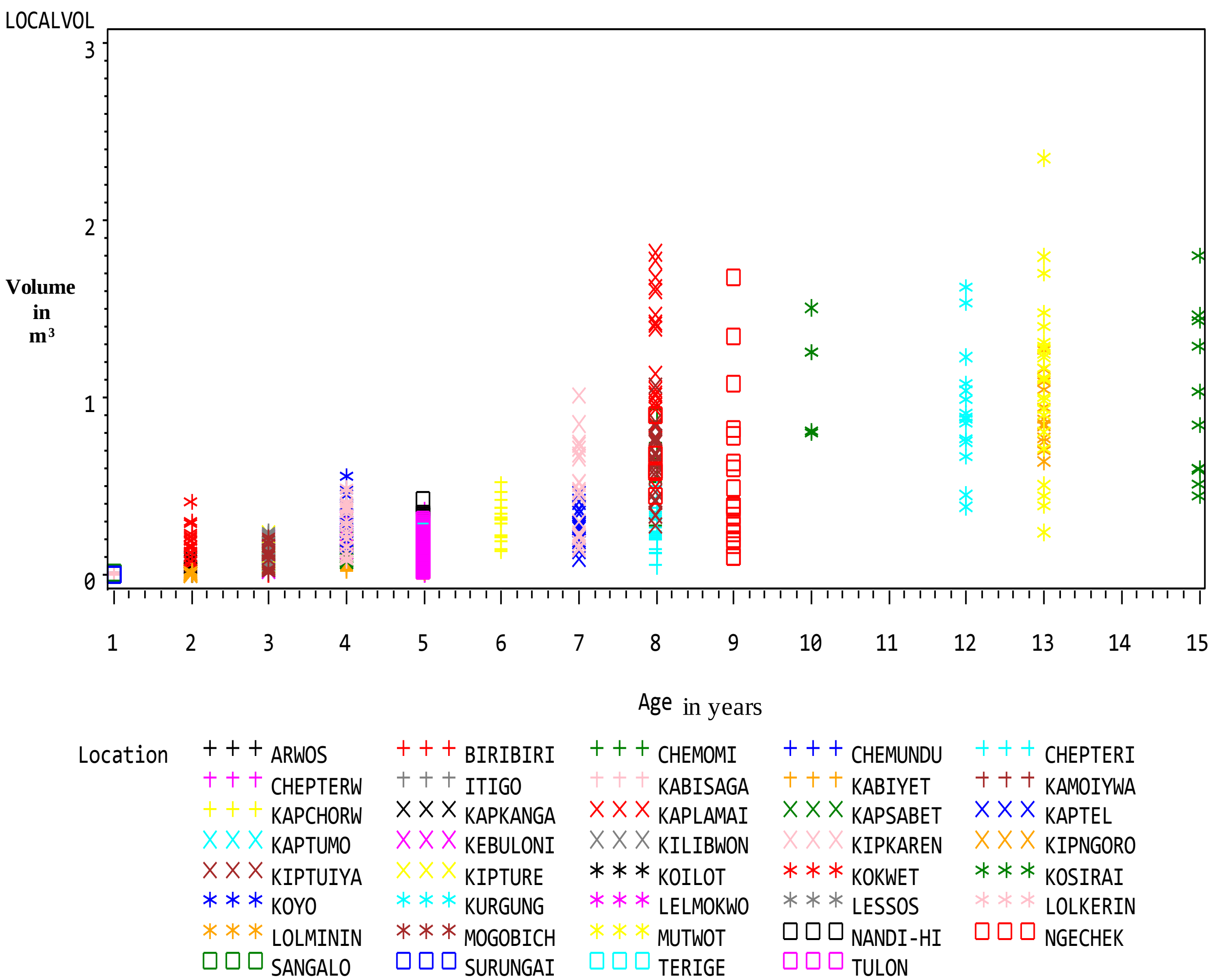


Figure 4. 11: Plot of *Grevillea robusta* trees volume by age in Nandi County

4.3.1 Volume Equation

Volume was modeled using the local volume equation; $V = (Dbh)^2Ht$ because no farmer allowed their trees to be cut, where V = Tree volume, Dbh = Tree diameter and Ht = Tree height. Tables 4.5 and 4.6 illustrate statistical significance of the model. The p value < 0.0001 shows that the model is significant.

Table 4. 5: Anova table for local volume equation

Source	DF	Sum of Squares	Mean Square	F Value	P > F
Model	42	111.7008775	2.6595447	2220.25	< 0.0001
Error	942	1.1283845	0.0011979		
Corrected Total	984	112.8292620			

Table 4.6 shows acceptable distribution of data about the mean.

Table 4. 6: Moments for volume

Number	985	**Sum Weights**	985
Mean	0	**Variance**	0.00114673
Std Deviation	0.03386343	**Kurtosis**	4.65355864
Skewness	-0.0899845	**Corrected SS**	1.1283845
Uncorrected SS	1.1283845	**Std Error Mean**	0.00107898

Residual by predicted plots showed acceptable trends of normality illustrated in Figures 4.12, 4.13, 4.14 and 4.15. The normal distribution in Figures 4.12 and 4.13 is symmetric.

