ALLOMETRIC EQUATIONS FOR ESTIMATING *GREVILLEA ROBUSTA* BIOMASS IN FARMING LANDSCAPES OF MARAGUA SUB-COUNTY

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A THESIS SUBMITTED TO THE SCHOOL OF NATURAL RESOURCES AND ENVIRONMENTAL STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN FORESTRY (FOREST BIOLOGY AND SILVICULTURE) OF KARATINA UNIVERSITY

OCTOBER 2018

DECLARATION

Declaration by the Student

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This thesis has been submitted with our approval as university supervisors

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DEDICATION

This study is dedicated to my wife Alice Nyawacha and my children Grace, Eunice, Juliet, Richard, Solomon and granddaughter Faith for supporting my academic life.

ACKNOWLEDGEMENT

First and foremost I thank the administration of Kenya Forest Service for allowing me time to pursue further studies at Karatina University. The University is highly appreciated for offering me an opportunity to study. I express my highest gratitude to my supervisors Dr. Mwangi Kinyanjui and Dr. Mugo Mware for their continuous guidance, support, motivation and encouragement during the development of this thesis. I also appreciate the academic staff provided by Karatina University and particularly the School of Natural Resources and Environmental Studies for their generous support, comments and suggestions during development and finalization of this thesis.

I thank Mr. Richard Maturu Department of Natural Resources Technician for his tireless assistance during data processing. Special thanks to Alice Mutemi, Humphrey Nderi, Josephine Muringo, James Kariuki, James Thuku and Murigi for the excellent work during planning and biomass sampling. Also without the support of farmers who allowed their trees to be uprooted, this study would not have taken place. In addition, I thank all Msc. Forestry 2014 – 2015 students for making my study enjoyable and satisfying.

Finally, very special and sincere appreciation to my wife Alice Nyawacha and my children, Grace, Eunice, Juliet, Solomon and Richard not forgetting granddaughter Faith. You gave me continuous reasons to push on.

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ABBREVIATIONS AND ACRONYMS

AEZs	Agro ecological zones.
AGB	Above ground biomass.
ANOVA	Analysis of variance
ASL	Above sea level
B	Billion
BGB	Below ground biomass.
cm	Centimeters
CO_2.	Carbon dioxide
D	Diameter
DAO	District Agricultural Officer
DBH	Diameter at breast height
df	Degrees of freedom.
e.g.	For example
F_0	Foliage
F	F value calculated from analysis of variance.
FAO	Food and Agriculture Organization of the United Nations
F crit.	F value from analysis of variance tables
FRA	Forest Resource Assessment
FIS	Forest Information Section
GHG	Greenhouse gases
GIS	Geographical Information System.
gm	Grams

GOK	Government of Kenya
GPS	Global Positioning System
GW	Green weight
ha	Hectare
HT	Total tree height
IPCC	Intergovernmental Panel on Climate Change
KFS	Kenya Forest Service
Kg	Kilograms
LB1	Ferralsols – well drained very deep, dark red clay soils
ln	Natural logarithm
m	Meter
MOA	Ministry of Agriculture
mm	Millimeter
MRV	Measurement, reporting and verification
MS	Mean square
MV2	Andosols – well drained, very deep dark reddish to brown clay loam soils
NEMA	National Environmental Management Authority
^{0}C	Degree Celsius
P	Probability value
r	Correlation coefficient
R^2	Coefficient of determination
RB1	Ando humic Nitisols with humic Andosols – well drained deep dark reddish brown to dark brown friable clay soils with acidic humic top soils
RB2	Humic Nitisols – well drained deep dusky dark red to dark reddish brown

	friable clay with an Acid humic top soil
RB3	Nitosols and Cambisols - well drained deep dusky red to dark reddish brown clay soils
REDD++	Reducing emissions from deforestation and degradation including the whole landscape
RS	Root shoot ratio based on biomass
R/H	Root depth/tree height ratio
SEE	Standard error of the estimate
RME	Residual mean error
SOF	State of forests
SS	Sum of squares
t crit.	t value from t-test tables
ton	Metric ton
t stat.	t value calculated by t- test
TTB	Total tree biomass
UNEP	United Nations Environmental Programme

ABSTRACT

*Grevillea robusta (*Silk Oak) is widely interplanted with food crops in Maragua to enhance tree Biomass on farms. a practice that enhances biomass content on farms. However, models for estimating total biomass of *G. robusta* are lacking. This study sought to develop allometric equations for estimating *G. robusta* tree biomass using easily measurable predictor variables of bole diameter and height hypothesized as Biomass does not vary among tree components in different Agroecological Zones (AEZ), Tree component biomass does not differ with trees sizes *G. robusta* biomass stocks does not vary among AEZs. A stratified systematic sampling on Geographical Information System (GIS) platform was used to subdivide each of the four AEZs, Upper Midland 1 (UM1), Upper Midland 2 (UM2), Upper Midland 3 (UM3) and Upper Midland 4 (UM4) into three equal polygons. At the centre of each polygon, a one hectare sample plot was established and Diameter at Breast Height (DBH) for all *G. robusta* trees measured. Thirty three sample trees were randomly selected for destructive biomass measurements. They were felled, stumps uprooted and tree divided into different components. Samples for each component were weighed for fresh weights and oven dried at 105^0C (woody components) and 70^0C (foliage). Biomass data for all sample trees was used to develop allometric equations. Fresh/dry weight ratios were computed and used to derive total biomass for each of the tree components and for the whole tree. The above ground and below ground biomass was used to calculate root/shoot biomass ratio (R/S) while root length and tree height were used to calculate root depth/tree height ratios. The linear, exponential, logarithmic, power and polynomial functions were used to estimate biomass from DBH and height data. The best fit equation was selected based on the lowest Standard Error of the Estimate (SEE), lowest Mean Residual Error (MRE) and Coefficient of determination (R^2). Of the fitted functions the polynomial equations had the highest R^2, lowest SEE and lower MRE values. The equation to estimate Total Tree Biomass (TTB) = $0.322DBH^2+7.934DBH-19.26$ ($R^2=0.99$), Above Ground Biomass (AGB) = $0.248DBH^2+6.243DBH-15.45$ ($R^2=0.98$) and Bellow Ground Biomass (BGB) = $0.074DBH^2+1.688DBH-3.791$ (R^2 0.98). Use of height/or product of height and DBH as predictors resulted in a decrease in R^2 and high SEE values. T-test for (AGB, BGB, TTB) indicated no difference between predicted and actual biomass (T=0.54,P=0.601,T=1.714,P= 0.117 and T = 0.422 ,P = 0.68 respectively). Developed equations were also compared with other existing equations for validation. The best fit equation estimated TTB in the AEZs was 13.926 $tonha^{-1}$,13.109 $tonha^{-1}$,10.869 $tonha^{-1}$ and 11.827 $tonha^{-1}$ in UM1, UM2, UM3 and UM4 respectively, showing uniformity of stocking across the landscape (F=2.87,P=0.675). DBH was found to be a reliable predictor of biomass (AGB, BGB and TTB) in farming landscapes of Maragua Biomass allocation to different tree components does not differ in the 4 AEZ implying that one allometric equation can be used to estimate the biomass of a specific tree component in all the AEZ of the study area but tree Biomass varies with tree sizes.. The developed equations will be useful in estimating *G. robusta* tree/component biomass in the farms in support of marketing for energy, timber and other wood uses in the area.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Forests play a significant role in climate change mitigation by acting as sinks absorbing carbon from the atmosphere and storing it in the woody biomass and in the soil (Gunn, Bailey, & Farrar, 1999). Through photosynthesis, plants absorb CO_2 from the atmosphere (Douglas, & Simula, 2010). Since forests are extensive blocks comprising of many and massive plants (Lohbeck et al., 2014) the process of removal of the carbon dioxide (CO_2), often referred to as sequestration is large scale (Matta, 2009). Trees either in forests or on farms play a major role in stabilizing global and micro climates for the benefits of humankind (Millennium Ecosystem Assessment, 2005).

In agricultural ecosystems trees play a role in carbon sequestration as they capture and store carbon that would otherwise be emitted and remain in the atmosphere (Henry et al., 2010). Nair, Kumar and Nair (2009) noted trees on farms are the main carbon stores through fixation of CO_2 from the atmosphere into biomass some of which is sequestered into soil organic carbon during putrefaction. The trees also alleviate the pressure on natural forests by supplying fuel wood, timber and other forest produce which would otherwise be sourced from forests (Albrecht & Kandji, 2003) resulting to their destruction. Planting of trees in agricultural ecosystems is therefore important and majority of the population still rely on wood fuel for energy (International Energy Agency *(*IEA*),* Organization, 2010).

Apart from carbon sequestration, trees on farms also provide nutrients locked deep in the soil making them available to the crops (Nair et al., 2009), the leguminous plants fix nitrogen which enhances the soil nutrients. In addition, trees on farms provide shade to plants and fodder for animals. Kiplagat, Wang and Li (2011) noted that tree planting on farms is also spurred by the increasing need for woody biomass as feed stocks for bio-energy.

Kenya being a wood deficient country has 80 percent of the national wood supply going to fuel wood (FAO, 2010) with the bulk of this source being wood from outside state forests, mainly in farmlands and drylands. FAO (2011) further states that majority of timber and non-timber wood products in Kenya are obtained from farm estates which presents additional income. Kenya seeks to have a 10 percent forest cover by the year 2030 (GOK, 2010). In support of this, the farm forestry rules were developed with the aim of supporting the realization of the Vision 2030 goals by enhancing tree farming in croplands (GOK, 2009.)

Based on the global guidelines on REDD+ increased forest cover will be attained by enhancing stocks in the forests and on farms though planting and conservation of existing stocks among others (Verbist, Vangoidsenhoven, Dewulf, & Muys, 2011). Tree planting in this country is mainly farm based with a mixture of exotic and indigenous trees dominating the landscape (Jamnadass et al., 2011). The commonly planted agroforestry trees in Kenya include *Cordia abysinica, Eucalyptus spp, Grevillea robusta, Markhamia lutea, Croton macrostachyus* and *Leucaena leucocephala* among others (Gachathi, 2007).

Although trees were previously planted separately from crops, most trees are currently planted on farms, along boundaries or integrated with crops depending on land size or the utility of the species (Kuyah et al., 2012). When integrating trees with crops, farmers select trees that can grow with crops without reducing yields significantly but still provide social, economic and environmental services that would have required heavy financial investment (Jamnadass et al., 2011).

Due to diminishing wood resources in the state forests and the need to enhance conservation measures (Ludeki, Wamukoya, & Walubengo, 2006) there has been an increasing tendency to source timber and non-timber wood products from farms. This presents an opportunity for farmers to have access to additional income from their lands (FAO, 2011). Many smallholder farmers plant multipurpose trees that complement other enterprises on the farm. Furthermore, payments from carbon sequestration are an incentive to enhancing integration of trees in farmlands (Kinyanjui et al., 2014).

Trees require nutrients for growth and development (Gunn et al., 1999). Through photosynthesis, carbon dioxide from the atmosphere and nutrients from the soil are converted into the woody biomass that is stocked in trees. In the tropics, soils are often depleted of nutrients due to intense agricultural use (Shepherd & Soule, 1998). Integration of trees in the farms enhances the productivity of these ecosystems because some deep rooted trees circulate nutrients making them available to crops (Nair et al., 2009). Biomass production and partitioning is also affected by nutrient elements depending on the limitation and function (Keith, Barrett, & Keenan, 2000). Deficiency of nutrients retards growth and partitioning of biomass in various components through shifting of partitioning between foliage and fine roots (Gower, Vogt, & Grier, 1992).

Traditionally foresters did not estimate tree biomass and instead estimated tree volumes (Philip, 1994). Currently assessment of biomass in forests has gained more attention due to the role trees play in global carbon cycle (Albrecht & Kandji, 2003). Measurement approaches designed to predict harvest yield, help to assess biomass loss or accumulation over time and show allocation of biomass in the wood components are required. Noting that 50 percent of wood biomass is carbon, biomass estimation is an essential component of monitoring carbon fluxes in forested ecosystems (Eamus, McGuinness, & Burrows, 2000).

Tree biomass can be estimated using either direct or indirect methods. Direct methods involve cutting and weighing trees in the field and are the most accurate ways to quantify biomass (Brown, 1997), though time consuming, destructive, labor intensive, expensive and difficult to implement (Brown, 2002). Indirect approaches include use of allometric relationships (Brown, 1997), photographic techniques (Jonckheeva et al., 2004), remote sensing (Gibbs, Brown, Niles, & Foley*,* 2007) and fractal branch analysis (Van Noordwijk & Mulia, 2002). Although these indirect methods exist and have many advantages, direct methods are still indispensable (Chave et al., 2005).

1.2 PROBLEM STATEMENT

Grevillea robusta is one of the major agroforestry tree species in Kenya. It thrives well in regions of limited moisture and is easily integrated with food crops (Karanja, Mwendwa, & Zapata, 1999). It is adaptable to a variety of agro ecological regions in Kenya (Githiomi & Mugendi, 2012). In addition to the agroforestry benefits of this tree, it is also a source of energy, timber and supports carbon sequestration potential of the agricultural ecosystems (Chikamai, Githiomi, Gachathi, & Njenga, 2001). Specifically in Maragua, the tree has been widely planted and its potential to enhance the productivity of the agroforestry resources has highly been promoted due to its ease of workability (Chikamai et al., 2001; Githiomi & Mugendi, 2012). It also provides cheap timber for constructions and the demand in the market is quite high.

The specific roles of this species as a source of energy, fodder, timber and carbon sequestration are of paramount importance. Since the uses and marketing of these tree products are influenced by the tree sizes, there is a need to establish a quick method for establishing its quantities. In Maragua, *G. robusta* is widely planted on farms for commercial purposes (Githiomi & Mugendi, 2012). Mechanisms for assessing the tree component's biomass. Such mechanisms may involve development of models for estimating biomass quantity in a tree or its component's and relating them to market prices. In addition such a method may provide the basis for estimating the carbon quantities sequestered by a tree. It is therefore necessary to develop models that will estimate tree biomass quantities on farms.

Some allometric equations have been developed to estimate tree biomass quantities using easily measurable parameters such as DBH and height. Henry et al. (2009) and Kuyah et al. (2012) constructed equations for estimating tree biomass in agricultural landscapes in Western Kenya while Kinyanjui et al. (2014) constructed an equation for inventory of the above ground biomass in the Mau Forest Ecosystem. However, in all these studies, it is proposed that an allometric equation may be needed for every geographical area, to accurately estimate the woody biomass. Such equations have not been developed for the study area. Therefore, it is essential to develop equations for estimating *Grevillea robusta* biomass quantities in farming landscapes of Maragua.

1.3 JUSTIFICATION

Trees on farms represent a vital source of food for many of the world's poorest people, providing both stable and supplemental foods such as fruits, edible leaves and nuts, fodder and brows for livestock and fuel for lighting, cooking and food processing (Acharya, 2006). They provide a variety of non-wood products like resin, honey, medicine, vegetables among others including sources of income and are also important in conservation of biological diversity, water and soil conservation (Henry et al., 2009).

Quantification of the amount of carbon stored in trees is an important component in the implementation of the emerging carbon market (Velarde et al., 2010). Developing countries including Kenya can benefit from $REDD^+$ related mechanisms by providing accurate information about their forest and tree resources. REDD+ requires countries to establish measurement, reporting and verification (MRV) methods (Verbist et al., 2011). This may consists of inventory of forests/trees in sampled plots and application of appropriate allometric equations to estimate biomass (Brown, 2002). Biomass estimates eventually are converted into carbon and CO_2 equivalents. Hence the allometric equations developed in this study will be useful for *G. robusta* biomass assessment on farms in Kenya.

Most of the small scale farmers in Maragua integrate trees (mainly *G. robusta*) in their farms. They are therefore likely to benefit economically if tree biomass and/or Carbon sequestered are appropriately accounted and sold. Additionally, trees on farms are major sources of energy for the local communities and industries. A method that helps establish biomass stocks of this energy pool and provides accurate information about the available timber resources from this species would help in its management and conservation. It is against this background that this study sought to develop equations for estimating *G. robusta* biomass.

1.4 OBJECTIVES

1.4.1 Main Objective

The overall Objective of this study was to develop an allometric equation that estimates biomass components for *G. robusta* trees in agricultural landscapes of Maragua.

1.4.2 Specific Objectives

The specific objectives of the study were:

1) To assess *G. robusta* Biomass characteristics in 4 AEZs of the study area.
2) To develop allometric equations that relates *G. robusta* component biomass with easily measurable parameters.
3) To assess variation in biomass stocks of *G. robusta* in 4 AEZs of the study area.

1.4.3 Hypothesis

Hypothesis related to objective 1

Biomass does not vary among tree components in different AEZ of the study area.

Hypothesis related to objective 2

Tree component biomass does not differ with trees sizes.

Hypothesis related to objective 3

G. robusta biomass stocks do not vary among AEZs of the study area.

CHAPTER TWO

LITERATURE REVIEW

INTRODUCTION

This chapter discusses the roles played by trees/forests as carbon sinks on farming landscapes. Highlights on tree biomass and biomass modeling and narrows down on the problem of estimating forest/tree produce and in particular biomass production and partitioning. It also describes biomass estimation using allometric equations singling out some of those in use in Kenya.

2.1 FORESTS AND TREES IN FARMING LANDSCAPES

2.1.1 An Overview of Forests and Trees in Farming Landscapes

Forests currently cover about four billion hectares (4B ha) which is approximately 31 percent of the Earth's surface (Gallaun et al., 2010). In Africa forests currently covers about 23 percent of the land (Verkerk, Anttila, Eggers, Lindner, & Asikainen, 2011). The Forest Resource Assessment (FRA) Report for Kenya (FAO, 2011) reported an area of 4,193,000 hectare of Kenyan's land as naturally regenerated forests and 220,000 ha as planted forests. This translates to a total of 4,413,000ha which is approximately 7 percent forest cover. Wooded lands are estimated to cover an area of 9,365,000 ha. This together with forested area is 13,778,000 ha wooded land which is 23.74% of Kenya land area (Bailis, Drigo, Ghilardi, & Masera, 2015).

Beyond the trees in forests, trees in farms and in grasslands are equally important. Recognizing this, the Farm Forestry Rules (GOK, 2009**)** were developed to encourage all farmers in Kenya to plant at least 10 percent of their farms with trees so as to sustain the agricultural lands and meet the households' needs.

Most of the trees are planted along boundaries or integrated with crops, depending on land size and/or the utility of the species (Kituyi et al., 2001). Boundary planting is adopted to minimize competition with crops while competitive trees such as *Eucalyptus* species are often planted in woodlots for households with large land sizes (Kuyah, 2008). When integrating trees with crops, farmers select trees that can grow with crops without reducing yields significantly and providing social, economic and environmental services, which would otherwise require heavy financial investment (Jamnadass et al., 2011).

The planting of such trees has reduced pressure on forest estates because they provide basic wood requirements to the livelihoods (FAO, 2011). In Kenya, the majority of timber and non-timber wood products are obtained from farm estates (FAO, 2011) presenting an opportunity for farmers to have access to additional income from their land. This trend increases the need for woody biomass as feed stocks and for bio-energy (Kiplagat et al., 2011). Despite the effort to increase tree cover on farms, the demand for wood and non-wood tree products in the country outstrips their supply, largely due to a rapidly increasing human population and depletion of natural sources (Kiplagat et al., 2011). To meet the high demand for tree products and services, the Country is increasingly focusing on conserving and increasing trees in the landscape (Ludeki et al., 2006). Considerable success has been achieved through introduction of fast growing tree species and adoption of agroforestry technologies (Jamnadass et al., 2011). Enhanced integration of trees in farmlands has also been promoted by the opportunity to receive payments from carbon sequestration (Nair et al., 2009).