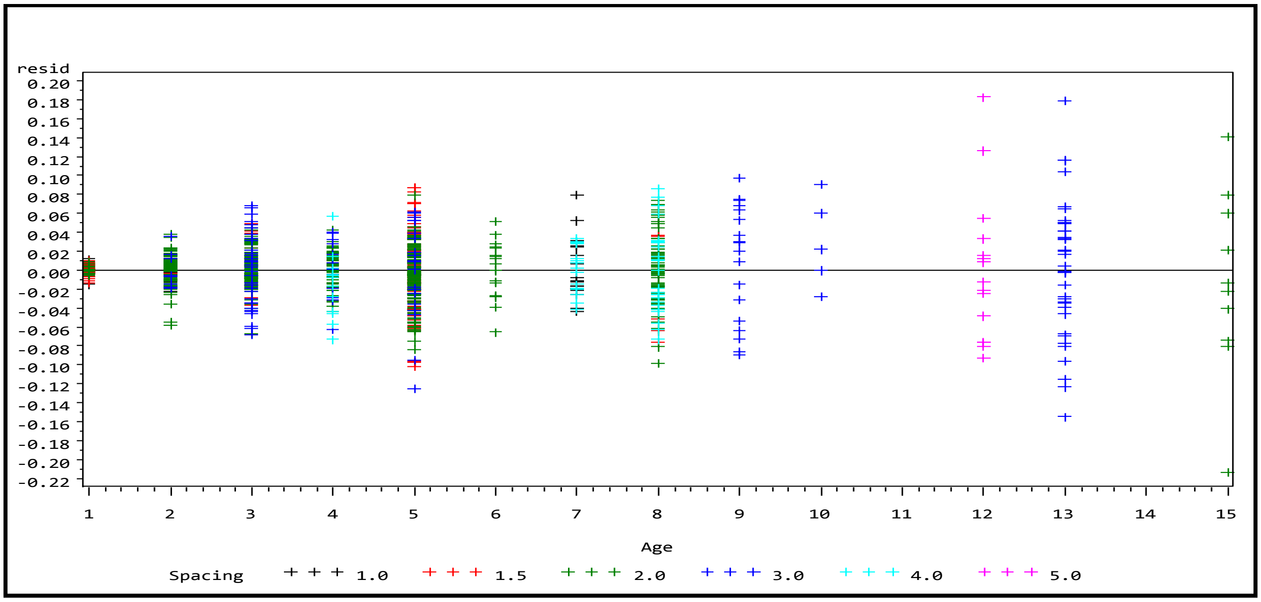


Figure 4. 12: Residuals by age of the volume model

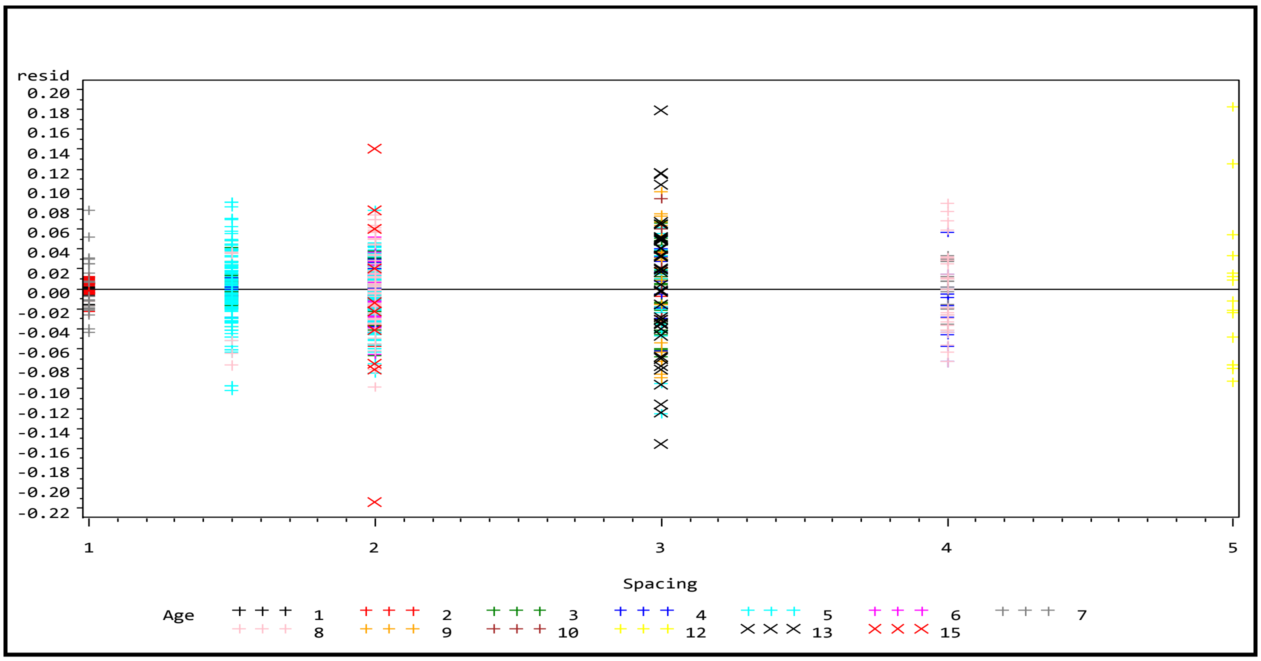


Figure 4.13: Residuals by spacing of the volume model

The residual plots show little or no bias implying that the models fitted were good in estimating volume. The data fits the normal curve though with little disparity.

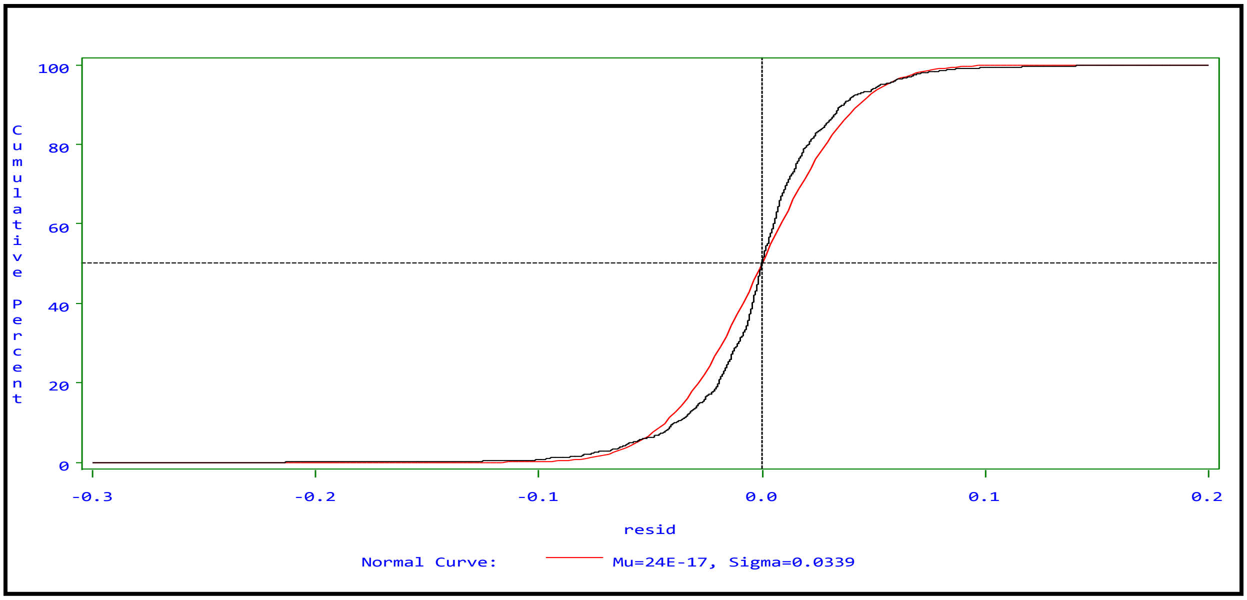


Figure 4. 14: Normal Curve for the Volume model

The frequency distribution of residuals in Figure 4.15 is acceptable.

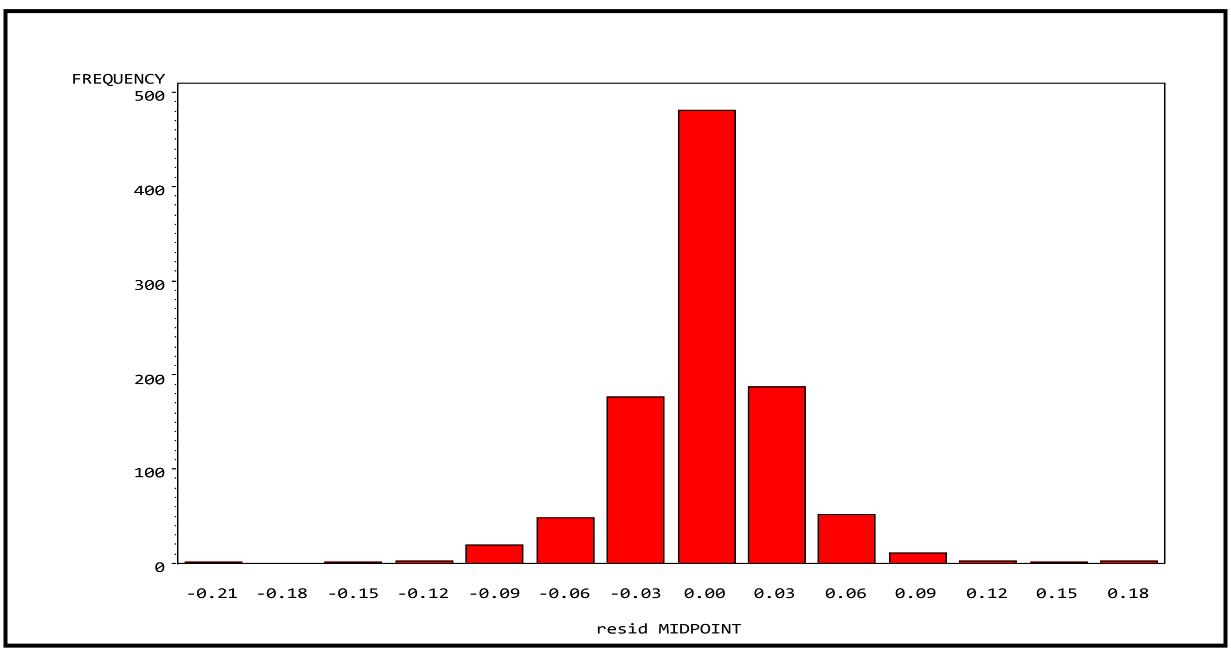


Figure 4. 15: Graph of frequency distribution of residuals of the volume model

4.3.2 Fitted regression model for Local volume of *Grevillea robusta* trees in linear spacing

In a bid to understand the most significant variable influencing volume (*Local Volume* = D^2H), a regression was fitted using the forward selection method. The independent variables tried were; BA, height, age, spacing and location. The results showed that BA, Height, Age and Location had significant effects ($P < 0.0003$) and spacing was not significant ($P = 0.1993$) as shown in Table 4.7. This is because linear spacing, unlike square or rectangular spacing, trees face less competition from neighbors.

Table 4. 7: Anova showing the variables influencing the local tree volume

Source	DF	Type III SS	Mean Square	F Value	P > F
BA	1	17.28002529	17.28002529	14425.7	< 0.0001
Ht	1	0.02792965	0.02792965	23.32	< 0.0001
Spacing	1	0.00197637	0.00197637	1.65	0.1993
Age	1	0.01606938	0.01606938	13.42	0.0003
Location	38	1.45469109	0.03828134	31.96	< 0.0001

4.4 Effects of Spacing on growth and yield of *Grevillea robusta* trees in Nandi County

Although results in Table 4.7 from the ANOVA indicated that spacing was not significant, further analysis showed that it had significant influence on growth in height and dbh as the trees advanced in age (Table 4.8 and 4.9). Height and dbh were not sensitive to spacing at ages below 3 years because the trees had enough growing space but as from 4 years and above, tree height and dbh was sensitive to spacing because there was competition for resources. In this study, there was a significant difference (α=0.05) in height and dbh of trees grown at wider spacing.

Table 4. 8: Mean separation of effects of spacing at age 4 for height (α = 0.05)

The GLM Procedure
Tukey's Studentized Range (HSD) Test for Ht

Alpha	0.05
Error Degrees of Freedom	93
Error Mean Square	1.344352
Critical Value of Studentized Range	3.69972

Comparisons significant at the 0.05 level are indicated by ***.

Spacing comparison	Difference between means
2 - 1.5	0.0328
2 - 4	2.5717 ***
2 - 3	4.1578 ***
1.5 - 4	2.5389 ***
1.5 - 3	4.1249 ***
4 - 3	1.5861 ***

Table 4. 9: Mean Separation of effects of spacing at age 4 for Dbh (α = 0.05)

The GLM Procedure
Tukey's Studentized Range (HSD) Test for Dbh

Alpha	0.05
Error Degrees of Freedom	93
Error Mean Square	7.824319
Critical Value of Studentized Range	3.69972

Comparisons significant at the 0.05 level are indicated by ***.

Spacing comparison	Difference between means
4 - 2	2.7556 ***
4 - 1.5	3.3023 ***
4 - 3	8.1536 ***
2 - 1.5	0.5466
2 - 3	5.3979 ***
1.5 - 3	4.8513 ***

This same trend is exhibited as age increases. This is a clear indicator that spacing affects growth in height and Dbh as age increases in boundary planting (line spacing).

Trees at Kipkaren were grown at a close proximity to a nearby bush in comparison to trees grown in the open at Kaptel. The volume of trees (at age seven years) in the two locations at α=0.05 were significantly different (Table 4.10)

Table 4. 10: Mean Separation of volume of trees at Kipkaren and Kaptel at age 7 years

Tukey Grouping	Mean	No of trees	Location
A	0.47143	22	KIPKAREN
B	0.27819	16	KAPTEL

4.4.1 Effects of Spacing with Age on Growth and yield of *Grevillea robusta* in Nandi County

A spacing of one meter compared to that of four meters at age 7 years were significantly different at α = 0.05. At four meters, trees neighborhood zones were still big compared to one meter where there is intra-competition between *G. robusta* trees. At age 7 years, the trees are big in terms of volume and crown closure thus increasing competition in one meter spacing compared to that of four meters. This accounts for the difference between the two spacings (Table 4.11)

Table 4. 11: Mean Separation of 1m and 4m spacing at age 7 years

Tukey Grouping	Mean	No of trees	Spacing (m)
A	0.47143	22	1
B	0.27819	16	4

Means are significantly different α = 0.05

The same trend is recorded in volume as in height and Dbh at age 7 years. At this age and above beside slower growth, farmer's management may not be intensive and more necessary as in the early years.

Table 4.12 shows analysis of volume of trees grown at different spacing at age 8 years. Volume of trees grown at closer spacing were significantly different from those grown at a wider spacing. There was a significant difference in volume of trees at α=0.05 grown at spacings of 1.5 m and 2 m with those grown at 4 m. There was no significant difference in volume of trees grown at a spacing of 1.5 m and 2 m because of their minimal difference. This same observation was seen in height and dbh.

Table 4. 12: Mean separation for local volume test spacing comparisons at age 8 years

The GLM Procedure

Tukey's Studentized Range (HSD) Test for LOCALVOL

Alpha	0.05
Error Degrees of Freedom	84
Error Mean Square	0.067653
Critical Value of Studentized Range	3.37428

Comparisons significant at the 0.05 level are indicated by ***.

Spacing comparisons	Difference between means	Simultaneous 95% confidence limits		
4 – 1.5	0.46583	0.16180	0.76986	***
4 – 2	0.62075	0.47265	0.76884	***
1.5 – 2	0.15491	-0.13415	0.44397	

G. robusta height, dbh and volume were significantly different at different spacings and locations at the same age at 95% confidence level. The height was high at age 12 years (spacing of 5m) due to reduced intra-competition. At spacing of 1 m at age 7 years trees were taller due to competition compared to spacing of 4m at the same age. The optimum spacing was found to be 3m and 4m recommended because they differed significantly from the others.

CHAPTER FIVE

DISCUSSION

The height growth was best described by the equation; Ht= -22.1003 + 25.0071 * ($Age^{0.1566}$) from the form; $Ht = \alpha + \beta * (Age^{\theta})$. The equation has been found suitable by (Kirongo 2000, Kirongo and Muchiri, 2009, Kirongo *el al.*, 2011 and Mbelase 2012). The growth trajectory of *G. robusta* represents reliable outputs as compared to observations made in the field. Residuals by predicted plots showed acceptable trends of normality. This was also observed in Dbh growth.

The dbh model was best described by the equation Dbh = -4.4506 + 7.2629 * ($Age^{0.5971}$) from the form; $Dbh = \alpha + \beta * (Age^{\theta})$ which is in line with other researchers (Mugo *et al.*, 2011 and Muchiri *et al.*, 2002). Both height and Dbh trajectory represents reliable outputs as compared to observations made in the field especially in the early years before the full effects farmers' level of management and the effect of intra-competition is realized.

The results from this study indicated a high correlation in tree volume with diameter and height. The Local volume equation, $V = (Dbh)^2 Ht$ best described the volume of *G. robusta* because famers did not allow cutting of their trees. Location played a role in the growth of trees and may be attributed to site factors like soil, weather and topography. The growth of *G. robusta* was different for trees of the same age and from the same Agro-ecological zone. This may be explained by farmer's input. Location at $\alpha = 0.05$ was also significant and this affected the volume of trees.