2.1.2 Roles of Forests and Trees on Farms

Forests provide resources for people including a renewable source of energy (UNEP, 2011). For the global economy to be sustainable, land use Principles, Policies and Practices collectively known as Sustainable Forest Management must be practiced all over the World (Anderson et al., 2015). Net carbon dioxide ($CO_{2)}$ in the atmosphere will decline as long as new trees are planted to replace those that are cut. Currently, emissions from deforestation have been estimated at about 17 percent of all global emissions (UNEP, 2011). Therefore stabilizing forest ecosystems plays a major role in the global reduction of greenhouse gases emissions and mitigates climate change. Forests contribute approximately 80 percent of the aboveground and 40 percent of the belowground carbon storage (Kirschbaum, 1996).

Use of wood as basic material for furniture, wood carving, handicrafts and other small or medium enterprises increases investments in wood based enterprises and generate employment, create real and durable assets and help revitalize lives of millions of poor people in rural areas (FAO, 2011). Trees provide raw materials for building, communication infrastructure, food and fuel for cooking. All the wood used in Africa, 80 percent is for fuel (Fan & Dong, 2001). Forests and trees on farms are a vital source of food for many of the world's poorest people, providing both stable and supplement foods including fruits, edible leaves and nuts, fodder and browse for livestock and fuel for lighting, cooking and food processing (Solaro, Barbiero, Manzi, & Ferrari, 2011)

Forests rank high as some of the most important assets in terms of economic, environmental, social and cultural values. They provide utility products such as timber, poles, fuel wood and pulp wood (UNEP, 2011). They also provide a variety of non-wood products like resin, honey, medicine, vegetables among others and are also important in conservation of biological diversity, water and soil conservation and are major habitats of wildlife. They are therefore influenced by farming and herding practices of the local inhabitants but still support a forest cover of solely or mainly indigenous species (Wantzen, Wagner, Suetfeld, & Junk, 2002).

Agricultural ecosystems represent an important component in tree biomass and carbon (C) sequestration (Penman et al., 2003). Trees in agro-ecosystems store carbon through fixation of atmospheric CO_2 into biomass, some of which is indirectly sequestered as soil organic C during putrefaction (Nair et al., 2009). Thus, planting trees on farms enhances the wood biomass and the carbon sequestered in the farms (Xiao, White, Hooten, & Durham, 2011).

Overall, trees on farms alleviate the pressure on natural forests by supplying goods including timber and fuel wood, which would otherwise be sourced from forests (Albrecht & Kandji, 2003). Furthermore, trees are widely being included in farmland to expand existing C sinks, conserve available C pools and substitute fossil fuel with green energy (Velarde et al., 2010).

2.2 TREE BIOMASS AND BIOMASS MODELLING

2.2.1 Tree Biomass

Trees require nutrients for growth and development (Gunn et al., 1999). Through photosynthesis, carbon dioxide from the atmosphere and nutrients from the soil are converted into the woody biomass that is stocked in trees. The IPCC (2006) describes wood biomass as the oven dry equivalent of a piece of wood of which 50 percent is pure carbon. Different trees accumulate biomass at different rates based on their growth rates, nutrient content, sunlight and moisture content and this makes equatorial regions the most productive in terms of biomass (Leigh et al., 2004).

In the tropics, soils are often depleted of nutrients due to intense agricultural use (Shepherd & Soule, 1998). Integration of trees on farms enhances the productivity of these ecosystems because some deep rooted trees circulate nutrients making them available to crops (Nair et al., 2009). Biomass production and partitioning is also affected by nutrient elements depending on the limitation and function (Keith et al., 2000). Deficiency of nutrients retards growth and partitioning of biomass in various components through shifting of partitioning between foliage and fine roots (Gower et al., 1992).

High nutrient availability results in increased growth rate, increased canopy components and high shoot to root ratio. (Keith et al., 2000). Total tree biomass accumulates throughout the development of individual trees though partitioning among components change with age (Gower et al., 1992).

2.2.2 Biomass Modeling

Biomass estimates are of scientific importance to understanding the quantitative role of forest carbon sequestration on the earth's climate system (Eamus et al., 2000). Forest inventories have been concentrating in tree volume estimation, especially merchantable volume (Philip, 1994). Tree biomass is related to tree volume and the relation varies substantially depending on tree species and the peculiarities of individual trees based on elevation, provenance and site qual (Macauley, Morris, Sedjo, Farley, & Sohngen, 2009). Estimates of biomass and carbon stocks from volume have been done by various researchers. In the study by Brown et al. (1989), biomass estimation models were developed using destructive method. The study recommended use of developed allometric equations where species and site specific models do not exist. Allometric equations are derived through conversion of easy to measure parameters like Diameter at Breast Height (DBH), Height (HT) or combination of DBH with HT to biomass. These parameters are regressed to show the relationship between biomass and its predictor variables (Philip, 1994).

Allometric equations describing natural relationships in trees are not always linear (Kuyah et al., 2012). Different models are fitted to the data until the model that best describes a particular species or environmental condition is obtained. Therefore, allometric equations may be required for individual species or for species in a limited geographical area. Allometric power function equations are commonly used in biomass estimation although some studies have reported the use of polynomial equations (Henry et al., 2011). Studies have also reported power function relationships that relate tree biomass with structural parameters as DBH, HT or DBH in combination with HT (Brown, 1997; Chave et al., 2005).

In sampling trees for developing allometric equations, the individual tree is the unit of sampling (Philip, 1994). However in selecting areas to obtain the trees for sampling, the conventional sampling methods are used. Generally the forests are stratified to ensure that the varieties of forest characteristics that influence allometry are captured (Henry et al., 2011). Such characteristics may include site indices and agro ecological conditions. To reduce bias among selected individuals, systematic sampling methods are always proposed where the sample units are defined by specific intervals in the pattern (Black et al., 2004). By taking a sample in each polygon created in a stratified systematic manner, there is no bias in the identification of samples and the samples selected are a good representation of the trees in the population.

2.2.3 Common Allometric Equations Used in Kenya

Published equations used for tropical species are constructed for estimating aboveground biomass (AGB) by Brown (1997) or belowground biomass (BGB) by Mokany, Raison, and Prokushkin, (2006). Total Tree Biomass (TTB) is then obtained by adding the two (AGB and BGB). Estimates derived from equations may not be accurate because of the "species specific" or generalized nature of the equation used (Nair et al., 2009). Despite there being a number of allometric equations globally, there are several limitations with allometry development in East Africa.

Some of the published allometric equations in Kenya include, the equation of Henry et al. (2009) constructed from data collected in Western Kenya; the equations of Kuyah et al. (2012) constructed for estimating tree biomass in agricultural landscapes in Western Kenya, the equation of Kinyanjui et al. (2014) constructed for inventory of the AGB in the Mau Forest Ecosystem. In all these studies, it is proposed that for every geographical area, an allometric equation may be needed to accurately estimate the wood resources because the biomass estimating parameters differ with location, land cover type and management practices. There is need to develop allometric equations for tree species regarding AEZs, different planting arrangements, management regimes and different age classes.

2.3 SUMMARY OF FINDINGS FROM THE REVIEW

1. Trees in the farming landscapes are an option towards enhancing tree cover in Kenya and farmers have a variety of benefits to gain by including the tree component in their agricultural fields but biomass contained in the farms is not known.
2. There are efforts to enhance forest conservation and increase tree cover to 10 percent by the year 2030 in Kenya. Farm forestry is an option towards attaining this vision.
3. Trees accumulate biomass as they grow in different sites. However, differences in climatic and edaphic conditions influence the biomass accumulation characteristics of the trees.

4. Allometric equations are a quick method of estimating tree biomass using easily measurable parameters like diameter and height. Some allometric equations have been developed for general use in Kenya but literature recommends that these should be done per species and geographical region to allow better accuracy of biomass estimation.
5. *Grevillea robusta* is one of the widely grown agroforestry trees in Kenya due to its good adaptability and the variety of uses that it provides for the farmer and the general public. However, regional specific biomass estimating models are lacking for this species.

CHAPTER THREE

MATERIALS AND METHODS

INTRODUCTION

The chapter describes the study area, sampling design and methods used to carry out measurement of biomass. It describes the study area, land use activities, and then explains the destructive sampling to determine fresh weights followed by sub-sampling to determine dry weights. It further outlines measurements of DBH, Tree Height, Branches, Foliage and Root system. A summary of data recording and analysis is highlighted. Finally regression analysis to develop the equations, equation validation and analysis of variance (ANOVA) to compare biomass among agro ecological zones are highlighted.

3.1 DESCRIPTION OF THE STUDY AREA

The study area was Maragua in Murang'a County (Figure 3.1). The area covers a total of 839 Km^2 (NEMA, 2004), extending between Longitude 36^0 30'E to $37^0$30'E and latitude $00^0$30'S to 1^0S. The area rises from altitude 1,000 m ASL in the East to 2,500 m ASL in the West (Table 3.1). Jaetzold, Schmidt, Hormetz, and Shisanya (2006) indicate the study area consists of four upper midland Agro ecological Zones (AEZ); upper midland 1 (UM 1), upper midland 2, (UM 2), upper midland 3 (UM 3) and upper midland 4 (UM 4).

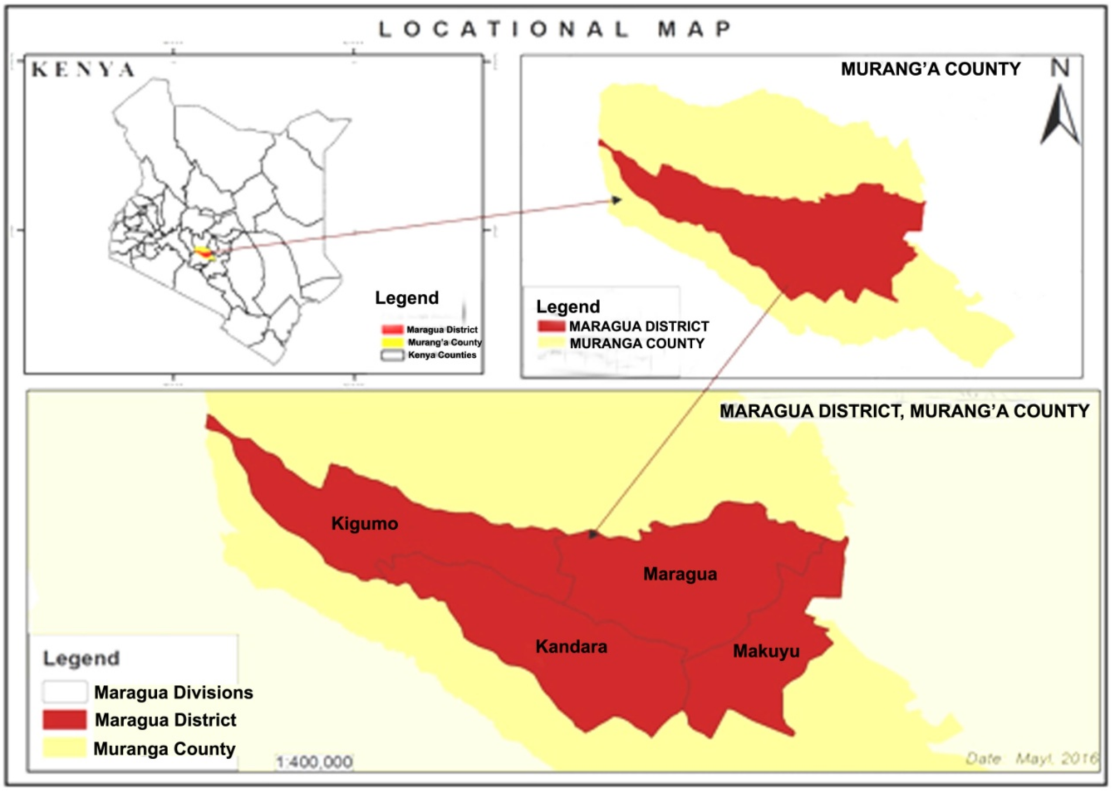

Figure 3.1: The Location of the Study Area in Murang'a County

3.1.1a Biophysical and Climatic Conditions

Annual rainfall ranges from 900 mm to 2,500 mm decreasing eastwards. The mean annual rainfall in the four agro ecological zones UM 1, UM 2, UM 3 and UM 4 are 2,200 mm, 1,537.5 mm, 955 mm and 970 mm respectively (Table 3.1). It follows a bimodal distribution with long rains from March to July and short rains from October to December (NEMA, 2004). The reliable rainfall allows two cropping seasons per year mainly in the Eastern side (NEMA, 2004) Temperatures for the year range from a minimum of 18.0^0C to a maximum of 21.7^0C (Jaetzold et al., 2006). Mean annual Temperatures for the agro ecological zones UM I, UM 2, UM 3 and UM 4 are 18.4^0C, 19.3^0C, 20.2^0C and 21.2^0C respectively (Table 3.1).

Table 3.1: Biophysical and Climatic Conditions of Maragua – Sub County

Attribute	**Upper midland 1 (UM 1)**	**Upper midland 2 (UM 2)**	**Upper midland 3 (UM 3)**	**Upper midland 4 (UM 4)**
Altitude range (m)	1730 - 2430	1500 – 1730	1340 – 1500	1060 - 1340
Mean annual rainfall (mm)	2200	1537.5	955	970
Mean annual temperature (^{0}C)	18.4^{0}C	19.3^{0}C,	20.2	21.2
Soils	MV2	RB1, RB2	RB3	LB1

Source: (Jaetzold et al., 2006)

The area is one of the major sources of hydrological cycle which causes relief type of rainfall. It is a major source of numerous springs and rivers that drain into River Tana through rivers: Maragua, Irati, Sabasaba, Kabuku, Makindi, Thuki, Thamuru, and Thika (Jaetzold *et al.* 2006). In the study area, Jaetzold et al. (2006) classified soils in various AEZs as shown in Table 3.2.

Table 3.2: Classification of Soil in Maragua – Sub County

AEZ	**Physiographic Lithology**	**Soil description**
UM 1	MV2	Well drained, very deep, dark reddish to dark brown, very friable and smeary, clay loam to clay, with thick acid humic topsoil, in places shallow to moderately deep and rocky: Humic ANDOSOLS, partly lithic phase
UM 2	RB1	Well drained, extremely deep, dark reddish brown to dark brown, friable and slightly smeary clay with an acid humic topsoil: Ando-humic NITISOLS: with humic ANDOSOLS.
	RB2	well drained, extremely deep, dusky red to dark reddish brown, friable clay with an acid humic topsoil: humic NITISOL
UM 3	RB3	Well drained, extremely deep, dusky red to dark reddish brown friable clay; with inclusion of well drained, moderately deep, dark red to dark reddish brown, friable clay over rock, pisoferric or petroferric materials. Eutric NITISOLS: with nito-chromic CAMBISOLS and chromic ACRISOLS and LUVISOLS, partly lithic, pisoferric or petroferric phase
UM 4	LB1	Well drained, very deep, dark red, very friable clay: Nito-rhodic FERRALSOLS.

Jaetzold et al. (2006) further described rainfall and temperatures in every AEZ of Maragua - Sub Count as shown in Table 3.3.

Table 3.3: Rainfall and temperature characteristics in Maragua

AEZ	Rainfall and temperature characteristics
UM1	Humid, Upper Midland. Length of growing period greater than 270 days. Evergreen, Annual mean temperature 15-18^{0}C, Monthly minimum 8-11^{0}C, no frost
UM2	Sub-humid, Upper Midland. Length of growing period is 180-270 days. One or two dry months. Annual mean temperature, 15-18^{0}C, Monthly minimum 8-11^{0}C, no frost
UM3	Semi-humid, Upper Midland. Three to five dry months, Annual mean temperature, 15-18^{0}C, Monthly minimum 8-11^{0}C, no frost
UM4	Transitional, Upper midland with two dry seasons. Annual mean temperature, 15-18^{0}C, Monthly minimum 8-11^{0}C, no frost

Source **(**Jaetzold et al., 2006**)**

3.1.1b Demographic Conditions

Maragua is densely populated with a density of 447persons/km^2 and a total p0pulation of 387,969 people (GOK 1999) the number of persons per household stood at 4.3. Its main economic activity is agriculture which is zoned into tea zone; main coffee zone; marginal coffee zone; and sunflower maize zone (Jaetzold et al., 2006).

3.1.2 Land Use Activities

Farmers in the study area have actively adopted agroforestry (Githiomi et al., 2012). Land use systems in Maragua range from subsistence small holder farms to more cash crop oriented farms which relatively range from 3.75 to 5 acres (GOK, 2012). Glenday (2006) states that woody vegetation forms part of the agricultural landscape which varies from single tree to small stands that consists of mainly exotic trees and isolated indigenous trees managed in different ways. Trees are grown around homesteads, in woodlots, croplands and along farm boundaries (Scherr, Shames, & Friedman, 2012). Githiomi et al. (2012) further states that trees and shrubs are grown around the homestead, in woodlots, cropland and along farm boundaries and that woodlots are in small mono specific clusters of trees mainly in lower areas of the study area. According to Jaetzold et al., (2006), Maragua's agriculturally viable land is about 68,000 ha with two main cash crops coffee and tea grown on 6,500 ha and 4,000 ha respectively. Tea yields 11,000 $kgha^{-1}$ of green leaves while coffee yields 2,800 $kgha^{-1}$ per annum.

3.2 DATA COLLECTION METHODS

3.2.1 An Overview of the Data Collection Method

In this study, the work included subdividing each AEZ into three equal portions for data collection, measurement of all standing *G. robusta* trees (DBH) in the plots, selecting trees for destructive sampling and uprooting them, debranching, removing leaves and cross cutting the trees. Handling of the green tree components together with their samples followed. Field data were recorded on prepared data sheets (Appendix 1a, b, c and d). Field and Laboratory data were entered in excel work sheets for analysis.

3.2.2 Sampling Design, Sample Plot Location and Selection of Sample Trees

Land map of the study area was obtained from Kenya Forest Service (KFS), Forest Information Section (FIS) (Figure 3.1). The area was identified and stratified into four Agro ecological zones (UM 1, UM 2, UM 3 and UM 4. A stratified systematic sampling was used on a Global Information System (GIS) platform to select sampling sites in each of the four AEZs (UM 1, UM 2, UM 3 and UM 4) (Magnussen & Reed, 2004). This involved subdividing each AEZ into three equal portions (polygons). The centre of each polygon was used as the reference data collection point (Figure 3.2).