From the ANOVA table for local volume model, basal area, height, age and location were significant variables while Spacing was not at 95% significance level. This is because in line spacing, there is a reduced competition especially at the age less than three years. Nutrients, water and sunlight are available but as the trees advanced in age, spacing was significant due to intra-competition. Further analysis of spacing especially as the tree grow older indicated that it contributes to growth in height and dbh. There was a significant difference ($\alpha = 0.05$) in height and dbh between trees grown at wider spacing over those grown at closer spacing. Planting of *G. robusta* in rows and at wider spacings therefore favours faster diameter growth and hence individual tree volume which is in line with Kalinganire (1996). *G. robusta* yield in Nandi County was significantly different at $\alpha = 0.05$ spacing of 1 m and 4 m at age 7 years. This is attributed to competition as the tree increases in size (root size and crown closure) which limits access to nutrients, water and sunlight. Trees in boundary planting (linear spacing) had better yield than those in square or rectangular spacing because competition is unidirectional (along the line). The volume of trees grown at close proximity to other trees were significantly different at $\alpha = 0.05$ from those grown at wider spacing. This was similar to results of a study done by Kirongo *et al.*, (2013) where the growth and survival of *Casuarina* were affected by spacing.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following growth and yield models can be used in Nandi County:

- $Height = -22.1003 + 25.0071 * (Age^{0.1566})$,for height,
- $Diameter\ at\ breast\ height = -4.4506 + 7.2629 * (Age^{0.5971})$, for Diameter at breast height and
- $Volume = (Dbh)^2 Ht$, for volume.
- The optimum spacing for boundary planting (line spacing) of *G. robusta* in Nandi County was 3-4 m. This differs with the observation by other researchers (Kalinganire, 1996; Spiers and Stewart, 1992) that *G. robusta* is normally planted in rows with spacing of 2-2.5 m between trees. The difference may be attributed to architectural orientation, management levels and the trees proximity to the neighbors.

Growth and yield model involving height, dbh and volume of *G. robusta* grown on farm boundary in Nandi County can be used by local forest managers and farmers in making informed decisions about the growth of trees.

6.2 Recommendations

- Boundary planting (line spacing) of *G. robusta* is a good system to be adopted in Nandi County. It is a better option because the size of farm lands are getting smaller and smaller, making use of the farm boundaries, which would otherwise be left for non-economic use, to raise productivity and income and increase tree cover.

- A program should be developed that will make procurement of seeds and seedlings of high quality to nursery owners and farmers respectively available to increase tree growing on farm and the overall increase in tree cover. This will contribute to the government's commitment to increase tree cover to 10%.

- There is need to provide farmers with high quality germplasm of a wider range suited to the diverse environments and socio-economic conditions of smallholder farmers.

- There is a need to demonstrate to farmers through an economic appraisal the financial gains they would derive from producing high quality trees by improving their tree management practices such as weeding, fertilization, pruning and thinning.

REFERENCES

Adensinu A. and Chianu J. (2002). Determinants of farmers'adoption and adaptation of alley farming technology in Nigeria, *Agro forestry System*, 55: 99-112

Akyeampong E., Hitimana E., Torquebiaus E. and Munyemana P.C. (1999). Multistrata agroforestry with beans; bananas and *Grevillea robusta* in the highlands of Burundi. *Experimental Agriculture* 35: 357–369 and Annual General Meeting held at the Sunset Hotel, Kisumu. 30th September.

Auld B.A, Menz K.M and Tisdel C.A (1987). *Weed Economics*, Academic press

Christian, N.B. (1975). Decision making Principles and cases.I.U: *Forest Resource Management*. Duerr, W.A., Teeguarden, D.E Guttenberg, S. and Christiansen, N.B (Eds.), Vol 1, Part 3.O.S.U. Book stores Inc. U.S.A P. 8-11

Coomes D.A. (2006). *National Center for Biotechnology Information*; Scaling of Tree Vascular Transport Systems along Gradients of Nutrient Supply and Altitude; Sept.27, 2006

Evan H.B.L. (1990). Forestry Extension in EMI districts, Kenya. *Commonwealth Forestry* Review 69: 309–312.

Evans J (1982). *Plantation forestry in the tropics*, Second Edition. Clarendon Press Oxford. Pp 268

FAO. (2003). *Forestry outlook study for Africa*. FAO, Rome.

FAO. (2007). *State of the world's forests 2007*. FAO, Rome.

Farahat, M. M., Mazhar, A. A. M., Mahgoub, M. H., & Zaghloul, S. M. (2013). Salt Tolerance in *Grevillea robusta* Seedlings via Foliar Application of Ascorbic Acid, *14*(1), 9–15. doi:10.5829/idosi.mejsr.2013.14.1.2955

Githiomi J. (2010). Micro-level wood energy planning for Kiambu, Thika and Maragwa districts; a case study for decentralized wood energy plan in Kenya. PhD Thesis,Department of Environmental Studies, Kenyatta University, p. 176

Githiomi JK, Mugendi DN, Kung'u JB (2011). Household tree planting and its related constraints in meeting woodfuel production for Kiambu, Thika and Maragwa districts in Central Kenya. *Journal of Horticulture and Forestry* Vol4(7). pp 120- 125

Goulding, C.J. (1975). Growth and Yield models. IN: *Forestry hand book*-Don Hammond (ed.). New Zealand Institute of Foresters (Inc.) p. 111-113

Harwood C.E. and Booth T.H. (1992). Status of *Grevillea robusta* in forestry and agroforesty. In: Harwood C.E. (ed.), *Grevillea robusta* in Agroforestry and Forestry. Proceedings of an International Workshop. *International Centre for Research in Agroforestry*, pp. 9–16.

Harwood, C.E. (1989). *Grevillea robusta: an annotated bibliography*. Nairobi: ICRAF, 131 pp.

Holding C, Carsan S, Njuguna P (2006). Smallholder timber and firewood marketing in the coffee and cotton/tobacco zones of eastern Mount Kenya. In: Wall, S. ed. *Small-scale forestry and rural development*. The intersection of ecosystems, economics and society. Proceedings of the IUFRO 3.08 conference. Galway-Mayo Institute of Technology, Galway Ireland, 18-23 June 2006.

Hyink D. M. and Zedaker S. M. (1987). Stand dynamics and the evaluation of forest decline. *Tree Physiology*, *3*, 17–26. Retrieved on 6th July 2012 from http://www.ncbi.nlm.nih.gov/pubmed/14975832

Imo, M., D. O. Ogweno, A. Matano, and B. Orinda, (2001). Adoption of agro-forestry and improved land use practices in Kipkaren river catchment, Kenya. 1st National Scientific Conference, Lake Victoria Environmental Management Project, Kisumu, Kenya. 15th - 19th October, 2001.

Jaetzold R., Schmidt H. (1983). *Farm Management Handbook of Kenya*. Part B: Rift Valley and Central Provinces. Ministry of Agriculture, Republic of Kenya, Nairobi, Kenya.

Kalinganire A, 1996. Performance of Grevillea robusta in plantations and on farms under varying environmental conditions in Rwanda. *Forest Ecology and Management*, 80(1-3):279-285; 20 ref.

Kalinganire, A, (1995). Performance of *Grevillea robusta* in plantations and on farms under varying environmental conditions in Rwanda. *Institut des Sciences Agronomiques du Rwanda, Arboretum de Ruhande*, B.P 617 Butare, Rwanda. Accepted 25 June 1995. Available online 1 March 1999. Ethiopian Journal of Natural Resources. (1999)

Kamweti, D.M. and Hanna J.E. (1987). *A review and update of fuelwood supply data and modeling for Kenya*. Nairobi: Ministry of Energy and regional Development.

Kenya Forest Service strategic plan (2009). *Forest Landscape and Kenya's vision 2030.*

Kenya National Bureau of Statistics (KNBS) - *Ministry of Planning, National Development and Vision 2030, 2009 Report*.

Kenya National Bureau of Statistics (2009) *Kenya Population & Housing Census*

Kirongo B (1996). Effects of Non-crop Vegetation Management on growth and productivity of young radiate pine. MSc. Thesis, University of Canterbury (Christchurch, New Zealand). Pp. 152.

Kirongo B (2000). Modelling growth responses of juvenile radiate pine (pinus radiate D. Don) clones subjected to different weed competition levels in Canterbury, New Zealand. Ph.D. Thesis, University of Canterbury (Christchurch, New Zealand). pp. 28-35.

Kirongo Balozi, Mbelase Angela, Kingiri Senelwa, Joseph Hitimana and Lazare Etiegni (2012). Spacing and Genotype on Height and Diameter growth of four Eucalyptus under short rotation. *Journal of Tropical Forest Management* (*Manajemen Hutan Tropika)* Vol. XVIII (1): 1-9

Kirongo, B. B., Christine, K., & Kimani, G. K. (2005). The effects of intra-specific competition on survival in a *Casuarina Equisetifolia* spacing trial in Gede , Malindi , Kenya*: KEFRI Gede Scientific Reports.*

Kirongo, B. B., Christine, K., and Kimani, G. K. (2013). The effects of intra-specific competition on survival in a *Casuarina Equisetifolia* spacing trial in Gede , Malindi , Kenya, *4*(7), 293–298.

Kituyi, E. (2008) Climate Change Mitigation by Schools in Kenya: Policy Options for Scaling up Sustainable Fuel wood Consumption and Production. *Renewable Energy Technology Assistance Programme, Policy Brief Series No. 1, 2008*. Nairobi, Kenya.

Klaus, V.G., and Gangying, H. (2001). *Modeling Forest Development*. Kluwer Ac. Pub.

Kuuluvainen T. and Pukkala T. 1989. Effects of Scots pine on the density of ground vegetation and tree seedlings. *Silva Fennica* 23: 159–167.

Lott, J.E., Ong, C.K., Black, C.R., (2000). Long-term productivity of a Grevillea robusta-based overstorey agroforestry system in semi-arid Kenya. II. Crop growth. *Forest Ecology Management*. 139, 187–201.

Matano., A.S and Ogweno., D.O., (2003). *Potentials for farm forestry in the Lake Victoria Basin, Kenya*. Case study for North Nandi.

Mathu, W. and Philips M.S. (1979). Growth and Yield studies of Cupressus lusitanica in Kenya. *Division of Forestry University of Dar es Salaam*. Record No 5, 1979, 16 pp.

Mbelase A. S (2012). Modeling Tree Growth, Yield and Biomass of Short Rotation Forest Crops in two Sites in Western Kenya. MSc.Thesis, Chepkoilel University College, Kenya.

Mburu, F., Dumarcay, S., Bocquet, J.F., Petrissans, M. and Gerardin, P. (2008). Effect of chemical modifications caused by heat treatment on mechanical properties of Grevillea robusta wood. 93.401-405

Meadows, D. H., & Robinson, J. M. (2002). The electronic oracle: computer models and social decisions. *System Dynamics Review*, *18*(2), 271–308. doi:10.1002/sdr.239

Miina, J., & Pukkala, T. (2002). Application of ecological field theory in distance-dependent growth modelling. *Forest Ecology and Management*, *161*, 101–107. doi:10.1016/S0378-1127(01)00489-3

Ministry of Energy (2002) Study on Kenya's Energy Demand, Supply and Policy Strategy for Households, *Small scale Industries and Service Establishments*. Kamfor Consultants, Nairobi, Kenya.

Muchiri, M.N, Miina J, Pukkala T. (2002). Modelling trees' effect on Maize in the Grevillea robusta + Maize System in Central Kenya. *Agroforestry Systems* 55: 113-123

Mugo J.M., Njunge J.T., Malimbwi R.E., Kigomo B.N., Mwasi B.N. and Muchiri M.N. (2011).Models for predicting stem diameter from crown diameter of open grown trees in Sondu-Nyando River Catchment, Kenya. *Asian Journal of Agricultural Sciences* 3(2):119–126,2011.

Mugo, F.W. (2001) The role of woodfuel conservation in sustainable supply of the resource: The case for Kenya. Paper presented at charcoal stakeholders Ministry of Energy (2004) *Sessional Paper No. 4 on Energy*. Government printers, Nairobi, Kenya.

Namirembe, S., (1999). Tree management and resource utilisation in agroforestry systems with Senna spectabilis in the drylands of Kenya. Ph.D. thesis, University of Wales, Bangor, UK, 206 pp.

Nellie, O., Githiomi J (2009). Forest Energy for Livelihoods; A paper presented in the 4th *Forestry Society of Kenya Scientific Conference* November, pp. 15-34

NEMA, (2004) State of Environment report. National Environmental Management Authority. Nairobi, Kenya

Ngugi, A.W., and P. N. Brabley, (1986). Agroforestry, Soil Conservation and Wood fuel in Murang'a District. Nairobi, *The Beijer Institute*.October, 2008

Ogweno D.O. and Mugabe R.O. (2008). Models for estimating biomass and carbon stocks of Eucalyptus woodlots in eastern and central Kenya. Unpublished report.

Ogweno D.O., Opanga P.S. and Obara A.O. (eds 2009). *Forest Landscape and Kenya's vision 2030*.

Ogweno, D.O., M. Imo, A. Matano, and B.Orinda, (2001). Evaluation of the management and sustainability of private tree nurseries in Kipkaren river catchment, Kenya. 1st National Scientific Conference, Lake Victoria Environmental Management Project, Kisumu, Kenya. 15th - 19th October, 2001.

Okello, B.D., O'Connor, T.G., Young, T.P., (2001). Growth, biomass estimates, and charcoal production of Acacia drepanolobium in Laikipia, Kenya. *Forest Ecology Management*. 142, 143–153.

Orwa C, Mutua A , Kindt R , Jamnadass R, Simons A. (2009). Agroforestree Database:a tree reference and selection guide version 4.0. Retrieved on 22nd April 2014 from (http://www.worldagroforestry.org/af/treedb/)

Otengi, S.B.B., Stigter, C.J., N'ganga, J.K., Mungai, D.N., (2000). Wind protection in a hedged agroforestry system in semi-arid Kenya. *Agroforestry Systems*. 50, 137–156.

Phiri A.D.K., Kanyama-Phiri G.Y. and Snapp S. (1991). Maize and sesbania production in relay cropping at three landscape positions in Malawi. *Agroforestry Systems* 47: 153–162.

Poulsen, G. (1983). Using farm trees for fuel wood. *Unasylva*. 35: 26-29.

Pukkala T. (1989). Methods to describe the competition process in a tree stand. *Scandinavian Journal of Forest Research* 4: 187–202.

Raju K.R.T. (1992). Silver Oak (*Grevillea robusta*) a multipurpose tree for arid and semi-arid regions. In: Harwood C.E. (ed.), *Grevillea robusta* in Agroforestry and Forestry. Proceedings of an International Workshop. *International Centre for Research in Agroforestry,* pp. 55–58.

Reddy A.N.Y. (1992). *Grevillea robusta* in coffee plantations of Karnataka. In: Harwood C.E. (ed.), *Grevillea robusta* in Agroforestry and Forestry. Proceedings of an International Workshop. *International Centre for Research in Agroforestry,* pp. 59–66.

Reid R. and Stephen P., (2001). The farmer's forest: multipurpose forest for Australia farmers. *RIRDC publication no. R01/33*. RIRDC, Canberra, 167p

Republic of Kenya (2007) *Kenya Vision 2030*. Government printers, Nairobi, Kenya.

Schuren D.J, Snelder R.D (2008). *Tree growing on farms in Northern Luzon (Philipines*): Small holders motivations and other determinants for adopting agroforestry systems

Shainsky L.J, Newton M, radosevish S.R (1992). Effects of intra- and inter-specific competition on root and shoot biomass of young *D. fir* and red alder. *Canadian Journal of Forest Research* 22: 101-110.

Spiers N, Stewart M, (1992). Use of G. robusta in Embu and Meru districts of Kenya. In: *Harwood C.E, ed. Grevillea robusta in Agroforestry and Forestry*: Proceedings of an International workshop. Nairobi, Kenya: ICRAF: 37-48.