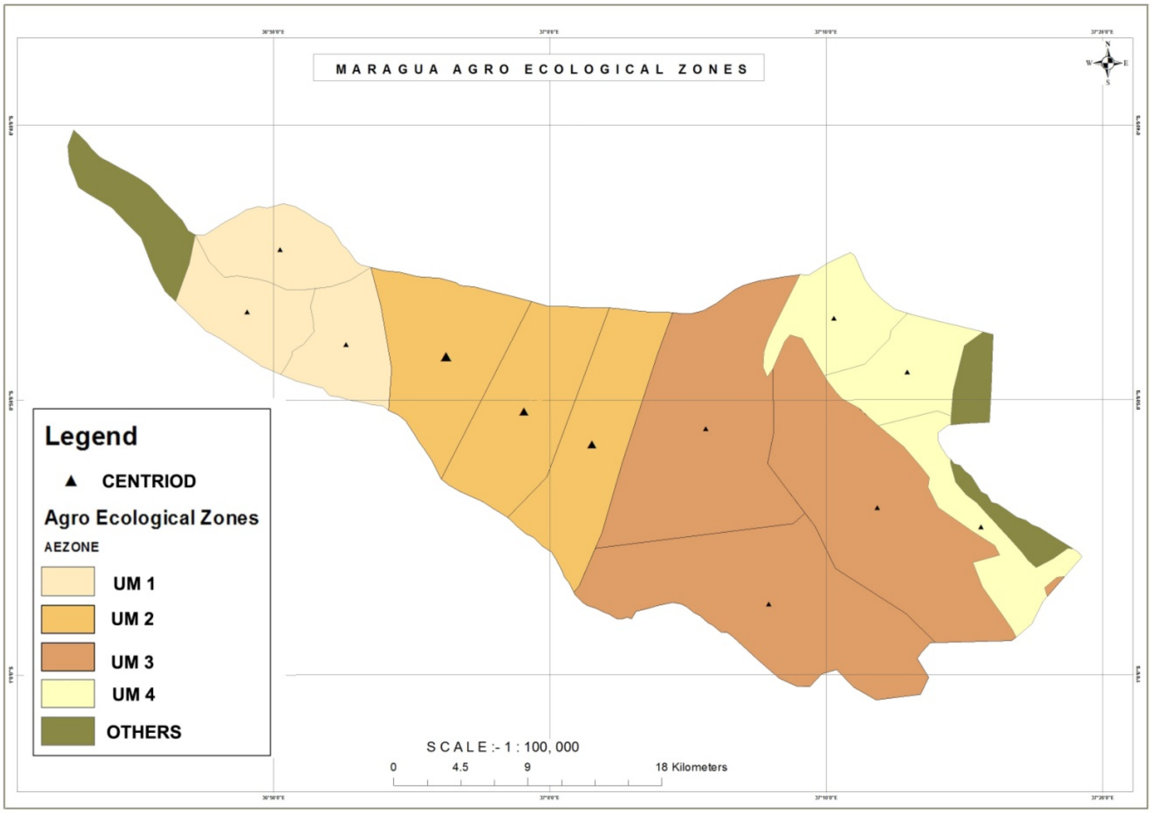

Figure 3.2: Maragua Agro ecological Zones, Polygons and Points for Data Collection

The position of each of the (GIS) selected data collection reference point in each of the AEZ was identified on the Topographic map, coordinates recorded (Table 3.4) and stored in a GPS, and then traced on the ground. The owner of the farm was identified and requested to allow data collection and trees to be destructively sampled after payment for compensation at the market rate. A one hectare plot (100 m x100 m) was then established at the reference point which was the center of the polygon aligned using a GPS to the North-South and East –West grids.

Table 3.4: Co-ordinates of Data Collection Points for all the AEZs

Agro ecological Zone	Portion	Eastings (m)	Nothings (m)
UM 4	1	305449.791	9900308.287
	2	301575.475	9908749.165
	3	297040.133	9914658.828
UM 3	1	290497.054	9896663.132
	2	298551.514	9903069.450
	3	289507.887	9901526.723
UM 2	1	281419.488	9909982.717
	2	276445.967	9904576.637
	3	268721.854	9911103.375
UM 1	1	263165.408	9896663.132
	2	259196.650	9918509.281
	3	256504.015	9914786.820

All the *G. robusta* trees in the plot were counted numbered and DBH of every tree measured and categorized into three classes (table 3.5). Out of the trees measured, one was randomly selected from each class giving a total of three trees per plot.

Table 3.5: Categories of Sampled Trees

Class	Diameter (DBH) Range (cm)	No of trees
1	1.1 – 13.0	-
2	13.1 – 26.0	-
3	26.1 – 40	-
4	> 40	-

3.2.3 Tree Parameters Measurement and Assessment of Green Biomass

The data collected included DBH, heights of trees, roots depth of the trees, green weights of stems, branches, foliage and roots. Aliquots green weights of all the destructively sampled trees components were weighed and recorded**.** All the field data were recorded on data sheets (Appendix 1a, b, c and d) prepared before field work and used during the actual field activities to capture all the required information for biomass measurements.

3.2.3.1 Diameter, total tree height and above ground biomass measurements

Diameter at Breast Height (DBH) is commonly used for estimating biomass as it can be easily measured (West, 2009; Sileshi, 2014). Its measurement follows commonly acknowledged forestry conventions. DBH of all the *G. robusta* trees (Appendix 5) in the established one hectare plot were measured and recorded in four DBH classes (1.1–13.0, 13.1–26.0, 26.1- 40.0 and > 40cm). It was measured using diameter tapes held tightly and horizontally to the tree axis and recorded to one decimal point.

The three selected trees in each sample plot were uprooted. A strong rope was used to guide the tree to the felling direction based on the inclination of the tree and the surroundings. Tarpaulin sheets were spread on felling direction to avoid loss of foliage. After uprooting, the total tree length (distance from the base of the tree to the uppermost point of the tree) was measured using a linear tape and recorded in meters to two decimal places The tree was then cross cut at the root collar using a power saw (big trees) or bow saw (small trees). Big branches were cut using a power saw while small ones were cut by using a bow saw. The tree was then divided into various components; main trunk (stem) from the base to the tip of the tree, branches and foliage (twigs, leaves, pods and seeds).

Plate 3.1: Stem Log being Prepared for Weighing

The stem was then divided into at most five equal billets depending on the length of the tree trunk. The lengths of the billets varied with the tree lengths. Each billet was weighed for green weight (GW) (Plate 3.1) and the unmanageable ones further cross cut for easier handling and weighing (weighable pieces). The weights were recorded to the nearest 0.1kg (Appendix 2a). Aliquots were taken from the mid of each billet (log), that is at most five per tree for Laboratory oven drying. The aliquots were cut from the bark through to the centre of the log (pith) that is from the bark through the sapwood to the heartwood. They were weighed for green weight, recorded, labeled, tagged and put in bags. They were stored ready for transportation to the Laboratory for oven drying.

3.2.3.2 Measurement of Branches and Foliage Green Weights

The branches were trimmed, cross cut, measured at the midpoint and classified into four diameter classes as: $0 < D < 2$ cm (Class I), $2 \leq D < 5$ cm (Class II), $5 \leq D < 10$ cm (Class III) and $D \geq 10$ cm (Class IV) for ease of weighing (Appendix 1b). Their green weights were taken to the nearest 0.1 kg. The heavier ones were measured as individual billets while the lighter ones were bundled together and their green weights taken (Plate 3.2). Block samples of wood (aliquots) from each diameter class were randomly selected, their green weight taken and recorded to the nearest 0.01gm. Those from large branches (class III and class IV) were cut from the bark to the pith while those of class I and class II, a block of about 2 cm was cut. The aliquots weights were recorded, labeled, kept in bags and stored ready for transportation to the Laboratory.

Plate: 3.2: Branch Weighing

The foliage was stripped off on to a tarpaulin sheet, bundled into gunny bags (Plate 3.3) whose weights were known and weighed them. Their total green weights was calculated by getting the difference between gross weight and the weight of the empty gunny bags and recorded to the nearest 0.1 kg This included leaves, twigs, flowers, pods and seeds. A sample of about 500 g of the foliage was randomly taken from the combined mass of the foliage, weighed, recorded to the nearest 0.01 gm (Appendix 1c) and kept in well labeled polythene bags for transportation to the laboratory for oven drying.

Plate 3.3: Foliage Processing for Weighing

3.2.3.3 Root Green Weight Biomass Measurement

Excavation of the tree was done manually until all the roots were removed (Plate 3.4). The taproot was followed to its endpoint and its length measured by using a linear tape in meters to two decimal places and recorded in the data sheets. Soil embedded in the stump joints and on root surface was removed by use of a brush and water. The roots were measured at the mid point and classified into size classes as: $0 < D < 2$ cm (Class I), $2 \leq D < 10$ cm (Class II) and $D \geq 10$ cm (Class III) for ease of weighing. Roots green weights were taken by size classes and recorded. Samples of roots from each class were randomly selected, aliquots extracted and their green weight taken, recorded (Appendix 1d), tagged, put in gunny bags and stored ready for transportation to the Laboratory for oven drying.

All the assembled samples (aliquots) for aboveground and belowground components were weighed in the field; weight recorded, labeled, tagged and put in well labeled containers. They were then transported to the Laboratory for oven drying.

Plate 3.4: Root Processing by the Uprooting Crew

3.2.4 Laboratory Determination of Dry Weight

The assembled aliquots from the field were taken to the laboratory for dry weight determination. Large sized aliquots were broken into smaller sizes to fit into the oven while maintaining their labels from the field. The oven drier was set at 105^0C for the woody materials 70^0C for foliage. The aliquots were left in the oven drier (plate 3.5) and changes in dry weight monitored on a daily basis until they reached a constant weight. This was done in order to determine the biomass ratio (dividing oven dry weight over green weight). The aliquots after reaching the constant weight were removed from the oven and their dry weights taken and recorded.

Plate 3.5: Oven Drying of Tree Aliquots in the Laboratory

3.3 METHODS OF DATA ANALYSIS

Measured DBH for all *G. robusta* trees in the plot, total heights of the thirty three destructively sampled trees, root depths, above and belowground dry weights were entered in the computer spread sheets for subsequent use in data analysis. The green weight and oven dried aliquots were used to get the Dry: Green weight ratios which were multiplied by the green weight of the tree component to get its dry weight which is the component's biomass. The total aboveground biomass (AGB) of a tree was obtained by getting the sum of the biomass of the stem, branches and foliage. Similarly the total belowground biomass (BGB) was obtained by summing up dry weights of all root sections of that given tree. Finally the total tree biomass (TTB) was obtained by adding up AGB and BGB. Root shoot biomass ratios (RSs) were obtained by dividing the BGB by the AGB of every tree while root depth: tree height ratios (R/Hs) were obtained by dividing root depth by tree height.

3.3.1 Comparing Biomass across Agro Ecological Zones

The total tree biomass (TTB) of the thirty three destructively sampled trees were compared across AEZs. This was to determine if developed equations would apply in all the AEZs or different equations would be developed for each zone. RSs and R/H were compared across the AEZ and also among tree sizes to determine if partitioning for both above and belowground biomass varied with tree sizes. These ratios are also useful for indicating if there are similarities of growth characteristics of *G robusta* in different AEZs of the study area and also to gauge whether the developed equations would be different for every AEZ.

3.3.2 Development of Biomass Predicting Equations

Thirty three destructively sampled trees were used for developing biomass estimation allometric equation. Scatter plots were used to identify the relationship between biomass and its predictor variables of DBH and Height. Determination of correlation coefficient (r) was done to show if there is a linear relationship between the predictor and the predicted variables. This was also to determine the magnitude of the correlation. Graphs of different functions (power, linear, exponential, logarithmic or polynomial were fitted on the scatter plots like the example shown in Figure 3.3. The values of predictor variables (DBH, Height and DBH*Height) for the sampled tree were regressed to the dry weight (biomass) of the total tree, section (Aboveground, belowground) or component (Branches, Foliage) using least square simple regression analysis. This was followed by a multiple regression analysis using DBH and Height. The following functions were used for developing equations:

Table 3.6: Functions used for Developing Equations

$y = ae^{bx}$	*Equation 1 (exponential function)*
$y = a + bx$	*Equation 2 (linear function)*
$y = a + b\ln(x)$	*Equation 3 (logarithmic function)*
$y = a + bx^2 + bx$	*Equation 4 (polynomial function)*
$y = ax^b$	*Equation 5 (power function)*

where "y" is the dependent variable (Biomass)," x" is the independent variable," (DBH, HT) a" is the intercept of the dependent variable and "b" is the scaling exponent of the independent variable.

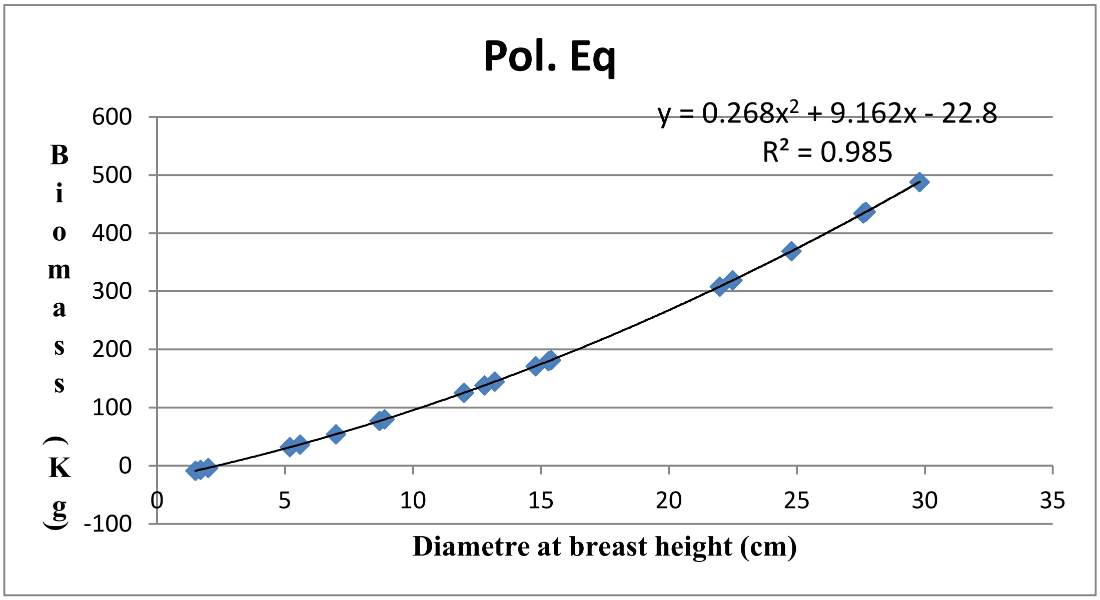

Figure 3.3: Relationship between Predictor (DBH) and Predicted Variables (Biomass)

The power function equations are commonly used in biomass estimation (Henry et al., 2011) although some studies have reported the use of polynomial equations (Brown et al., 1989). They have also reported power function relationships that relate tree biomass with structural parameters as diameter at breast height, Height or diameter at breast height in combination with Height (Brown, 1997; Chave et al., 2005). In choosing the best relationship, a small standard error of the estimate (SEE), small residual mean error (RME) and a high coefficient of determination (R^2) were preferred.

3.3.3 Validation of Developed Allometric Equations

To validate the developed equations, statistical F-testing was done for ABG, BGB and the TTB. The tree biomass generated by the developed equations was compared with biomass values generated using other existing equations of the destructively sampled trees (Henry et al., 2009; Rurangwe et al., 2018).

To validate the equations further, bias was used to show if the developed equations were within agreeable limits of less than 5% (Kinyanjui, 2011). The bias was calculated as: Bias% = [(predicted biomass – measured biomass)/measured biomass]* 100 according to Chave et al. (2005).

The TTB equation developed in this study was compared with an equation of Kuyah et al. (2012) developed in Western Kenya. Total biomass was generated using the Kuyah et al. (2012) equation for the eleven destructively sampled trees. The equation developed in this study was also used to generate biomass for same trees. The two sets of biomass values were subjected to a t-test to find if differences occur in their biomass estimates.

3.4 G*revillea Robusta* Stocks among Agro ecological Zones

The biomass values per tree were generated from DBH using the developed equation for every AEZ. Total tree biomass (Kg) for all trees in each AEZ was divided by the total number of trees in that zone giving mean biomass value per tree (Kg) in that zone. The average number of trees in the three hectare plots in every AEZ was computed by dividing the total number of trees by three to get the tree stocking (Stems/Ha). The biomass stocks were computed by multiplying the mean tree biomass (Kg) of the zone by the mean number of trees in that zone (stems/Ha). The product (Kg/ha) was divided by 1,000 to get biomass stocks in metric tons per hectare (tonha$^{-1)}$). Comparison for the variability of biomass across AEZs was done using one way analysis of variance (ANOVA).

CHAPTER FOUR

RESULTS AND DISCUSSIONS

INTRODUCTION

This chapter outlines the findings and discusses of the study which includes variations of; total tree biomass, root shoot biomass and root depth/tree height ratios, comparisons of these ratios, development and choice of the allometric equations, generation of biomass stocks in Maragua AEZs and analysis of variance for biomass across AEZs. The chapter presents results in tables, figures and narrative form. It also discusses the performance of the developed allometric equations and *G. robusta* biomass stocks among the AEZs in Maragua.

4.1 *G. ROBUSTA* BIOMASS ACROSS AEZS

4.1.1 General Findings

A total of 1,090 trees were measured for DBH in the 12 sample plots, and 33 trees destructively sampled. Nine trees were destructively sampled in each of the three AEZs (UM 2, UM 3 and UM 4) while six were sampled in AEZ UM 1. This was because one plot in UM 1 had no trees and the sampling procedure adopted did not allow replacement of plots (Magnussen & Reed, 2004). None of the sampled trees, had a DBH of more than 40cm, limiting the study to three diameter class categories (Table 4.1 and Appendix 2a, b, c and d)

Table 4.1: Number of *G. robusta* Sample Trees by DBH Class in Maragua

Class	Diameter (DBH) Range (cm)	No of trees
1	1.1 – 13.0	15
2	13.1 – 26.0	13
3	26.1 – 40	5
4	> 40	0

The DBH measurements for the sampled trees ranged from 1 cm to 39.5 cm with a mean of 11.4 cm and standard deviation of 0.27 while respective Height values ranged from 6.0 m to 24.8 m with a mean of 13.04 m and standard deviation of 0.15. Tap root depths ranged from 1.0 m to 3.6 m with a mean of 2.26 m and standard deviation of 0,002. The RSs ranged from 0.12 to 0.55 and R/Hs ranged from 0.06 to 0.4 and standard deviation of 0.003. The assessed biomass of the sampled trees, RSs and R/Hs are as shown in Appendix 3a and 3b.

4.1.2 Aboveground, Belowground and Total Tree (*G. robusta)* Biomass across AEZs.

The Biomass of sampled trees for each AEZ shown in appendix 4 is summarized in Table 4.2.

Table 4.2: Biomass Partitions and Total Tree Biomass of *G. robusta* in Maragua

Zone	Stem	Branches	Foliage	AGB	BGB	TTB
UM 1	550.25	129.84	81.05	761.14	166.81	927.95
UM 2	1,011.10	218.8	87.36	1,317.26	372.56	1,689.82
UM 3	1,201.53	332.89	145.24	1,679.66	535.29	2,214.95
UM 4	838.14	213.13	109.07	1,160.34	335.74	1,496.08
Total	3,601.02	894.66	422.77	4,918.40	1,410.4	6,328.80
Percentage to TTB	56.9	6.68	22.28	77.72	22,28	100

The total AGB for the 33 trees was 4,918.40kg (Table 4.2; Appendix 3a and 3b) with biomass proportion in the tree components equivalent to 56.9 percent stem, 14.14 percent branches, 6.68 percent foliage and 22.28 percent roots. This illustrates partitioning of 77.72 percent of the tree biomass to aboveground biomass section and 22.28 percent to belowground. Stem accounted for the largest proportion of AGB across all AEZs in Maragua, followed by branches and foliage respectively. Belowground biomass is a very important biomass component for many vegetation types and land-use systems (IPCC 2006).

One way Analysis of variance (ANOVA) gave no significant difference in TTB, AGB and BGB across AEZs, (Table 4.3) implying that these *G. robusta* trees have similar growth characteristics across all agro ecological conditions of the study area. This formed the basis of developing the equations to apply across the AEZ.

Table 4.3: Analysis of Variance for TTB, BGB and AGB of *G. robusta* in Maragua

Attribute	**F_{stat}.**	**p-value**	**F_{crit}.**
TTB	0.47	0.708	2.93
BGB	0.86	0.472	2.93
AGB	0.37	0.777	2.93

4.1.3. Variation of *G. robusta* Sample Trees Root Shoot Biomass Ratios (RSs) across AEZs in Maragua

The mean values for Root shoot biomass ratios (RSs) were 0.208, 0.289, 0.329 and 0.301 for the AEZ UM 1, UM 2, UM 3 and UM 4 respectively. RSs values for the thirty three trees ranged between 0.12 and 0.55 and aggregated between 0.2 and 0.35 with a mean of 0.29 and a median of 0.315. The median RS in this study is lower than 0.36 (Levy et al., 2004), slightly above 0.3 (IPCC 2006) but more than 0.28 (Kuyah et al., 2012). The mean of 0.29 obtained in this study is also in line with 0.28 reported by IPCC (2006). The results show that the mean RS was highest in zone UM 3 and lowest in zone UM 1. A one way ANOVA test showed that there was no significant difference in RSs across the AEZs (F_{stat}. = 2.38, Fcrit. = 2.93). The fact that there was no variation in RSs supports the above indication that there are similarities of growth characteristics of *G robusta* in different agro ecological conditions of the study area.

The mean root depth: tree height ratio (R/Hs) values for AEZs were 0.258, 0.188, 0.168, and 0.168 for the AEZs UM 1, UM 2, UM 3 and UM 4 respectively. The results show that the mean R/H was highest in zone UM 1, the wettest zone as compared to zone UM 3 and UM 4 which had the lowest mean. R/Hs ranged between 0.06 to 0.4 with a mean and a median of 0.19. The values mainly aggregated between 0.10 and 0.26. The variability of R/H however did not show a significant difference across AEZ (F_{stat}. = 2.16, Fcrit. = 2.93). This still supports the above indication that there are similarities of growth characteristics of *G. robusta* in different agro ecological conditions of the study area. It should be noted that *G. robusta* is one of the most extensively planted agroforestry trees in Kenya (Lott et al., 2009) with a wide adaptability of agro ecological zonation. The results further indicate its adaptability to wide conditions of growth where it does not show much variation in its above and belowground characteristics in the upper midland AEZ. This further emphasizes that the equations developed in this study can be used in all the AEZs of Maragua.

The results of RSs and R/Hs for the sampled trees classified in tree sizes are as prescribed in table 4.4. The RSs values for DBH range 1.1 – 13 cm ranged from 0.12 to 0.55 with a mean of 0.29, DBH range 13.1 – 26 cm from 0.18 to 0.46 with mean 0.27 while for DBH range 26.1 – 40 cm ranged from 0.26 to 0.34 with a mean of 0.31. The variability of RS ratios with tree sizes did not show a significant difference (F_{stat}. =0.27, p-value =1 F_{crit}. = 1.79).

Table 4.4: Categories of RSs and R/H in their respective *G. robusta* sizes in Maragua

Class 1. Diameter (DBH) Range 1.1 - 13cm		**Class 2. Diameter (DBH) Range 13.1 - 26cm**		**Class 3. Diameter (DBH) Range 26.1 – 40cm**	
RSs	RHs	RSs	RHs	RSs	RHs
0.22	0.24	0.24	0.14	0.34	0.1
0.21	0.31	0.26	0.13	0.34	0.13
0.32	0.19	0.21	0.19	0.31	0.10
0.55	0.17	0.32	0.06	0.26	0.14
0.41	0.09	0.35	0.14	0.30	0.08
0.30	0.21	0.46	0.11	-	-
0.30	0.35	0.20	0.12	-	-
0.28	0.27	0.19	0.25	-	-
0.45	0.27	0.30	0.20	-	-
0.20	0.23	0.33	0.16	-	-
0.26	0.23	0.18	0.18	-	-
0.31	0.19	0.18	0.26	-	-
0.19	0.40	-	-	-	-
0.12	0.24	-	-	-	-
0.20	0.21	-	-	-	-
0.37	0.26	-	-	-	-

The R/Hs values for DBH range 1.1 – 13 cm ranged from 0.09 to 0.35 with a mean of 0.24, DBH range 13.1 – 26 cm from 0.06 to 0.26 with mean 0.16 while for DBH range 26.1 – 40 cm, they ranged from 0.08 to 0.14 with a mean of 0.11. The variability of R/Hs with tree sizes showed a significant difference (F_{stat}. = 12.8, p-value = 1.5E -12, Fcrit. = 2.03). Further, pairwise test using F test for two sample analysis showed that the difference was due to variation between small sized trees; (1.1 – 13.0 cm DBH) and large sized trees (26.1 – 40 cm) {F_{stat}. = 8.8. P-value = 0.024, F_{crit}. = 5.86} (Appendix 8a).

The smaller sized trees in this study had a higher mean R/H (0.24), medium sized trees (0.16) and the large trees (0.11). This shows that R/H reduces with increasing DBH.

These findings show that root depth of *G. robusta* is approximately one quarter of the tree height tending to one fifth as the tree grows older and higher culminating to one tenth at the maturity where there is no further root depth and tree height growth. This finding may also explain why the linear function did not result in the best fit equation although it had high correlation coefficient (r).

4.2 ALLOMETRIC EQUATIONS FOR PREDICTING *G. ROBUSTA* BIOMASS (AGB, BGB, TTB) FROM DBH AND HEIGHT

The data for developing the equations for estimating TTB, AGB and BGB is presented in Appendix 3a.

4.2.1 Correlation Coefficient (r) Between Predictor Values and Biomass (TTB, AGB and BGB).

Determination of correlation coefficient (r) between the predictor values and biomass had values as indicated in table 4.5 below. Correlation coefficients showed very high positive relations between DBH and the component and/or total tree biomass (> +0.9) more than where height was used.

Table 4.5: Coefficient of correlation (r) values between predictor variables (DBH and HT) and biomass (TTB, AGB AND BGB) for 33 trees

Predictor variable	Tree/component biomass	R
DBH	AGB	0.93
	BGB	0.91
	TTB	0.96
HT	AGB	0.85
	BGB	0.80
	TTB	0.87

4.2.2 Allometric Equations to Estimate *G. robusta* Biomass (AGB, BGB, and TTB) Using DBH

Results of the five different functions fitted (Appendices 7a, b, c and d) to the 33 destructively sampled tree biomass data (Appendix 3a) are as shown in Tables 4.6 a, b and c. The equations and their values of the selection criteria are also shown. The best equation for estimating biomass based on R^2, SEE and MRE criterion from the independent variable is **bolded.**

Table 4.6a: Allometric equations for estimating *G. robusta* AGB using DBH

Function	equation	MRE	R^2	SEE
Exponential	$AGB=8.474e^{(0.150x}$	*(15.359)*	*0.810*	*4.673*
Power	$AGB=1.384x^{1.665591}$	*6.665*	*0.973*	*2.124*
Logarithmic	$AGB=122.31\ln(x) - 146.9$	*137.189*	*0.930*	*5.986*
Linear	$AGB=13.99x - 56.96$	*0.038*	*0.862*	*2.775*
Polynomial	$\mathbf{AGB= 0.248x^2+6.243x-15.45}$	***6.465***	***0.975***	***2.174***

Table 4.6b: Allometric equations for estimating *G. robusta* BGB using DBH

Function	Equation	MRE	R^2	SEE
Exponential	$BGB = 2.311e^{0.151x}$	*4.728*	*0.801*	*1.593*
Logarithmic	$BGB = 35.14\ln(x) - 42.18$	*40.093*	*0.929*	*1.862*
Polynomial	$\mathbf{BGB = 0.074x^2+1.688x -3.791}$	***0.054***	***0.980***	***0.778***
Linear	$BGB = 4.013x - 16.24$	*-28.5317*	*0.823*	*1.298*
Power	$BGB = 0.401x^{1.642}$	*3.526*	*0.968*	*0.785*

Table 4.6c: Allometric equations for estimating *G. robusta* TTB using DBH

Function	Equations	MRE	R^2	SEE
Exponential	$TTB = 10.91e^{0.150x}$	*(27.088)*	*0.808*	*6.689*
Power	$TTB = 1.811x^{1.658}$	*5.921*	*0.970*	*2.158*
Polynomial	$\mathbf{TTB = 0.322x^2 + 7.934x - 19.26}$	***0.046***	***0.985***	***2.138***
Logarithmic	$TTB = 157.5\ln(x) - 189.1$	*5.880*	*0.975*	*2.158*
Linear	$TTB= 18.00x - 73.22$	*0.078*	*0.912*	*2.328*

The selected equations for estimating biomass using DBH are given in table 4.6d;

Table 4.6d: Selected allometric equations for *G. robusta* Biomass estimation using DBH

Equation	MRE	R^2	SEE
$AGB=0.248x^2+6.243x-15.45$	6.465	0.975	2.174
$BGB = 0.074x^2+1.688x -3.791$	0.054	0.980	0.778
$TTB = TTB = 0.322x^2 + 7.934x - 19.26$	0.046	0.985	2.138

4.2.3 Allometric Equations for Estimating *G. robusta* Biomass (AGB, BGB, and TTB) Using Height

To estimate biomass from height, five different functions were fitted to heights and biomass values of the 22 destructively sampled trees (appendix 3a). The output equations are as shown in Tables 4.7 a, b and c. The selected equations were **bolded**.

Table 4.7a: Allometric equations for estimating *G. robusta* AGB using HT

Function	Equation	MRE	R^2	SEE
Exponential	$AGB = 2.394e^{0.267x}$	- 7.398	0.700	5.417
Polynomial	**$AGB= 0.271x^2 + 15.84x - 109.7$**	**0.051**	**0.955**	**3.093**
Power	$AGB= 0.025x^{3.214}$	11.443	0.875	3.250
Logarithmic	$AGB = 246.9ln(x) – 465.9$	126.775	0.855	5.928
Linear	$AGB = 23.16x - 152.9$	0.046	0.714	3.287

Table 4.7b: Allometric equations for estimate *G. robusta* BGB using HT

Function	Equation	MRE	R^2	SEE
Exponential	$BGB = 0.634e^{0. 296x}$	23.121	0.995	1.806
Polynomial	**$BGB = 0.67x^2 + 4.792x - 32.56$**	**0.103**	**0.982**	**1.115**
Power	$BGB = 0.006x^{3.239}$	10.001	0.860	1.202
Logarithmic	$BGB = 70.67ln(x) - 133.1$	29..072	0.854	1.797
Linear	$BGB= 6.605x - 43.26$	- 0.001	0.644	1.133

Table 4.7c: Allometric equations for estimating *G. robusta* TTB using HT

Function	Equation	MRE	R^2	SEE
Exponential	$TTB = 3.072e^{0.267x}$	89.051	0.991	7.127
Polynomial	**$TTB = 0.338x^2 + 20.64x - 142.3$**	**0.044**	**0.966**	**3.690**
Power	$TTB = 0.033x^{3.216}$	10.887	0.868	4.112
Logarithmic	$TTB = 317.6ln(x) – 599.1$	174.536	0.876	7.753
Linear	$TTB = 29.77x – 196.2$	0.019	0.753	3.905

The selected equations for estimating biomass using height are given in table 4.7d below;

Table 4.7d: Selected allometric equations for *G. robusta* biomass estimation using HT

Equation	MRE	R^2	SEE
$AGB = 0.271x^2 + 15.84x - 109.7$	*0.051*	*0.955*	*3.093*
$BGB = 0.67x^2 + 4.792x - 32.56$	*0.103*	*0.982*	*1.115*
$TTB = 0.338x^2 + 20.64x - 142.3$	*0.044*	*0.966*	*3.690*

4.2.4 Allometric Equation for Estimating *G. robusta* Branches Biomass (BR) Using DBH

The equations for estimating BR using DBH results are shown in Tables 4.8 bellow. The equation selected is **bolded.**

Table 4.8: Allometric equations for estimating BR using DBH

Function	Equation	MRE	R^2	SEE
Exponential	$BR = 1.287e^{0.156x}$	*7.648*	*0.817*	*6.443*
Logarithmic	$BR = 22.31\ln(x) - 26.9$	*36.654*	*0.57*	*7. 62*
Polynomial	$\mathbf{BR = 0.030x^2 + 1.574x - 4.984}$	***- 0.079***	***0.982***	***0.625***
Linear	$BR = 2.523x - 10.06$	*0.423*	*0.748*	*2.746*
Power	$BR = 0.195x^{1.733}$	*6.981*	*0.924*	*1.785*

4.2.5 Allometric Equation for Estimating *G. robusta* foliage Biomass (F_O) Using DBH

The equations estimating F_O using DBH results are shown in Tables 4.9 bellow. The selected equation is **bolded**.

Table 4.9: Allometric equations for estimating F_0 using DBH

Function	Equation	MRE	R^2	SEE
Exponential	$F_O = 2.925e^{0.079x}$	*30.8*	*0.518*	*8.003*
Logarithmic	$F_O = 6.716\ln(x) - 3.442$	*4.456*	*0. 559*	*21.2*
Polynomial	$\mathbf{F_O = -0.043x^2 + 1.949x - 3.134}$	***2.76***	***0.93***	***0.133***
Linear	$F_O = 0.586x + 4.169$	*6.765*	*0.41*	*3.967*
Power	$F_O = 0.812x^{1.010}$	*- 5.015*	*0.924*	*0.27*

4.2.6 Summary of Selected Biomass Equations using Predictor Variables

The tables bellow (4.10a, b and c) show the selected equations for AGB, BGB and TTB using the three predictor variables. The best equations are **bolded.**

Table 4.10a: Best selected allometric equations to estimate *G. robusta* AGB using predictor variable (HT and DBH)

Equation	MRE	R^2	SEE
$AGB = 0.271HT^2 + 15.8HT - 109.7$	*0.051*	*0.955*	*3.093*
$AGB = 0.248DBH^2 + 6.243\ DBH - 15.45$	*6.465*	*0.975*	*2.174*

Regression analysis for AGB revealed that DBH had a significant relationship with AGB ($F_{stat.}$ = 125.73 p - value = 0.022 $F_{crti.}$ = 4.46E-10). The polynomial function whose R^2 (0.975) value was highest, SEE (2.174) value lowest and MRE (6.465) value second lowest, was the best selected equation in estimating AGB (***AGB = 0.248DBH² + 6.243 DBH - 15.45***). A scatter graph diagram illustrating this correlation is shown in Figure 4.1.

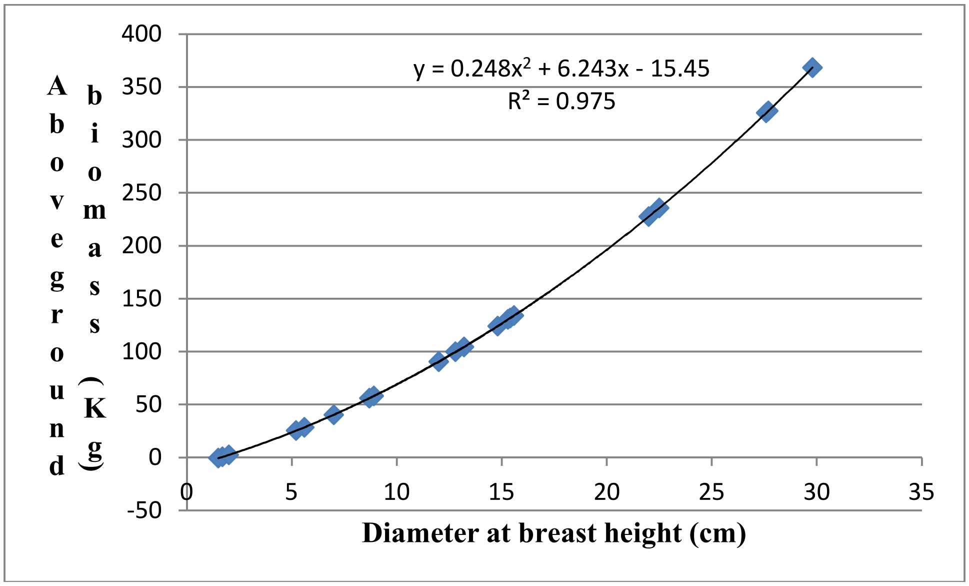

Figure 4.1: Relationship between DBH and AGB (Polynomial)

Table 4.10b: Best selected allometric equations to estimate *G. robusta* BGB using predictor variable (DBH and HT)

Equation	MRE	R^2	SEE
$BGB = 0.074DBH^2 + 1.688DBH - 3.791$	0.054	0.99	0.778
$BGB = 0.67HT^2 + 4.792\ HT - 32.56$	0.103	0.98	1.115

Regression analysis for BGB on DBH had a significant relationship ($f_{stat.}$ = 93.33, p - value = 0.038, $f_{crit.}$ = 5.64E-10). Polynomial equation whose R^2 (0.99) value was the highest, SEE (0.778) and MRE (0.058) values were the lowest, was the best in estimating belowground biomass (***BGB = 0.074DBH²*** + ***1.688DBH - 3.791***). A scatter graph diagram illustrating this correlation is shown in Figure 4.2.

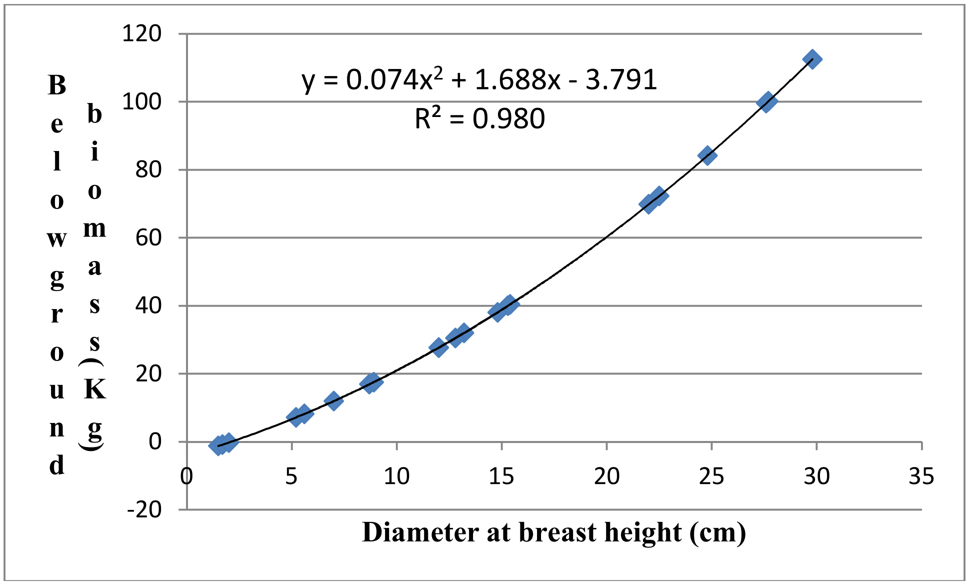

Figure 4.2: Relationship between DBH and BGB (Polynomial)

Table 4.10c: Best selected allometric equations to estimate TTB using variables (DBH, and HT)

Equation	MRE	R^2	SEE
$TTB = 0.322\ DBH^2 + 7.934DBH - 19.26$	0.046	0.99	2.138
$TTB = 0.338\ HT^2 + 20.64\ HT - 142.3$	0.044	0.966	3.690

Regression analysis for TTB on DBH had a strong and significant relationship ($F_{stat.}$ = 208.11, p - value = 0.04, $F_{crti.}$ = 4.93E-10). R^2 (0.99) value was the highest while SEE (2.138) and MRE (0.046) values were the lowest (Table 4.11c). This polynomial equation was the best in estimating total tree biomass (***TTB = 0.322 DBH***^{2} + ***7.934DBH - 19.26*****).** A scatter graph diagram illustrating this correlation is shown in Figure 4.3.