Swain, E.H.F. (1928). A silvicultural note on southern silky oak. *Queensland Forest Service Bulletin No. 9.*

Tejwani, K.G., (1987). *Agro-forestry practices and research in India*. *In*. Gholz, H.L. (Ed.). Agro-forestry: Realities, Possibilities and Potentials. Martinus Nihoff Publishers, Boston.

Tengnas B. (1994). *Agroforestry extension manual for Kenya*. Nairobi: International Centre

The State of the World's Forests (2009, 2007, 2005, 2003, 2001), Oxford: World’s and publications, 2009, 2007, 2005, 2003, 2001.

Theuri, K. (2002) *Woodfuel Policy and Legislation in Kenya*; A paper presented during the Regional Workshop on Woodfuel Policy and Legislation held in ICRAF, Nairobi, Kenya.

Tothill J.D. (1940). *Agriculture in Uganda*. Oxford: University Press.

U.N. FAO. (2005 & 2010). *Global Forest Resources Assessment for Research in Agroforestry*. FAO, United Nations.

Vanclay J.K. (1994). Modelling Forest Growth and Yield. Application to mixed Tropical Forest. *CAB International Wallingford UK.Vision 2030*. Proceedings of the 3rd Annual Forestry Society of Kenya (FSK) Conference

Wimbush, S. H. (1945). *The management of Cypress Plantation in Kenya*. Pamphlet 11. Nairobi: Forest Department of Kenya.

World Rainforest Movement, (2011) – Ghana: a dam at the cost of forests, January 2006. Retrieved on 7 May 2014, http://www.wrm.org.uy/deforestation/Africa/Kenya.html

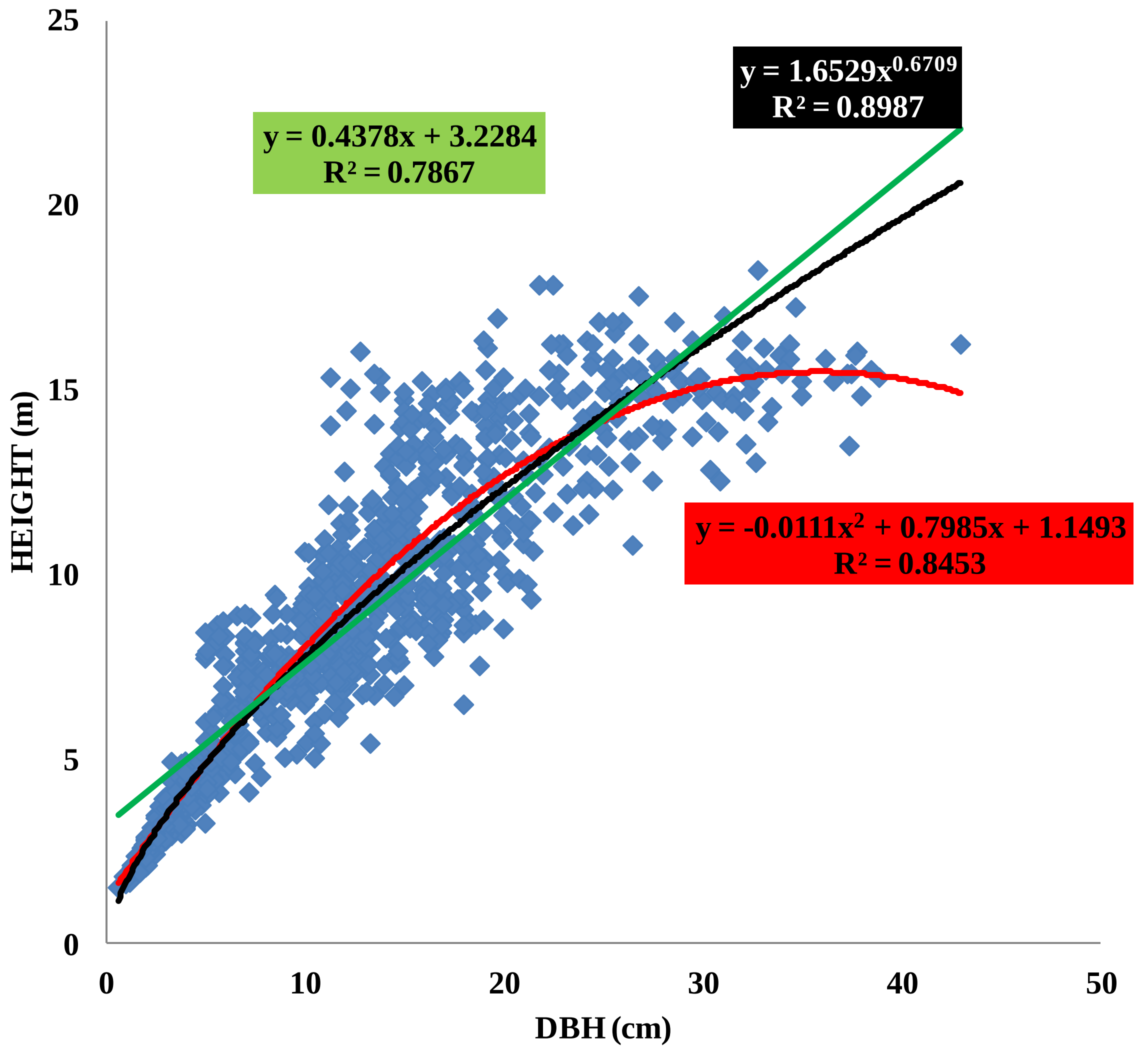
Wu H., Sharpe P.J.H., Walker J. and Penridge L.K. (1985). Ecological field theory: A spatial analysis of resource interference among plants. *Ecological Modeling* 29: 215–243.

APPENDICES

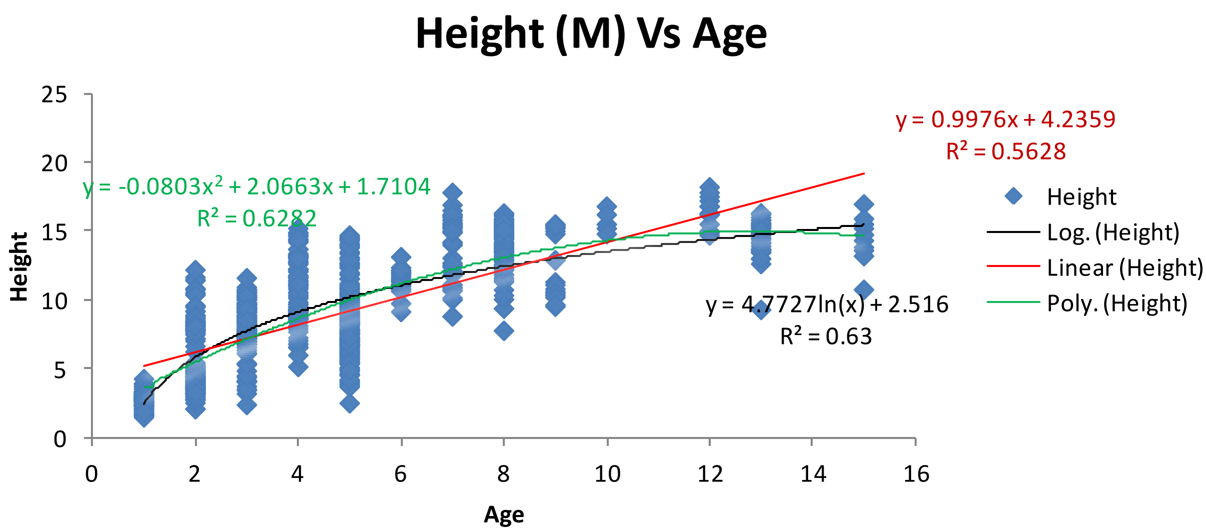
Appendix I: A summary of average dbh, height and spacing of 985 trees measured per age