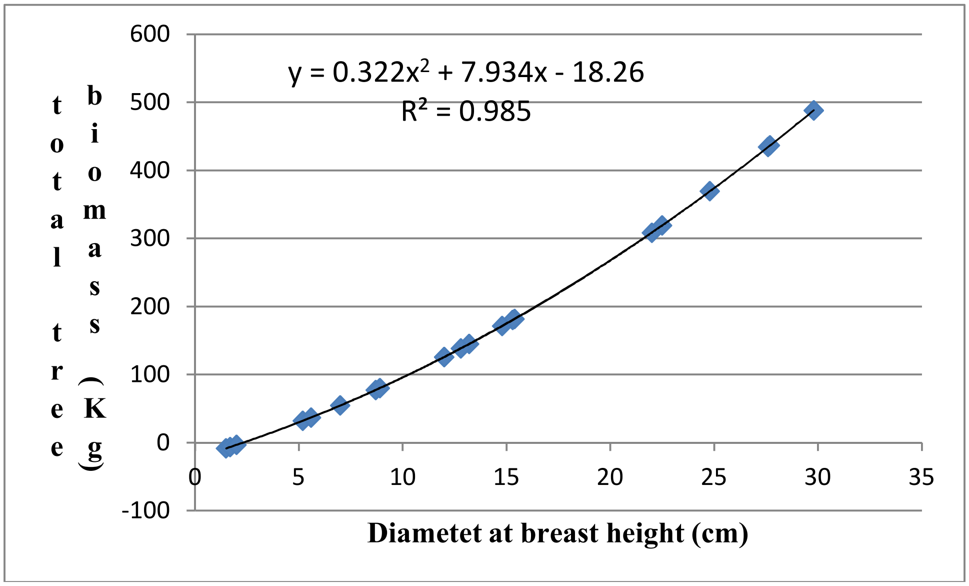

Figure 4.3: Relationship between DBH and TTB (Polynomial)

For estimates of branches (wood fuel) biomass, DBH had a strong relationship with branch biomass R^2 was *0.982* in the Polynomial function, 0.924 in the power function, 0.57 in the logarithmic function, 0.748 in linear function and 0.877 in exponential function (Table 4.9). The polynomial equations ***BR = 0.030DBH***^{2} + ***1.574DBH - 4.984*** which also had the lowest MRE (- 0.079) and lowest SEE (0.625) was the most preferred equation for estimating branches biomass.

Estimates for foliage biomass, DBH had a strong relationship with foliage biomass. R^2 was *0.93* in the Polynomial function, 0.924 in the power function, 0.559 in the logarithmic function, 0.41 in linear function and 0.518 in exponential function. The Polynomial equation **$F_0 = F_O = -0.043x^2 + 1.949x - 3.134$** had the lowest SEE (*0.133*) and lowest MRE (*2.76*) therefore selected as the best for estimating foliage biomass (Table 4.10).

The results of correlation coefficient (r) indicated that there were strong linear correlations between DBH and biomass (AGB, BGB and TTB). The linear equation was not the best fit equation because of the other set criterion used for selection. Regression analyses strengthened the linear relationship by having high coefficients of determination (R^2) for AGB (0.98), BGB (0.99) and TTB (0.99) and therefore confirming the overall model significance. In fitting the biomass estimation equation, Polynomial functions had better estimates than others. They were selected for estimating biomass for the tree portions and total tree biomass (AGB, BGB, BR, F_O and TTB).

The biomass DBH relationship is explained by a polynomial function more than any other function. Contrary to the findings, power function is the best (Chave et al., 2005; Kuya et al., 2012; and Kinyanjui et al., 2014). The study further found DBH was significantly correlated with the biomass of *G. robusta* trees, accounting for over 95 percent of the estimated biomass. The findings are supported by those reported by Sileshi (2014), Kuyah et al. (2015) and Zhao et al. (2010).

Chave et al. (2005) and Agevi et al. (2017) explain that an allometric equation can only be used within the diameter sizes within which it was developed. In this case the 40 cm DBH is the maximum size of trees that can be estimated by the developed equations in this study and any estimation of the biomass content in a tree above this diameter size should be cautioned. Lott et al. (2009) notes that *G. robusta* rarely grows beyond 40 cm DBH in Kenya and when these trees reach such sizes, they are normally cut for many uses including timber and furniture confirming why trees of more than 40 cm DBH were never encountered in the study area.

The use of DBH as the best estimator of biomass is of significance because DBH is the most commonly measured tree predictor variable and is possible to measure with great accuracy (Philip, 1994; Nelson et al., 1999; Chave et al., 2005; West, 2009; Sileshi, 2014).

It is noted that many forestry measurements have indicated the difficulty of accurately measuring tree heights (Chave et al., 2005; Bastien-Henri et al., 2010; Cole & Ewel, 2006; Henry et al., 2011; Baccini et al., 2012; Hunter et al., 2013; Kinyanjui et al., 2014; Agevi et al., 2017). The results of this study found that accuracy decreased when height was used and also lowered the accuracy of biomass estimates. These findings contrasted those observed by Basuki et al. 2009; Bastien-Henri et al. 2010; Henry et al. 2011 and Agevi et al. 2017 that use of height improves the accuracy of biomass estimation.

4.2.7 Validation and Performance of Developed Allometric Equations

Data for validation was obtained as explained in chapter 3 sections 3.2.3 to 3.2.5. Using the thirty three destructively sampled trees, F-test results for AGB indicated that there was no significance difference ($t_{stat.} = 0.54$, p - value = 0.30, $t_{crit.} = 2.23$) between the predicted biomass using developed equation and the Rurangwe et al. 2018) equation generated biomass (appendix 8b). Similarly, for BGB F-test results show that there was no significance difference ($t_{stat.} = -1.71$, p - value = 0.06, $t_{crit.} = 2.23$) between the predicted biomass and the Rurangwe et al. 2018) equation generated biomass values

(Appendix 8b). The same test applied for TTB, the t-test results revealed no significance difference ($t_{stat.}$ = -0.42, p-value = 0.34, $t_{crit.}$ = 2.23) between the predicted biomass and the Rurangwe *et al*. 2018) equation generated biomass values (Appendix 8b).

Validation of the equations based on the bias of the equation in estimating specific diameter sizes is illustrated in Residual plots shown in Figure 4.4.

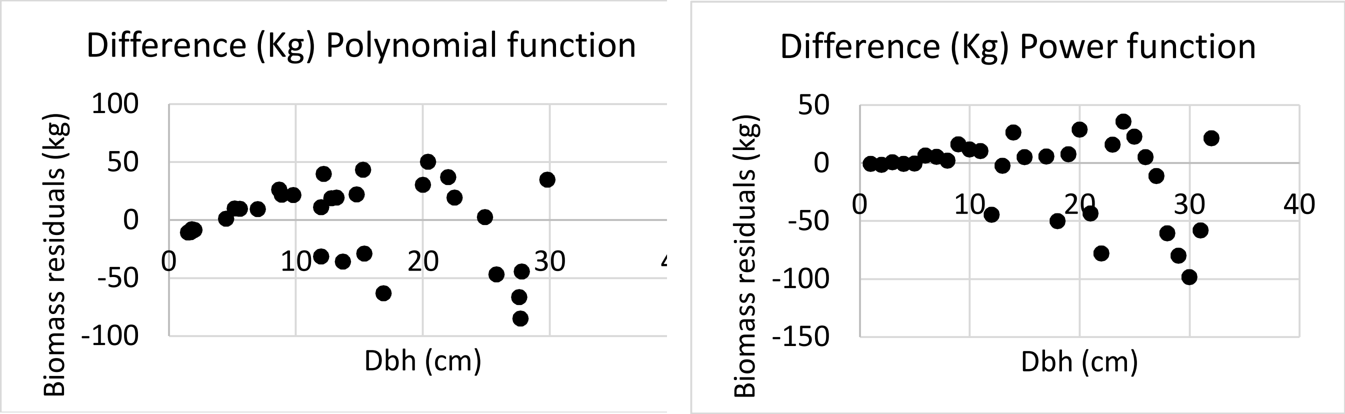

Figure 4.4: Residual scatter plots of total tree biomass using polynomial and power function for TTB

A third validation to compare biomass estimates from the preferred equation and that of similar studies shows that the developed equation compares well with other equations developed in agroforestry conditions of Kenya (Henry et al., 2009; Kuyah et al., 2012 and Rurangwe et al., 2018) but is not applicable in biomes far from the study area (Benedicto et al. 2017). This finding illustrates that the process of destructive sampling to develop new allometric equations within a small geographical range may not enhance accuracy of estimates and an equation applicable in a similar land and tree management activity may as well be applicable in another one. The results are illustrated in table 4.12 bellow.

Table 4.11: A Validation of the Equation with Similar Equations Using the F Values of the paired t-test

Author	F calculated	F critical	Comments	Discussion
Kuyah et al. 2012	1.5375557	1.8283	There is no significant difference	The Kuya equation was developed in similar Agroforestry conditions but in a different AEZs of Kenya.
Henry et al. 2009.	0.817302	1.8283	There is no significant difference	The equation was developed for Agroforestry trees of Western Kenya in a different AEZ.
Benedicto et al. 2017	2.070408	1.8408	There is a significant difference.	The equation was developed in Mexico. A totally different biome and may not be applicable in the study area.
Rurangwe et al. 2018	1.118687	1.8408	There is no significant difference	Rurangwa developed this equation in Agroforestry trees of Ruanda which is within East Africa.

The residual scatter graphs for the TTB equation (Figures 4.4 and 4.5) show similar trends of no difference between measured and predicted biomass. The TTB equation in estimating tree biomass gave a mean error of 3.6 percent (Table 4.12). The variation in estimation of biomass for small sized trees to up to DBH of 17cm gave a difference of only 3.8 Kg for a tree of 16.9 cm DBH. The bias increased for bigger trees where the biggest tree used in the validation data was 27.8 cm DBH which gave a percentage variation of 11.51percent (Table 4.13). The positive signs of mean residual error indicate that the equations underestimate the biomass by the respective percentages.

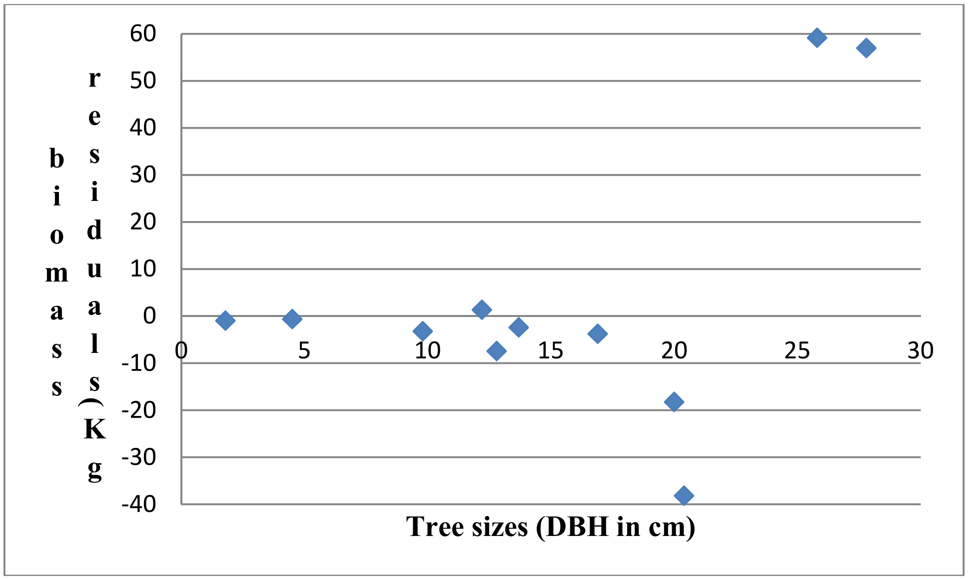

Figure 4.5: Relationship between DBH and Biomass Residuals Derived from Predicted and Actual TTB

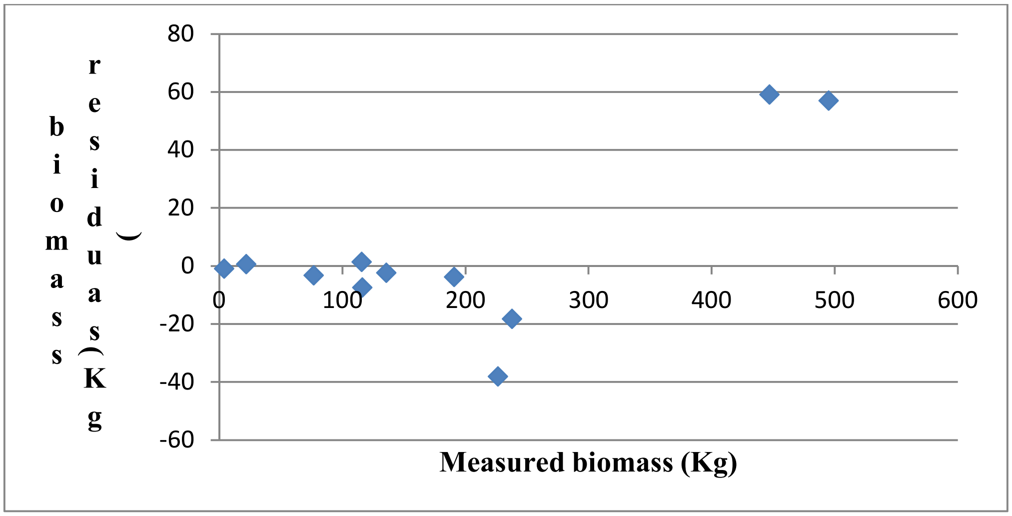

Figure 4.6: Relationship between Measured TTB and Biomass Residuals Derived from Predicted and Measured TTB

Table 4.12: Total Tree Biomass Equation Efficiency (Bias Percent)

DBH	Actual biomass (Kg)	Estimated biomass (Kg)	Residual	Percent efficiency of model estimation
1.8	4.1	5.069694	-0.96969	(23.650
13.7	135.89	138.3122	-2.42225	(1.78)
20	237.91	256.1655	-18.2555	7.67
16.9	190.9	194.7019	-3.80194	(1.99)
9.8	76.9	80.14014	-3.24014	(4.21)
25.8	446.95	387.8567	59.09327	13.22
12.2	115.81	114.5046	1.305383	1.13
12.8	116.35	123.8192	-7.46917	(6.42)
27.8	494.99	438.0178	56.97215	11.51
4.5	21.92	22.55413	-0.63413	(2.89)
20.4	226.41	264.5638	-38.1538	(16.85)
Mean				3.6

The TTB equation which gave an average mean residual error of 3.6 percent, the variation in estimation of biomass was still very low for small sized trees. The deviation is higher for bigger trees implying that the equation should be limited to small sized trees (DBH). However, underestimate and overestimate tendencies for different tree sizes resulted to a general decrease in the total mean residual error observed. This deviation may be attributed to management regimes like pollarding to reduce light competition with food crops and pruning of branches to provide fuel wood (Lott et al., 2009). Estimates of biomass derived from the equations developed showed no significant difference ($p > 0.05$) when compared with the observed biomass implying that the developed equations estimate biomass accurately.

4.2.8 Comparisons of the Developed Equation with an Existing Equation

Further to validation done above a detailed comparison done revealed that; TTB estimates derived from the equation of Kuyah (2012) **($TTB = 0.1237*DBH^{2.4583}$)** compared with those derived from the equation developed in this study (***TTB = 0.322DBH^2 + 7.934DBH - 19.26)*** for the destructively sampled trees showed no significant difference (t_{stat}. = 1.54, p - value = 0.34, t_{crit}. = 1.83 (appendix 8b) Figure 4.7 show graphically the trend of the compared equations.

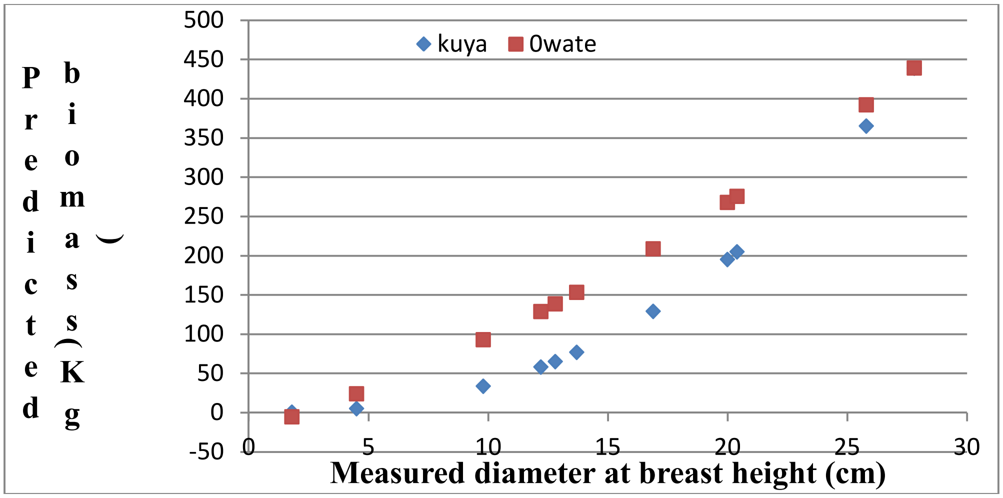

Figure 4.7: Comparing Kuyah and Owate equations predicted TTB

Similarly, AGB predicted from the developed equation AGB = **0.248DBH^2 + 6.243DBH - 15.45** and compared with that predicted using Kuyah et al., (2012) equation **AGB = 0.091*DBH$^{2.472}$** showed no significat difference t_{stat} = -1.59, t_{crit} = 2.22 and figure 4.8 shows the trends of the equations graphically.

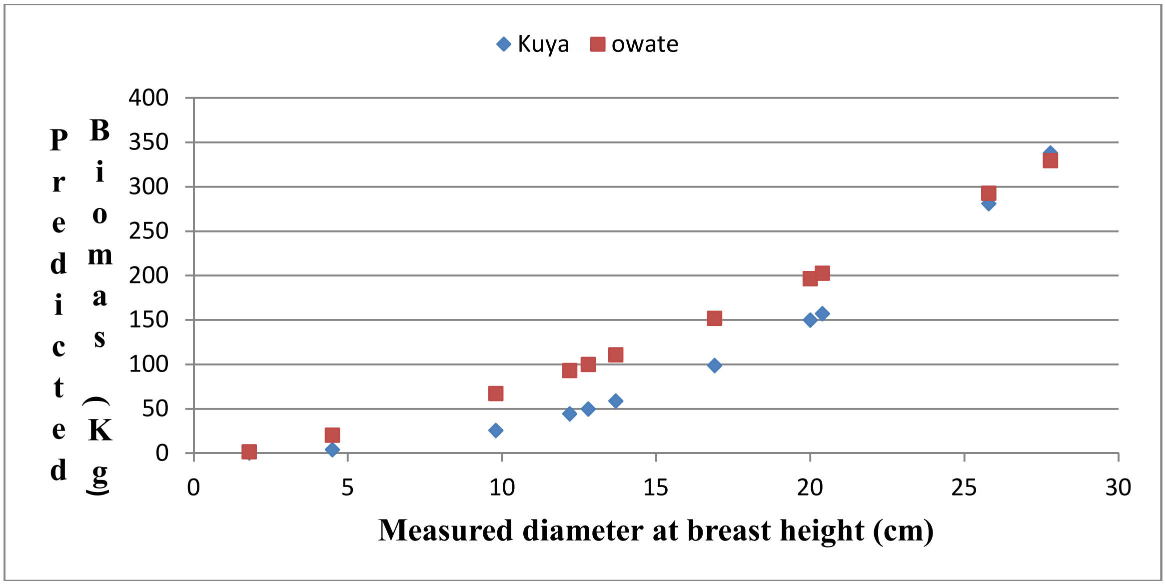

Figure 4.8: Comparing AGB predicted using Kuyah equation and those predicted using Owate equation

Finaly, BGB predicted by the developed equation (**BGB = 0.074DBH + 1.688DBH - 3.791)** and compared with that predicted using Kuyah (2012) equation **BGB = 0.049*DBH$^{\mathbf{0.923}}$**. showed no significant difference t_{stat} = 0.51, t_{crit} = 2.22 Figure 4.9 shows the trends of the equations graphically.