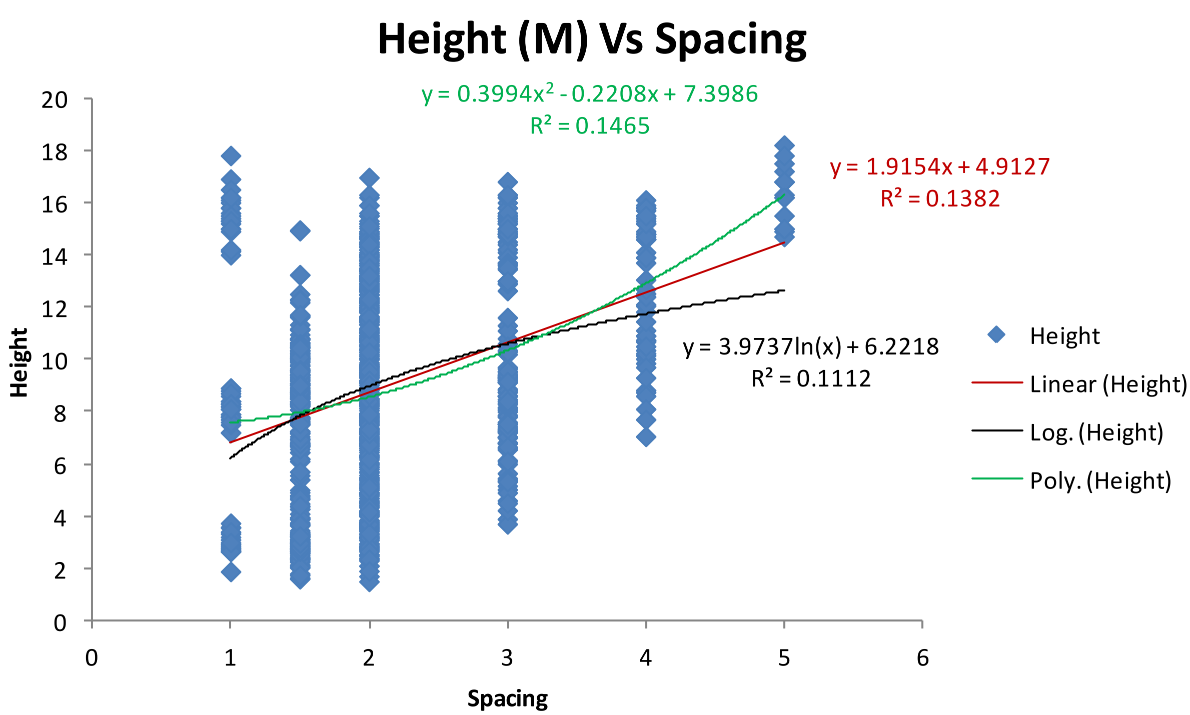
No. of Trees	Age	Average DBH	Average Height	Average Spacing
96	1	2.54	2.78	1.49
144	2	6.09	5.68	1.80
156	3	10.98	8.16	2.15
98	4	15.23	10.97	2.33
258	5	11.98	8.41	1.87
18	6	18.26	11.38	2.0
38	7	18.23	13.76	2.26
88	8	23.39	13.80	2.53
18	9	21.66	12.58	3.0
5	10	29.98	15.7	3.0
15	12	26.56	16.33	5.0
36	13	29.50	15	3.0
10	15	28.86	14.40	2.0

Appendix II: Scatter graph of height against dbh

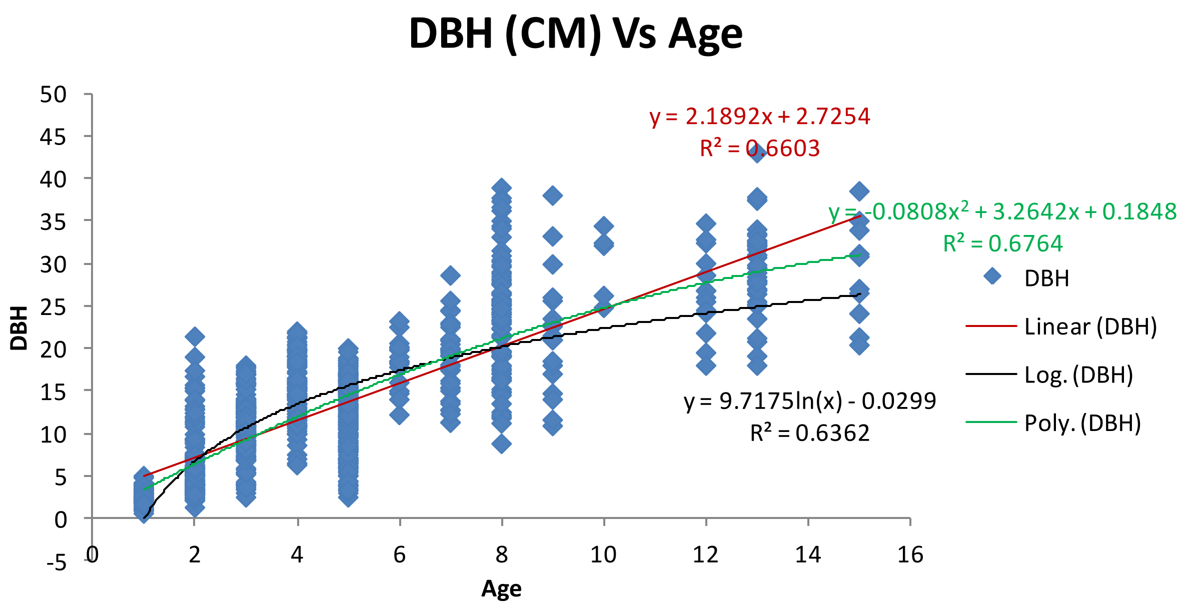


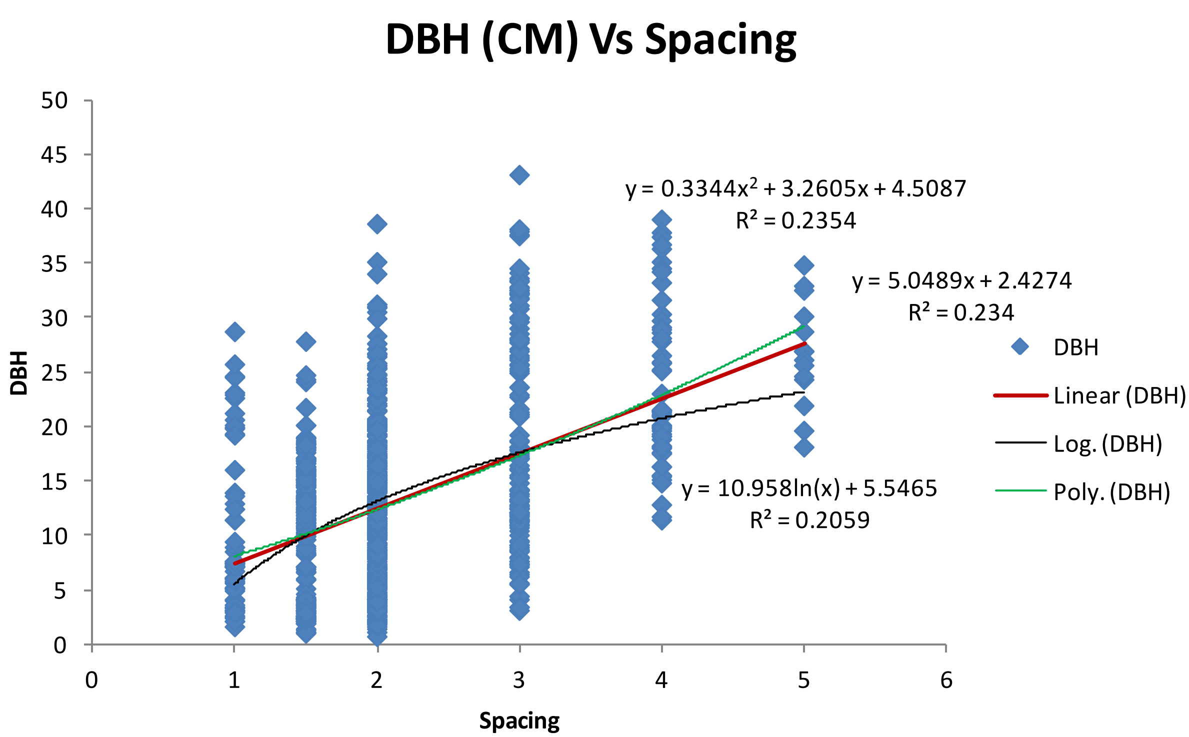
Appendix III: A plot of Height verses Age and Spacing