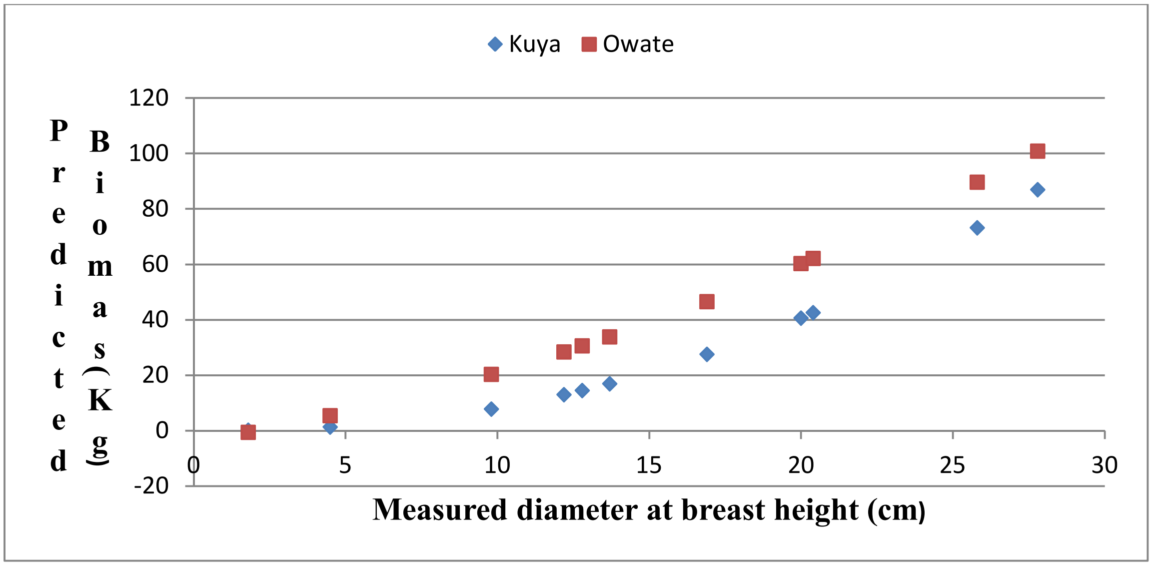

Figure 4.9: Comparing BGB predicted using Kuyah equation and those predicted using Owate equation

4.2.9 Performance of Allometric Equations Developed

Equations selected for estimating total tree biomass and various components of biomass; $TTB = 0.322DBH^2 + 7.934DBH - 19.26$, $AGB = 0.248DBH^2 + 6.243DBH - 15.45$, $BGB = 0.074DBH^2 + 1.688DBH - 3.791$, $BR = 0.030DBH^2 + 1.574DBH - 4.984$ and $F_O = 0.043DBH^2 + 1.949DBH - 3.134$ provided satisfactory estimates of biomass. The variations explained by the equations were estimated by the coefficient of determination (99 percent, 98 percent, 99 percent, 98 percent and 92 percent respectively). The equations compare well as their MRE of 0.046, 0.465, 0.058, 0.079 and minus 5 are within the recommended range of less than 5 percent, (Kinyanjui, 2011) whereby in economic terms, it is explained that an accuracy of 95% is acceptable for any tree manager and implies a slight underestimation or over estimation of the forest product as noted by Kinyanjui (2011).

4.3 BIOMASS AMONG AGROECOLOGICAL ZONES

The average biomass values per tree generated using developed total tree biomass equation (Appendix 5) (***$TTB = 0.322DBH^2 + 7.934DBH - 19.26$***) were 126.04 Kg, 140.49 kg, 113.80 Kg and 141.38 Kg in AEZs UM 1, UM 2, UM 3 and UM 4 respectively. The biomass stocks calculated from these trees translated to a *G. robusta* biomass average stock of 14.12 $tonha^{-1}$, 14.33 $tonha^{-1}$, 11.15 $tonha^{-1}$ and 12.16 $tonha^{-1}$ in the respective AEZs (Table 4.13). Variability of derived TTB across the four AEZs showed no significant difference (f_{stat}. = 2.21, p - value = 0.09, f_{crit}, = 2.61) (Appendix 8a). The average biomass across the AEZs is 12.95 $tonha^{-1}$

Table 4.13: Mean Biomass per hectare across AEZs

AEZ	Stocking (stems/hectare)	Mean biomass/stem (Kg)	Total mean biomass/hectare ($Kgha^{-1}$)	Total mean biomass/hectare ($tonsha^{-1}$)
UM1	112	126.04	14,116.48	14.12
UM2	102	140.49	14329.98	14.33
UM3	98	113.80	11,152.40	11.15
UM4	86	141.38	12,158.68	12.16
			Mean	12.94

Variability of generated biomass from developed TTB equation showed no significant difference ($p > 0.05$) among the four AEZs of the study area. This implies that *G. robusta* biomass contribution in all the zones does not vary and further supports the earlier findings that the developed equations can apply across all the AEZs. The landscape biomass for the four AEZs biomass stocks range from 11 – 14 $tonha^{-1}$. This gives an average biomass stock of 12.94 $tonha^{-1}$ across the study area implying that this is the mean amount of biomass stock contributed by *G robusta* in farming landscapes of Maragua. The range 11 – 14 $tonha^{-1}$ is supported by the findings of Albrecht and Kandji

(2005) 2-22 tonha^{-1}, Henry‘s (2009) 9 – 11 tonha^{-1} but lower than those reported by Kuyah (2012) of 16 tonha^{-1} all of which are for diverse species.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

This chapter highlights the conclusions and recommendations drawn based on the findings of this study including suggestions for further research.

5.1. CONCLUSIONS

The findings of this study concluded that there were no variations in total tree biomass and root shoot biomass ratios across agro ecological zones of Maragua indicating *G. robusta* trees have similar growth characteristics in the upper midland agro ecological zones. Thus, the developed allometric equations can be applied across the AEZs of the study area. The results further indicated that the species does not show much variation in its above and belowground biomass between the AEZs.

Among the two easily measurable independent variables (diameter at breast height and height), DBH had the highest correlation with the tree biomass and proved to be the most appropriate in estimating the tree's components' biomass. The allometric equations developed in this study provide a means for estimating *G. robusta* portions biomass (TTB, AGB BGB, BR and F). The equation for BGB allows biomass estimation of the roots. The respective, presented equations can adequately predict TTB, AGB BGB, BR and F from diameter at breast height. In particular, the selected equations ($TTB = 0.322DBH^2 + 7.934DBH - 19.26$ $(R^2 = 0.99)$, $AGB = 0.248DBH^2 + 6.243DBH - 15.45$ $(R^2 = 0.98)$, $BGB = 0.074DBH^2 + 1.688DBH - 3.791$ $(R^2 = 0.99)$, $BR = 0.030DBH^2 +$

$1.574DBH - 4.984$ $(R^2 = 0.98)$ ***and*** $F = 0.043DBH^2 + 1.1349DBH - 3.984$ $(R^2 = 0.92)$ can adequately estimate the trees' TTB, AGB BGB, BR and F respectively. The equations presented can be used by farmers in Maragua to quantify their tree component's biomass in order to get full value of the trees in the farming landscapes. The average biomass stocks contributed by the *G. robusta* trees in the study area is 12.94 ton/ha.

The biomass quantities contributed by *G. robusta* trees did not vary among the four upper midland agro ecological zones. Hence the conclusion that biomass of *G. robusta* trees does not vary a cross agro ecological zones in the farming landscapes of Maragua Sub County, further supporting the earlier findings that the developed equations can apply across all the AEZs of the study area.

5.2. RECOMMENDATIONS

Based on the findings of this study:

1. It is expensive and destructive to sample trees for biomass assessment. The data of this study may therefore be lumped up with other such data to develop equations that cover a larger geographical area and DBH size class.

2. There are other agroforestry tree species on farms that lack allometric equations. Such trees are poorly valued during marketing and for carbon market as well. Future efforts should be invested in other species including other vegetation as Bamboo, lianas and fruit trees which underlines the importance of including all components of biomass in carbon accounting.

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APPENDICES

Appendix 1a stem data collection sheets

AEZ	Plot No.	Tree No.	DBH (cm)	Length (m)	Green weight of logs		
					Log No.	Green weight (kg)	Aliquot green weight (gm)

Appendix 1b branches data collection sheets

AEZ	Plot No.	Tree No.	Diameter class	Total green weight (Kg)	Aliquot green weight (Kg)

Appendix 1c foliage data collection sheets

AEZ	Plot No.	Tree No.	Total Green weight (Kg	Aliquot Green weight (Kg)

Appendix 1d roots data collection sheets

AEZ	Plot No.	Tree No.	Diameter class	Green weight (Kg)		Root depth (M)

APPENDIX 2a: Field measured sample trees stem data with their dry weight

AEZ	Plot No.	Tree No.	DBH (cm)	Length (m)	Green weight of logs			Dry weight of logs	
					Log No.	Green weight (kg)	Aliquot green weight (gm)	Aliquot dry weight (gm)	Log's dry weight (Kg)
UM4	3	1	5.2	6.6	1	16	0.9	0.442	7.86
					2	5	0.2	0.092	2.3
		2	1.5	3.6	1	3	0.22	0.114	1.55
		7V	1.8	6	1	3	0.2	0.11	1.65
	2	3	12	14.3	1	86.5	0.3	0.144	41.52
					2	58	0.3	0.133	25.71
					3	33	0.2	0.097	16.01
					4	16.5	0.2	0.1	8.25
					5	5.5	0.2	0.08	2.2
		4	13.2	12.7	1	56.5	0.5	0.234	26.442
					2	35.5	0.3	0.157	18.58
					3	25.5	0.38	0.188	12.52
					4	17.5	0.2	0.098	8.58
					5	8	0.2	0.1	4
		8V	13.7	14.5	1	91.5	0.28	0.135	44.12
					2	59	0.28	0.136	28.66
					3	44	0.3	0.152	22.29
					4	25	0.58	0.298	12.84
					5	8.5	0.14	0.071	4.31
	1	5	22.5	16.7	1	120	0.24	0.1	50
					2	89.5	0.22	0.1	40.68
					3	97.5	0.2	0.09	43.88
					4	69	0.2	0.08	27.6
					5	10.5	0.14	0.06	4.2
		6	29.8	14.5	1	138	0.38	0.17	61.74
					2	172.5	0.27	0.12	76.7
					3	87.5	0.28	0.13	40.63
					4	106.5	0.3	0.14	49.7
					5	37.5	0.16	0.08	18.75
		9V	20	16.1	1	98.5	0.32	0.15	46.17
					2	82	0.29	0.13	36.76
					3	50.5	0.3	0.14	23.57
					4	29.5	0.52	0.24	13.62
					5	29.5	0.2	0.1	14.75
AEZ	Pl	Tr	DB	Le	Green weight of logs			Dry weight of	

								logs	
					Log No.	Green weight (kg)	Aliquot green weight (gm)	Aliquot dry weight (gm)	Log’s dry weight (Kg)
UM3	1	10	12	12.75	1	60.5	0.22	0.1	27.5
					2	41	0.14	0.06	17.57
					3	22.5	0.46	0.18	8.8
					4	9	0.14	0.08	5.14
		11	15.4	13.7	1	106	0.2	0.09	47.7
					2	70	0.2	0.1	35
					3	42.5	0.2	0.09	19.13
					4	13	0.3	0.14	6.07
					5	3	0.16	0.08	1.5
		16V	16.9	12.2	1	91.5	0.32	0.16	45.75
					2	61.5	0.36	0.18	30.75
					3	45.5	0.22	0.09	18.61
					4	40	0.24	0.13	21.67
					5	2.5	0.1	0.05	1.25
	2	14	27.6	19	1	256.9	0.24	0.11	117.75
					2	170	0.24	0.1	70.85
					3	117	0.18	0,08	52
					4	55.5	0.34	0.16	26.12
					5	8.5	0.2	0.09	3.83
		15	27.7	19.2	1	263.9	0.21	0.1	125.67
					2	185.5	0.24	0.11	85.02
					3	132.5	0.2	0.09	59.63
					4	66.5	0.24	0.11	30.48
					5	11.5	0.22	0.11	5.75
		18V	25.8	16.6	1	237.8	0.24	0.11	108.99
					2	165.5	0.26	0.12	76.38
					3	126.5	0.16	0.08	63.25
					4	52	0.14	0.06	22.29
					5	8.5	0.1	0.05	4.25
	3	12	7	8.65	1	25	0.28	0.14	12.5
					2	13.5	0.1	0.04	2.48
					3	5.5	0.2	0.09	2.48
		13	5.6	8.65	1	15.5	0.2	0.09	6.98
					2	9	0.14	0.07	4.5
					3	3	0.1	0.04	1.2
		17V	9.8	9,1	1	37	0.3	0.16	19.73
					2	19.5	0.14	0.07	9.75
					3	7.5	0.14	0.06	3.21

AEZ	Plot No.	Tree No.	DBH (cm)	Length (m)	Green weight of logs			Dry weight of logs	
					Log No.	Green weight (kg)	Aliquot green weight (gm)	Aliquot dry weight (gm)	Log's dry weight (Kg)
UM2	1	19	1.7	7.1	1	5	0.1	0.03	1.5
					2	1.5	0.1	0.03	0.45
		20	8.7	9.8	1	30.5	0.24	0.11	13.98
					2	16.5	0.16	0.08	8.25
					3	5.5	0.1	0.05	2.75
		23V	12.2	12.4	1	26.5	0.18	0.08	11.78
					2	30	0.12	0.06	15
					3	18	0.2	0.09	8.1
					4	8.5	0.12	0.06	4.25
					5	3	0.12	0.06	1.5
	2	21	15.3	14.3	1	52.5	0.24	0.1	21.88
					2	36	0.18	0.08	16
					3	23.5	0.16	0.07	10.28
					4	15.5	0.16	0.08	7.75
					5	7	0.12	0.05	2.92
		22	14.8	15	1	67.5	0.24	0.1	28.13
					2	46	0.24	0.1	19.17
					3	31	0.19	0.08	13.05
					4	14.5	0.18	0.08	6.44
					5	6.5	0.16	0.07	2.84
		24V	12.8	15.4	1	64.5	0.24	0.11	29.56
					2	42	0.14	0.05	15
					3	26	0.2	0.08	10.4
					4	14.5	0.18	0.07	5.69
					5	5.5	0.24	0.1	2.29
	3	25	22	17	1	167.9	0.36	0.14	65.29
					2	112	0.27	0.1	41.48
					3	81	0.32	0.13	32.91
					4	46	0.32	0.13	18.69
					5	15.5	0.22	0.09	6.34
		26	29.8	21.2	1	283.8	0.3	0.11	104.06
					2	206.2	0.16	0.05	64.44
					3	159	0.2	0.08	63.6
					4	57.2	0.2	0.08	22.88
					5	13.5	0.14	0.05	4.82
		27V	27.8	24.8	1	331.4	0.24	0.1	138.08
					2	121.8	0.22	0.1	55.36

					3	191.8	0.2	0.08	76.72
					4	74.5	0.14	0.08	42.57
					5	29.8	0.12	0.06	14.9
UM1	1	28	2	6	1	7.5	0.07	0.03	3.21
		29	8.9	9.9	1	34.5	0.35	0.13	12.81
					2	22	0.26	0.11	9.31
					3	12.5	0.17	0.07	5.15
					4	4	0.1	0.04	1.6
		30V	4.5	9.1	1	11	0.28	0.14	5.5
					2	7	0.24	0.11	3.21
					3	6.5	0.12	0.06	3.25
	2	31	12.8	13	1	95.5	0.16	0.07	41.78
					2	60.5	0.23	0.1	26.3
					3	50.5	0.28	0.12	21.64
					4	32.5	0.18	0.08	14.44
					5	22.5	0.15	0.07	10.5
		32	24.9	19	1	237	0.3	0.11	86.9
					2	174.4	0.27	0.1	64.6
					3	111	0.3	0.11	40.7
					4	108	0.27	0.11	44
					5	68.5	0.18	0.07	26.64
		33V	21.4	11.5	1	161.4	0.28	0.12	69.17
					2	130.2	0.2	0.08	52.08

APPENDIX 2b: Field measured sample trees branches data with their dry weight

AEZ	Plot No.	Tree No.	Diameter class	Total green weight (Kg)	Aliquot green weight (Kg)	Aliquot dry weight (Kg)	Total dry weight of branches (Kg)
UM4	3	1	0 < D < 2cm (class 1)	5	0.04	0.013	1.63
		2	0 < D < 2cm (class 1)	1.84	0.06	0.021	0.64
		7V	0 < D < 2cm (class 1)	1	0.06	0.02	0.33
	2	3	0 < D < 2cm (class 1)	24.5	0.06	0.026	10.62
		4	0 < D < 2cm (class 1)	22.5	0.06	0.029	10.88
			2 < D < 5cm (class II)	1.5	0.5	0.066	0.2
		8V	0 < D < 2cm (class 1)	44	0.1	0.056	24.64
			2 < D < 5cm	4.5	0.16	0.07	1.97

			(class II)				
	1	5	0 < D < 2cm (class 1)	57	0.1	0.04	22.8
			2 < D < 5cm (class II)	57.5	0.23	0.11	27.5
		6	0 < D < 2cm (class 1)	89	0.12	0.07	51.92
			2 < D < 5cm (class II)	57	0.2	0.1	28.5
		9V	0 < D < 2cm (class 1)	73.5	0.14	0.06	31.5
UM3	1	10	0 < D < 2cm (class 1)	27.5	0.08	0.02	6.88
		11	0 < D < 2cm (class 1)	49.5	0.1	0.05	24.75
		16V	0 < D < 2cm (class 1)	113.5	0.08	0.02	28.38
			2 < D < 5cm (class II)	28	0.22	0.12	15.27
	2	14	0 < D < 2cm (class 1)	145.5	0.1	0.05	72.75
			2 < D < 5cm (class II)	13	0.1	0.05	6.5
			5 < D < 10cm (class III)	30.5	0.2	0.09	13.73
		15	0 < D < 2cm (class 1)	118.5	0.1	0.04	47.4
			2 < D < 5cm (class II)	21.5	0.12	0.06	10.75
			5 < D < 10cm (class III)	50.2	0.2	0.1	25.1
		18V	0 < D < 2cm (class 1)	92	0.08	0.03	34.5
			2 < D < 5cm (class II)	63	0.13	0.06	29.08
	3	12	0 < D < 2cm (class 1)	12.5	0.1	0.04	5
		13	0 < D < 2cm (class 1)	7	0.1	0.04	2.8
		17V	0 < D < 2cm (class 1)	20	0.08	0.04	10
UM2	1	19	0 < D < 2cm (class 1)	1.5	0.05	0.02	0.6
		20	0 < D < 2cm (class 1)	15	0.14	0.06	6.43
		23V	0 < D < 2cm	32.5	0.07	0.03	13.93