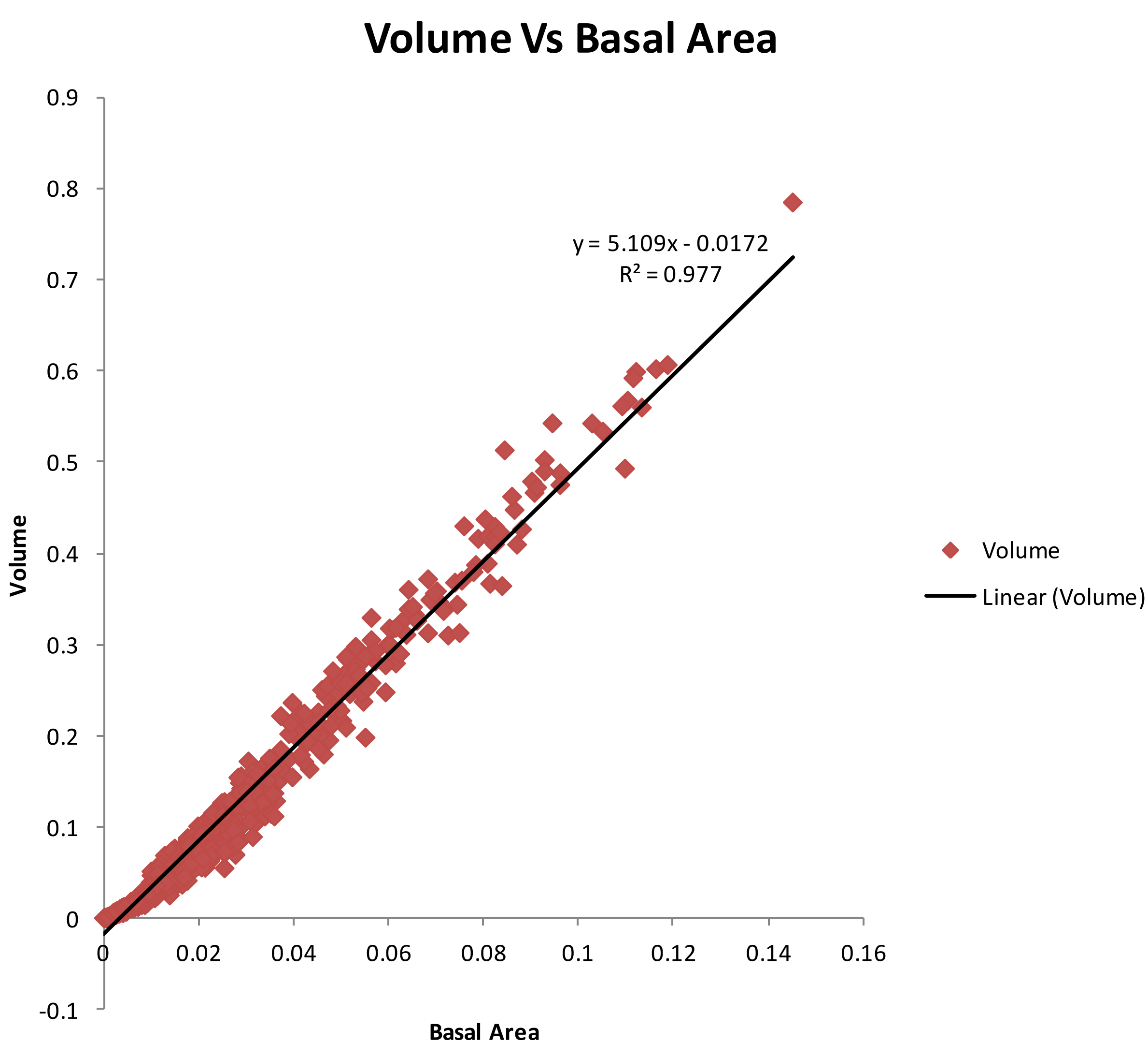


Appendix IV: A plot of dbh verses Age and Spacing





Appendix V: A Scatter plot of Volume Verses Basal Area



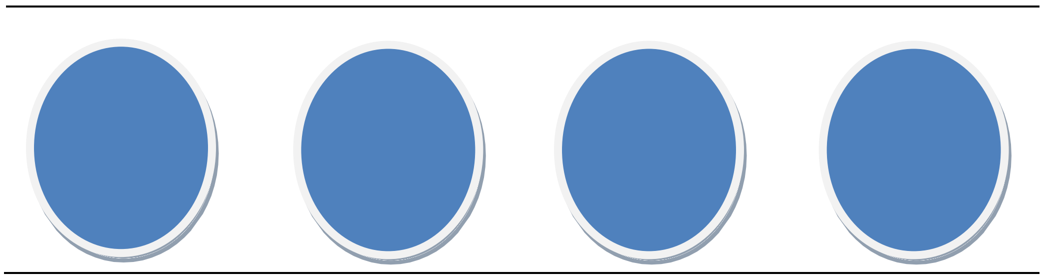
Appendix VI: Projected height over 15 years

Age(years)	Height(Meters)
1	2.9068
2	5.774042
3	7.601346
4	8.970034
5	10.07496
6	11.00685
7	11.81578
8	12.53247
9	13.17719
10	13.76408
11	14.30339
12	14.80282
13	15.2683
14	15.7045
15	16.11517

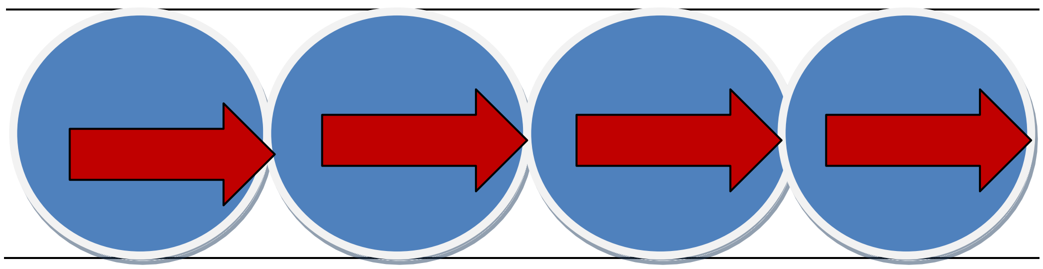
Appendix VII: Projected Dbh over 15 years

Age(years)	DBH
1	2.8123
2	6.535792
3	9.545246
4	12.16822
5	14.53678
6	16.72054
7	18.7617
8	20.68823
9	22.51985
10	24.27109
11	25.95304
12	27.5744
13	29.14216
14	30.66201
15	32.1387

Appendix VIII: Diagram showing hypothetical increase in individual tree's size with time until onset of competition



(a) Minimal competition during the early years of tree growth and/or when the trees are grown at wider spacing.



(b) Competition in one direction (along the line) due to increased size with time or when trees are grown at a close spacing.

Appendix IX: Scatter of height by Dbh