			(class 1)				
	2	21	0 < D < 2cm (class 1)	77	0.16	0.08	38.5
		22	0 < D < 2cm (class 1)	78.5	0.12	0.05	32.71
		24V	0 < D < 2cm (class 1)	41.5	0.13	0.06	19.5
	3	25	0 < D < 2cm (class 1)	69.5	0.12	0.04	23.17
			2 < D < 5cm (class II)	16	0.14	0.06	6.86
		26	0 < D < 2cm (class 1)	54	0.1	0.04	21.6
			2 < D < 5cm (class II)	29	0.1	0.04	11.6
		27V	0 < D < 2cm (class 1)	82.5	0.06	0.02	27.5
			2 < D < 5cm (class II)	41	0.1	0.04	16.4
UM1	1	28	0 < D < 2cm (class 1)	2.5	0.08	0.03	0.94
		29	0 < D < 2cm (class 1)	20.5	0.12	0.06	10.25
		30V	0 < D < 2cm (class 1)	5	0.04	0.02	2.5
	2	31	0 < D < 2cm (class 1)	74	0.08	0.03	27.75
			2 < D < 5cm (class II)	7.5	0.08	0.04	3.75
		32	0 < D < 2cm (class 1)	34	0.08	0.04	17
			2 < D < 5cm (class II)	41.5	0.24	0.12	20.75
		33V	0 < D < 2cm (class 1)	56	0.08	0.03	21
			2 < D < 5cm (class II)	61.5	0.19	0.08	25.9

APPENDIX 2c: Field sample trees measured foliage data and their dry weight

AEZ	Plot No.	Tree No.	Total Green weight (Kg	Aliquot Green weight (Kg)	Aliquot Dry weight (Kg)	Total dry weight of foliage (Kg)
UM4	3	1	9.84	0.5	0.265	5.22
		2	1.84	0.5	0.277	1.02
		7V	1.34	0.5	0.247	0.662
	2	3	24.5	0.5	0.247	12.1
		4	33	0.5	0.265	17.49
		8V	26.5	0.4	0.221	14.64
	1	5	50	0.48	0.22	22.92
		6	39	0.44	0.24	21.27
		9V	27.5	0.44	0.22	13.75
UM3	1	10	21.5	0.36	0.22	13.14
		11	38	0.46	0.25	20.65
		16	31	0.36	0.26	22.39
	2	12	12.5	0.4	0.24	7.5
		13	7.5	0.4	0.22	4.13
		17V	17	0.4	0.24	10.2
	3	14	34.5	0.48	0.25	17.97
		15	28	0.42	0.24	16
		18V	43.5	0.34	0.26	33.26
UM2	1	19	3	0.58	0.28	1.45
		20	15	0.36	0.21	8.75
		23V	26	0.52	0.27	13.5
	2	21	33.5	0.54	0.25	15.51
		22	24	0.39	0.17	10.46
		24V	14	0.32	0.16	7
	3	25	25.5	0.46	0.2	11.09
		26	23	0.38	0.18	10.89
		27V	20.5	0.4	0.17	8.71
UM1	1	28	2.5	0.4	0.19	1.19
		29	19.5	0.37	0.19	10.01
		30V	7.5	0.33	0.17	3.86
	2	31	56.5	0.38	0.21	31.22
		32	41.5	0.38	0.17	18.57
		33V	36	0.4	0.18	16.2

APPENDIX 2d: Field measured sample trees roots data

AEZ	Plot No.	Tree No.	Diameter class	Green weight (Kg)		Dry weight (Kg)		Root depth (M)
UM4				Whole	Aliquot	Aliquot)	Whole	
	3	1	0 < D < 2cm	2	0.09	0.034	0.756	1.55
			2 < D < 10cm	6.4	0.38	0.182	3.07	
		2	0 < D < 2cm	0.38	0.02	0.019	0.361	1.1
			2 < D < 10cm	0.82	0.12	0.064	0.44	
		7V	0 < D < 2cm	0.32	0.04	0.016	0.128	1
	2	3	0 < D < 2cm	14	0.06	0.024	5.6	2.7
			2 < D < 10cm	13.5	0.14	0.076	7.33	
			D = or > 10cm	49	0.18	0.09	24.5	
		4	0 < D < 2cm	4.5	0.1	0.05	2.25	1.8
			2 < D < 10cm	5.5	0.15	0.078	2.86	
			D = or > 10cm	33.5	0.22	0.114	17.36	
		8V	0 < D < 2cm	5.5	0.2	0.062	1.71	2.7
			2 < D < 10cm	8.5	0.14	0.075	4.55	
			D = or > 10cm	45.5	0.14	0.077	25.03	
	1	5	0 < D < 2cm	15	0.1	0.04	6	2.2
			2 < D < 10cm	11	0.14	0.06	4.71	
			D = or > 10cm	100.5	0.23	0.12	52.43	
		6	0 < D < 2cm	22	0.1	0.04	8.8	1.4
			2 < D < 10cm	30	0.12	0.06	15	
			D = or > 10cm	191.5	0.28	0.14	95.75	
		9V	0 < D < 2cm	10	0.14	0.06	4.29	1
			2 < D < 10cm	13.5	0.16	0.08	6.75	
			D = or > 10cm	93.5	0.2	0.1	46.75	
UM3	1	10	0 < D < 2cm	18.5	0.05	0.02	7.4	1.2
			2 < D < 10cm	11	0.22	0.1	5	
			D = or > 10cm	40	0.24	0.12	20	
		11	0 < D < 2cm	29.5	0.06	0.02	9.83	1.9
			2 < D < 10cm	14.5	0.07	0,03	6.21	
			D = or > 10cm	71	0.34	0.18	37.59	
		16V	0 < D < 2cm	25.5	0.05	0.02	10.2	1.4
			2 < D < 10cm	18	0.1	0.05	9	
			D = or > 10cm	121.5	0.2	0.11	66.83	
	2	12	0 < D < 2cm	8.5	0.1	0.05	4.25	1.85
			2 < D < 10cm	3.5	0.2	0.09	1.58	
			D = or > 10cm	8	0.18	0.09	4	
		13	0 < D < 2cm	4.5	0.18	0.08	2	3.05
			2 < D < 10cm	3	0.18	0.09	1.5	
			D = or > 10cm	5.5	0.18	0.08	2.44	
		17V	0 < D < 2cm	12	0.14	0.07	6	2.45
			2 < D < 10cm	4	0.1	0.06	2.4	

			D = or > 10cm	17	0.18	0.07	6.61	
	3	14	0 < D < 2cm	18.5	0.1	0.03	5.55	2.4
			2 < D < 10cm	44.5	0.14	0.06	19.07	
			D = or > 10cm	211.5	0.16	0.08	105.75	
		15	0 < D < 2cm	18.5	0.08	0.03	6.94	2
			2 < D < 10cm	31	0.16	0.08	15.5	
			D = or > 10cm	218	0.25	0.12	104.64	
		18V	0 < D < 2cm	11.5	0.1	0.05	5.75	2
			2 < D < 10cm	24	0.28	0.14	12	
			D = or > 10cm	143	0.2	0.08	57.2	
UM2	1	19	0 < D < 2cm	1	0.06	0.02	0.33	1.9
			2 < D < 10cm	2.5	0.12	0.07	1.46	
		20	0 < D < 2cm	8.5	0.11	0.05	3.86	2.3
			D = or > 10cm	12	0.09	0.03	4	
		23V	0 < D < 2cm	9.5	0.1	0.04	3.8	2.8
			2 < D < 10cm	9.5	0.08	0.04	4.75	
			D = or > 10cm	23	0.2	0.08	9.2	
	2	21	0 < D < 2cm	7	0.06	0.02	2.33	3.6
			2 < D < 10cm	21	0.08	0.03	7.88	
			D = or > 10cm	45	0.36	0.09	11.25	
		22	0 < D < 2cm	18.5	0.06	0.02	6.17	3
			2 < D < 10cm	16	0.16	0.07	7	
			D = or > 10cm	53	O.28	0.11	20.82	
		24V	0 < D < 2cm	4.5	0.06	0.03	2.25	2.9
			2 < D < 10cm	12.5	0.24	0.11	5.73	
			D = or > 10cm	44.5	0.3	0.13	19.28	
	3	25	0 < D < 2cm	15.5	0.06	0.02	5.17	2.8
			2 < D < 10cm	45	0.24	0.09	16.88	
			D = or > 10cm	123.5	0.16	0.06	46.31	
		26	0 < D < 2cm	16	0.06	0,02	5.33	3
			2 < D < 10cm	23.4	0.1	0.04	9.36	
			D = or > 10cm	172.4	0.24	0.09	64.65	
		27V	0 < D < 2cm	19.5	0.1	0.04	7.8	2
			2 < D < 10cm	58.5	0.16	0.06	21.94	
			D = or > 10cm	194.3	0.16	0.07	85.01	
UM1	1	28	0 < D < 2cm	0.5	0.04	0.01	0.13	2.4
			2 < D < 10cm	3	0.07	0.02	0.86	
		29	0 < D < 2cm	3.5	0.06	0.01	0.58	2.4
			2 < D < 10cm	4	0.12	0.05	1.67	
			D = or > 10cm	9.5	0.26	0.1	3.65	
		30V	0 < D < 2cm	1	0.06	0.03	0.5	1.9
			2 < D < 10cm	2	0.2	0.09	0.9	
			D = or > 10cm	5.5	0.2	0.08	2.2	
	2	31	0 < D < 2cm	13.5	0.1	0.04	5.4	3.4
			2 < D < 10cm	35.5	0.18	0.08	15.78	

			D = or > 10cm	75.5	0.24	0.14	44.04	
		32	0 < D < 2cm	9	0.1	0.04	3.6	3.4
			2 < D < 10cm	10	0.15	0.06	4	
			D = or > 10cm	127.2	0.26	0.1	48.9	
		33V	0 < D < 2cm	5	0.16	0.04	1.25	3
			2 < D < 10cm	21.5	0.2	0.08	8.6	
			D = or > 10cm	66	0.24	0.09	24.75	

APPENDIX 3a: Summary for the twenty two destructively sampled trees

Tree No	DBH (cm)	Height (m)	Tap root depth (m)	Dry weights of biomass in kg						RS (Weight)	R/H (Depth/Ht)
				Stem	Branches	foliage	AGB	BGB	TTB		
1	5.2	6.55	1.55	10.16	1.625	5.22	17.01	3.82	20.83	0.22	0.24
2	1.5	3.6	1.10	1.55	0.644	1.02	3.31	0.801	4.01	0.24	0.31
3	12	14.3	2.70	93.69	10.62	12.1	116.41	37.43	153.84	0.32	0.19
4	13.2	12.7	1.80	70.22	11.08	17.49	98.79	23.46	122.25	0.24	0.14
5	22.5	16.7	2.20	166.66	50.3	22.92	239.88	63.14	303.02	0.26	0.13
6	29.8	14.5	1.40	247.52	80.42	21.27	349.21	119.55	468.76	0.34	0.1
10	12.0	12.75	1.20	59.01	6.88	13.14	79.03	32.4	111.43	0.41	0.09
11	15.4	13.7	1.90	109.4	24.75	20.65	154.8	53.63	208.43	0.35	0.14
12	7.0	8.65	1.85	20.38	5.0	7.5	32.88	9.83	42.71	0.3	0.21
13	5.6	8.65	3.05	12.68	2.8	4.13	19.61	5.94	25.55	0.3	0.35
14	27.6	19.0	2.40	270.53	92.98	17.97	381.48	130.37	511.85	0.34	0.13
15	27.7	19.2	2.0	306.55	83.25	16.0	405.8	127.08	532.88	0.31	0.1
19	1.7	7.1	1.90	1.95	0.6	1.45	4.0	1.79	5.79	0.45	0.27
20	8.7	9.8	2.30	24.98	6.43	8.75	40.16	7.86	48.02	0.2	0.23
21	15.3	14.3	3.60	58.83	38.5	15.51	112.84	21.46	134.30	0.19	0.25
22	14.8	15.0	3.0	69.63	32.71	10.46	112.8	33.99	146.79	0.3	0.2
25	22.0	17.0	2.8	164.71	30.03	11.09	205.83	68.36	274.19	0.33	0.16
26	29.8	21.2	3.0	259.8	33.2	10.89	303.89	79.34	383.23	0.26	0.14
28	2.0	6.0	2.40	3.21	0.94	1.19	5.34	1.01	6.35	0.19	0.4
29	8.9	9.9	2.40	28.87	10.25	10.01	49.13	5.90	55.03	0.12	0.24
31	12.8	13.0	3.40	114.66	31.50	31.22	177.38	65.22	242.6	0.37	0.26
32	24.9	19.0	3.40	262.84	37.75	18.57	319.16	56.50	375.66	0.18	0.18

APPENDIX 3b: Summary for the eleven destructively sampled trees

Tree No	DBH (cm)	Height (m)	Tap root depth (m)	Dry weights of biomass in kg							
				Stem	Branches	foliage	AGB	BGB	TTB	RS (Weight	R/H (Depth/Ht
7V	1.8	6.0	1.0	1.65	0.33	0.662	2.64	1.461	4.10	0.55	0.17
8V	13.7	14.5	2.70	112.22	26.61	14.64	153.47	32.42	185.89	0.21	0.19
9V	20	16.1	1.0	134.87	31.5	13.75	180.12	57.79	237.91	0.32	0.06
16V	16.9	12.2	1.40	118.03	43.65	22.39	184.07	86.03	270.1	0.46	0.11
17V	9.8	9.1	2.45	32.69	10.0	10.2	52.89	15.01	67.94	0.28	0.27
18V	25.8	16.6	2.0	275.16	63.58	33.26	372.0	74.95	446.95	0.2	0.12
23V	12.2	12.4	2.80	40.63	13.93	13.5	68.06	17.75	85.81	0.26	0.23
24V	12.8	15.4	2.90	62.94	19.15	7.0	89.09	27.26	116.35	0.31	0.19
27V	27.8	24.8	2.0	327.63	43.9	8.71	380.24	114.75	494.99	0.3	0.08
30V	4.5	9.1	1.90	11.96	2.5	3.86	18.32	3.60	21.92	0.2	0.21
33V	20.4	11.5	3.0	128.71	46.9	16.2	191.81	34.60	226.41	0.18	0.26

APPENDIX 4: Tree components and total tree biomass summarized per AEZ (33 sampled trees)

AEZ	TREE No.	DBH	STEM	BRACH	FOLIAGE	ROOTS	TOTAL
UM4	1	5.2	10.16	1.6	5.22	3.826	20.806
	2	1.5	1.55	0.64	1.02	0.801	4.011
	3	12	93.69	0.33	0.662	0.128	94.81
	4	13.2	70.122	10.62	12.1	37.43	130.272
	5	22.5	166.36	11.08	17.49	22.47	217.4
	6	29.8	247.52	26.61	14.64	31.29	320.06
	9V	20	134.87	50.3	22.92	63.14	271.23
	7V	1.8	1.65	80.4	21.27	119.55	222.87
	8V	13.7	112.22	31.5	13.75	57.79	215.26
		TOTAL	832.142	213.13	109.072	336.425	1490.769
UM3	10	12	59.01	6.88	13.14	32.4	111.43
	11	15.4	109.4	24.75	20.65	53.63	208.43
	16V	16.9	118.03	46.65	22.39	86.03	273.1
	14	27.6	270.55	92.98	7.5	9.83	380.86
	18V	25.8	275.16	79.65	4.13	5.94	364.88
	12	7	17.46	63.58	10.2	15.01	106.25
	13	5.6	12.68	5	17.97	130.37	166.02
	12V	9.8	32.71	2.8	16	127.08	178.59
	15	27.7	306.55	10	33.26	74.95	424.76
		TOTAL	1201.53	332.89	145.24	535.24	2214.9
UM2	19	1.7	1.95	0.6	1.45	1.79	5.79
	20	8.7	24.98	6.43	8.75	7.86	48.02
	23V	12.2	40.63	13.93	13.5	17.72	85.78
	21	15.3	58.83	38.5	15.51	21.46	134.3
	22	14.8	69.63	32.71	10.46	33.99	146.79
	24V	12.8	62.94	19.5	7	27.26	116.7
	25	22	164.71	30.03	11.09	68.36	274.19
	26	29.8	259.8	33.2	10.89	79.34	383.23
	27V	27.8	327.63	43.9	8.71	114.75	494.99
		TOTAL	1011.1	218.8	87.36	372.53	1689.79
UM1	28	2	3.21	0.94	1.19	0.99	6.33
	29	8.9	28.87	10.25	10.01	5.9	55.03
	30V	4.5	11.96	2.5	3.86	3.6	21.92
	31	12.8	114.66	31.5	31.22	65.22	242.6
	32	24.9	262.84	37.75	18.57	56.5	375.66
	33	21.4	128.71	46.9	16.2	34.6	226.41
		TOTAL	550.25	129.84	81.05	166.81	927.95

APPENDIX 5: Residuals for eleven destructively sampled trees

DBH	Actual biomass (Kg)	Estimated biomass (Kg)	Residual
1.8	4.1	5.069694	-0.96969
13.7	135.89	138.3122	-2.42225
20	237.91	256.1655	-18.2555
16.9	190.9	194.7019	-3.80194
9.8	76.9	80.14014	-3.24014
25.8	446.95	387.8567	59.09327
12.2	115.81	114.5046	1.305383
12.8	116.35	123.8192	-7.46917
27.8	494.99	438.0178	56.97215
4.5	21.92	22.55413	-0.63413
20.4	226.41	264.5638	-38.1538

APPENDIX 6: Measured DBH and TTB equation generated tree biomass for each AEZ

UM 1		UM 2		UM 3		UM 4	
DBH	BIOM	DBH	BIOM	DBH	BIOM	DBH	BIOM
12.8	135.0317	13.9	153.2362	18.6	239.6371	30.3	516.7652
2.4	1.61632	1	11.004	17	208.608	29.8	503.1221
1	11.024	9.2	80.98688	9.1	79.56782	1	11.004
1	11.024	1	11.004	18.8	243.6317	4.4	21.88352
4.4	21.86352	1	11.004	14.6	165.1555	26.5	417.1155
15.4	179.2691	13.5	146.5335	18.5	237.6495	1	11.004
16	190.096	1	11.004	2.5	2.5775	1	11.004
10	92.26	16	190.116	16	190.052	1	11.004
10	92.26	3	7.44	19.4	255.7699	16	190.116
13	138.28	15.4	179.2891	10.8	103.9421	18	227.88
12.8	135.0317	21.5	300.1655	15.3	177.446	13.5	146.5335
20.9	287.1934	1.7	4.84162	12.8	135.0005	1	11.004
2.2	0.26672	12.2	125.4613	16.2	193.7117	14.8	168.6941
19	247.708	8	64.82	20.9	287.1298	17.5	218.1975
2	2.124	8.76	74.95135	19	247.652	16	190.116
8.9	76.83822	13	138.3	2.2	0.25552	15	172.2
1.4	7.54128	1	11.004	7.8	62.18448	18.5	237.7235
1.2	9.29552	1	11.004	5.2	30.68288	14	154.928
16.5	199.2955	1	11.004	4.5	22.9455	16.5	199.3155
12.6	131.8091	1.5	6.6345	4.5	22.9455	12.6	131.8291
15.3	177.4872	1	11.004	2.4	1.62672	15.3	177.5072
13	138.28	2	2.104	4.2	19.72608	1	11.004
11.8	119.1765	9.7	87.99678	5.1	29.55822	13	138.3

1.4	7.54128	9.6	86.58192	2.5	2.5775	11.8	119.1965
3.3	10.40878	12.2	125.4613	4.5	22.9455	14.5	163.4835
UM 1		UM 2		UM 3		UM 4	
DBH	BIOM	DBH	BIOM	DBH	BIOM	DBH	BIOM
1.5	6.6545	8.7	74.13798	5.4	32.95152	17.1	210.5674
2	2.124	8.3	68.77478	2.6	3.53472	1	11.004
1	11.024	10.9	105.4774	1	11.008	1	11.004
17.1	210.5474	6.8	49.58048	1	11.008	18	227.88
17.1	210.5474	6.9	50.81502	9	78.192	1	11.004
9	78.208	2.9	6.45662	10.5	99.5055	12.4	128.6323
11.4	113.0147	1	11.004	4.6	24.03152	11.4	113.0347
10.8	103.9653	5.1	29.57862	1	11.008	10.8	103.9853
11	106.956	11	106.976	1	11.008	9.3	82.37598
10.5	99.5275	1	11.004	1	11.008	11.8	119.1965
12	122.296	12	122.316	1	11.008	15.6	182.8723
7	52.036	10.4	98.08112	1	11.008	7	52.056
12.2	125.4413	5.2	30.70368	7	52.028	17.5	218.1975
11.1	108.461	11.1	108.481	5.3	31.81398	14.4	161.7595
13	138.28	6.1	41.11902	1.3	8.40682	11.8	119.1965
10	92.26	1	11.004	1.8	3.94272	10	92.28
12.8	135.0317	12.8	135.0517	1	11.008	13	138.3
20	268.2	6.8	49.58048	1	11.008	8	64.82
1	11.024	1	11.004	1	11.008	13.8	151.5509
10.4	98.06112	1	11.004	1	11.008	11.4	113.0347
14	154.908	1	11.004	9.8	89.37888	15.4	179.2891
16	190.096	10.4	98.08112	1	11.008	8.4	70.10592
19.5	257.8735	6.2	42.30848	1	11.008	7.8	62.21568
8.1	66.11182	9.5	85.1735	2.8	5.46848	22.5	322.2675
5.6	35.24832	8.5	71.4435	4.9	27.32822	1	11.004
5.2	30.68368	6.5	45.9155	4.2	19.72608	15.6	182.8723
10	92.26	8.1	66.13182	12.1	123.837	1	11.004
13	138.28	1	11.004	8.7	74.10318	1	11.004
16.9	206.771	1	11.004	5.6	35.24592	2.9	6.45662
21	289.336	8.2	67.45008	1	11.008	13.6	148.1995
21	289.336	5.7	36.42558	15	172.14	16.4	197.4627
13	138.28	1	11.004	20.2	272.3149	1	11.004
3.9	16.56022	6	39.936	29.7	500.294	1	11.004
17.3	214.3496	1	11.004	19.5	257.8155	17	208.676
16	190.096	1	11.004	23	333.468	16	190.116
16	190.096	1	11.004	2.3	0.68238	18.7	241.706
21	289.336	6.4	44.70672	18.3	233.6936	10.4	98.08112

18.7	241.686	4.8	26.24208	12	122.268	12.2	125.4613
3.9	16.56022	1	11.004	5.4	32.95152	13	138.3
13.2	141.5541	1	11.004	13.2	141.5213	18	227.88
UM 1		UM 2		UM 3		UM 4	
DBH	BIOM	DBH	BIOM	DBH	BIOM	DBH	BIOM
18	141.5541	1	11.004	2	2.112	1	11.004
5.8	227.86	1.5	6.6345	1	11.008	1	11.004
22	37.56928	1	11.004	27.7	447.4684	18.4	235.7419
15.7	311.116	1.3	8.40162	27.6	444.8947	15.5	181.0775
19.3	184.6536	6	39.936	1	11.008	19.3	253.808
13.5	253.788	14.2	158.3309	16.5	199.2495	17.4	216.2803
16.5	146.5135	12.9	136.6726	1	11.008	16.4	197.4627
13	199.2955	15.3	177.5072	25	380.24	13	138.3
5	138.28	18.4	235.7419	1	11.008	21.2	293.6605
3.3	28.44	7.8	62.21568	17.5	218.1275	14	154.928
17	10.40878	17.2	212.4653	1	11.008	25.3	387.5792
9.6	208.656	17.6	220.1211	9.6	86.54352	17.3	214.3696
10	86.56192	5	28.46	2.3	0.68238	10.4	98.08112
6.6	92.26	1	11.004	12.4	128.5827	14.4	161.7595
8.5	47.11072	2	2.104	1	11.008	10.2	95.16768
5	71.4235	3.4	11.43792	1	11.008	12.3	127.0436
14	28.44	17.5	218.1975	14.8	168.6349	20.1	270.3046
20	154.908	21.1	291.505	17.5	218.1275	16	190.116
12.8	268.2	20.9	287.2134	3.3	10.41558	12.8	135.0517
3.7	135.0317	10	92.28	1.4	7.52688	19.8	264.0701
8.5	14.48398	9.7	87.99678	5.8	37.56608	19.2	251.7749
15.9	71.4235	15.9	188.2954	2.4	1.62672	5	28.46
16	188.2754	21.3	295.8224	21	289.272	20	268.22
32	190.096	15.5	181.0775	14	154.872	16	190.116
20	564.336	20.4	276.5971	17.2	212.3965	16.4	197.4627
21	268.2	1	11.004	15.4	179.2275	2.4	1.63632
5.6	289.336	1	11.004	22	311.048	11.2	109.9925
8.9	35.24832	1	11.004	8.9	76.82262	1	11.004
8.8	76.83822	1	11.004	8.5	71.4095	16	190.116
17.8	75.47488	1	11.004	16.8	204.8453	14.2	158.3309
9.5	223.9677	5.5	34.1175	19	247.652	16.1	191.943
15	85.1535	18.6	239.7115	4	17.612	13.5	146.5335
7	172.18	1	11.004	1	11.008	9.5	85.1735
14.2	52.036	14.2	158.3309	3.3	10.41558	14.3	160.042
1.6	158.3109	20.1	270.3046	23.1	335.7454	16.6	201.1747
14	-5.76128	1	11.004	2.2	0.25552	17.4	216.2803

16.9	154.908	1	11.004	16.9	206.7234	13.8	151.5509
14	206.771	7	52.056	8.3	68.74158	14.1	156.6262
12	154.908	17.1	210.5674	5.4	32.95152	14.1	156.6262
3	122.296	9.1	79.60422	11.5	114.5195	17.8	223.9877
UM 1		UM 2		UM 3		UM 4	
DBH	BIOM	DBH	BIOM	DBH	BIOM	DBH	BIOM
6.3	43.48438	41.4	861.1027	25.8	399.6701	15.7	184.6736
30	508.54	32.3	572.9476	6.3	43.47918	6	39.936
9.5	85.1535	13	138.3	7.5	58.3275	1	11.004
17	208.656	13.4	144.8739	14	154.872	17	208.676
7.2	54.53728	12	122.316	1	11.008	10.8	103.9853
24.9	377.9198	28	455.34	1	11.008	9.5	85.1735
13.4	144.8539	21.2	293.6605	21.8	306.6413	14.7	166.9508
13	138.28	14	154.928	1	11.008	13	138.3
21.1	291.485	12	122.316	1.7	4.84842	8.8	75.49488
28	455.32	12.5	130.2275	15.2	175.6709	16	190.116
15	172.18	20.8	285.0773	1	11.008	6	39.936
21	289.336	22.3	317.7956	21	289.272	21.2	293.6605
15.6	182.8523	23.3	340.4128	5.5	34.0955	15.6	182.8723
16.8	204.8925	24.9	377.9398	22	311.048	16.6	201.1747
1.8	3.95552	19.3	253.808	23	333.468	12.4	128.6323
22	311.116	8.5	71.4435	22	311.048	10.9	105.4774
15	172.18	12.5	130.2275	15.2	175.6709	11.2	109.9925
11.9	120.733	11.9	120.753	9.2	80.95008	23.2	338.1221
1.5	6.6545	16.9	206.791	7.7	60.89238	7	52.056
2.1	1.19858	7	52.056	1	11.008	19	247.728
16.9	206.771	16.9	206.791	1.5	6.6405	9	78.228
1	11.024	7.5	58.3575	6.3	43.47918	13.5	146.5335
1	11.024	15	172.2	23.5	344.9195	7.9	63.51462
6.3	43.48438	18.3	233.7668	5.4	32.95152	8.6	72.78752
2.8	5.45968	12.5	130.2275	2.8	5.46848	18.9	245.7142
2.3	0.67158	24	356.628	13.6	148.1451	9.8	89.41808
1	11.024	4.8	26.24208	14.6	165.1555	7.3	55.81758
8.2	67.43008	14.3	160.042	2.8	5.46848	8.2	67.45008
10.1	93.70062	10.8	103.9853	10.1	93.68022	8.8	75.49488
21.6	302.3267	21.6	302.3467	13	138.248	6.2	42.30848
16	190.096	21.7	304.5344	8.3	68.74158	5.5	34.1175
7.7	60.90318	33	593.22	5.3	31.81398	17.2	212.4653
12.2	125.4413	32.6	581.5971	12.5	130.1775	7.7	60.92318
1	11.024	20.2	272.3957	6.4	44.68112	9.5	85.1735
1	11.024	33.5	607.8935	1	11.008	2.3	0.69158

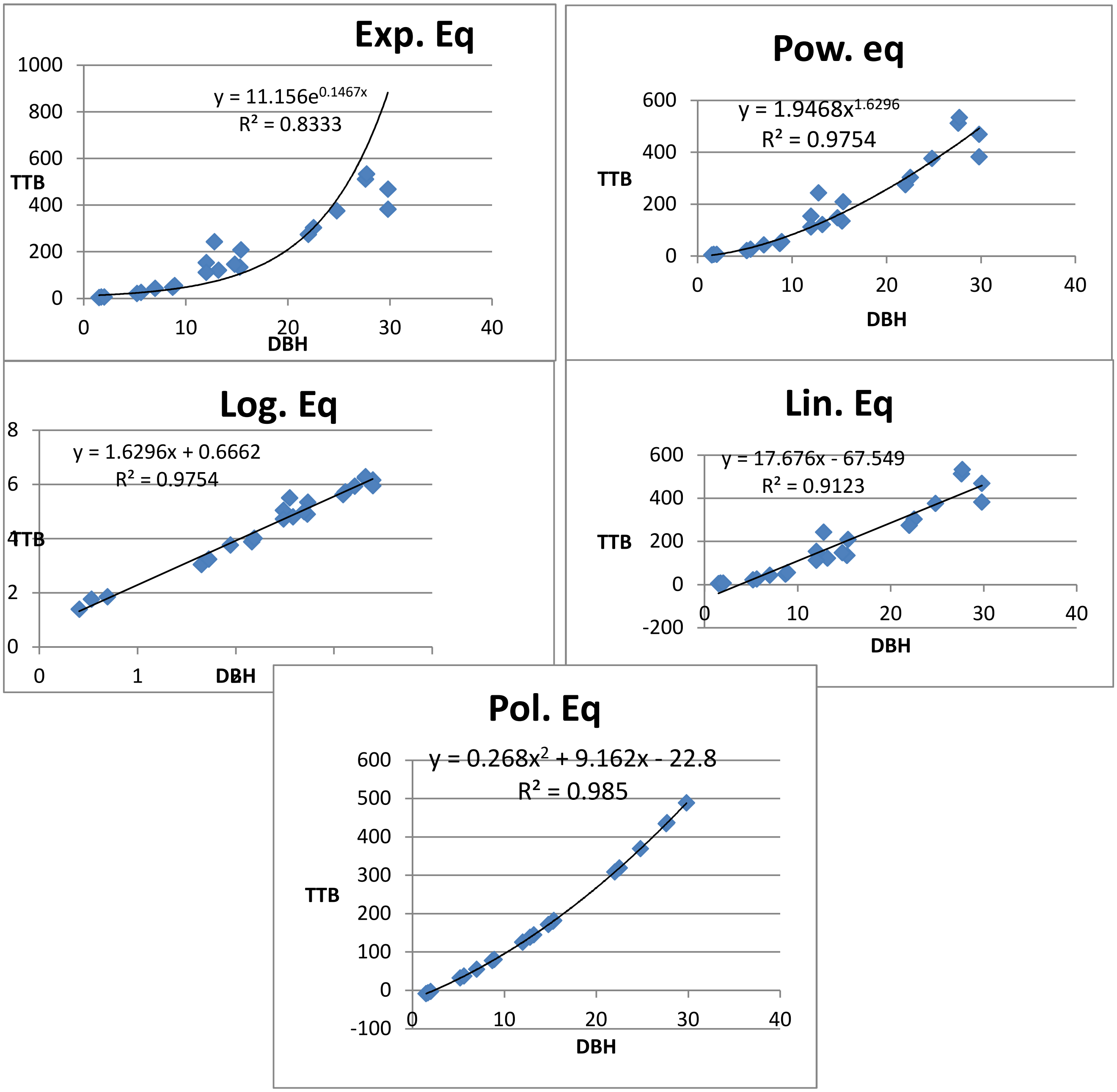
10	92.26	33.8	616.7749	5.4	32.95152	15.4	179.2891
6.5	45.8955	5.2	30.70368	24	356.532	17.1	210.5674
5.4	32.95312	10	92.28	3.3	10.41558	31	536.136
12.8	135.0317	8.5	71.4435	5.3	31.81398	27.8	450.1597
1	11.024	17.7	222.0512	17.9	225.859	32.2	570.0773
UM 1		UM 2		UM 3		UM 4	
DBH	BIOM	DBH	BIOM	DBH	BIOM	DBH	BIOM
6.6	47.11072	19.7	262.0048	6.6	47.10432	16	190.116
4	17.608	21.8	306.7285	4.7	25.12398	27	429.696
12.8	135.0317	19.7	262.0048	5.1	29.55822	16.8	204.9125
12	122.296	15	172.2	2.7	4.49838	26	404.696
8	64.8	14.9	170.4438	8.5	71.4095	34	622.728
1.5	6.6545	12.3	127.0436	1	11.008	29.5	495.0135
1.2	9.29552	11	106.976	5.7	36.40278	39.5	796.5335
2.9	6.43662	5	28.46	14.8	168.6349	27.5	442.4375
5.6	35.24832	16.2	193.7765	3.4	11.42432	23.5	345.0135
4.5	22.9435	16.9	206.791	2.9	6.44502	22	311.136
3.3	10.40878	22.5	322.2675	2.3	0.68238	5	28.46
10	92.26	1	11.004	8.7	74.10318	7.4	57.08432
20.9	287.1934	13.5	146.5335	1	11.008	9.9	90.84582
31.5	550.1455	10	92.28	1	11.008	8	64.82
20.4	276.5771	23.5	345.0135	1	11.008	3.9	16.58022
30.4	519.4931	26.4	414.6187	17.3	214.3004	5.5	34.1175
13	138.28	21.7	304.5344	21.3	295.7372	5.3	31.83518
8.3	68.75478	22.3	317.7956	11.2	109.9477	11.7	117.6464
5.3	31.81518	16.8	204.9125	12.2	125.4125	17	208.676
12.5	130.2075	11.4	113.0347	8.8	75.45968	16.6	201.1747
6.4	44.68672	11.7	117.6464	9.1	79.56782	13.1	139.9338
1	11.024	16.4	197.4627	6.3	43.47918	20.5	278.7075
5.4	32.95312	11.3	111.5104	20.5	278.6255	26.8	424.6445
24	356.608	33.4	604.9459	1	11.008	19	247.728
3.3	10.40878	43.6	938.7715	1	11.008	19.5	257.8935
5.3	31.81518	28.5	468.4035	13	138.248	24.8	375.5461
17.9	225.9106	43.6	938.7715	11.1	108.4366	24.8	375.5461
6.6	47.11072	14.4	161.7595	29.9	505.7182	6.5	45.9155
4.7	25.12278	36.3	693.0404	17.5	218.1275	10.2	95.16768
1	11.024	28	455.34	9.3	82.33878	3.3	10.42878
1	11.024	29.7	500.4128	17.6	220.0507	25.5	392.4375
17.3	214.3496	1	11.004	10.3	96.57998	6	39.936
21.3	295.8024	20.8	285.0773	3.8	15.52368	11.1	108.481
11.2	109.9725	1	11.004	28.1	457.8274	7.6	59.63712

12.2	125.4413	1	11.004	16	190.052	9.5	85.1735
8.8	75.47488	1	11.004	1	11.008	9.3	82.37598
9.1	79.58422	3.4	11.43792	16.8	204.8453	12.7	133.4372
6.3	43.48438	11.7	117.6464	13.3	143.1676	1.2	9.27552
20.5	278.6875	15.3	177.5072	29.8	503.0029	1	11.004
1	11.024	14.8	168.6941	35	652.74	12.1	123.8854
UM 1		UM 2		UM 3		UM 4	
DBH	BIOM	DBH	BIOM	DBH	BIOM	DBH	BIOM
1	11.024	1	11.004	32	564.228	4.1	18.68222
13	138.28	2.4	1.63632	20	268.14	9.8	89.41808
11.1	108.461	12.8	135.0517	32.3	572.8184	8.4	70.10592
6	39.916	14	154.928	22.8	328.9325	4.5	22.9635
4.4	21.86352	1	11.004	18.7	241.6312	9.4	83.77152
16.2	193.7565	17.5	218.1975	9.5	85.1355	15.9	188.2954
19.2	251.7549	19.3	253.808	9.3	82.33878	14.6	165.2139
10.8	103.9653	17.6	220.1211	12.7	133.3864	11.4	113.0347
6.5	45.8955	15.3	177.5072	1.2	9.28032	4.4	21.88352
7.9	63.49462	17.5	218.1975	1	11.008	6.4	44.70672
11	106.956	12.3	127.0436	12.1	123.837	8.3	68.77478
14.6	165.1939	8.7	74.13798	4.1	18.66582	4.4	21.88352
2.5	2.5675	7.2	54.55728	9.8	89.37888	5.5	34.1175
20.1	270.2846	7.4	57.08432	8.4	70.07232	9.6	86.58192
9.2	80.96688	15.5	181.0775	4.5	22.9455	5.5	34.1175
8.6	72.76752	14.3	160.042	9.4	83.73392	9.4	83.77152
13.7	149.852	15.3	177.5072	15.9	188.2318	9.1	79.60422
10.8	103.9653	18.4	235.7419	14.6	165.1555	8.5	71.4435
10.4	98.06112	2.8	5.47968	7.4	57.05472	9.2	80.98688
1	11.024	13.2	141.5741	15.5	181.0155	5.1	29.57862
15.7	184.6536	1	11.004	14.3	159.9848	10.1	93.72062
15.1	173.9426	13.3	143.2208	15.3	177.446	4.7	25.14278
7.2	54.53728	11.4	113.0347	18.4	235.6683	8.8	75.49488
1.3	8.42162	18	227.88	2.8	5.46848	8.8	75.49488
3	7.42	16.3	195.6164	13.2	141.5213	10.2	95.16768
4	17.608	25.3	387.5792	1	11.008	9.5	85.1735
2	2.124	8.9	76.85822	13.3	143.1676	7.5	58.3575
3	7.42	1	11.004	11.4	112.9891	7.2	54.55728
4	17.608	1	11.004	18	227.808	6.5	45.9155
2	2.124	21.6	302.3467	16.3	195.5512	6.3	43.50438
2	2.124	1	11.004	25.3	387.478	6.8	49.58048
16	190.096	1	11.004	8.9	76.82262	7.8	62.21568
1	11.024	1	11.004	3.2	9.41328	5.9	38.75942

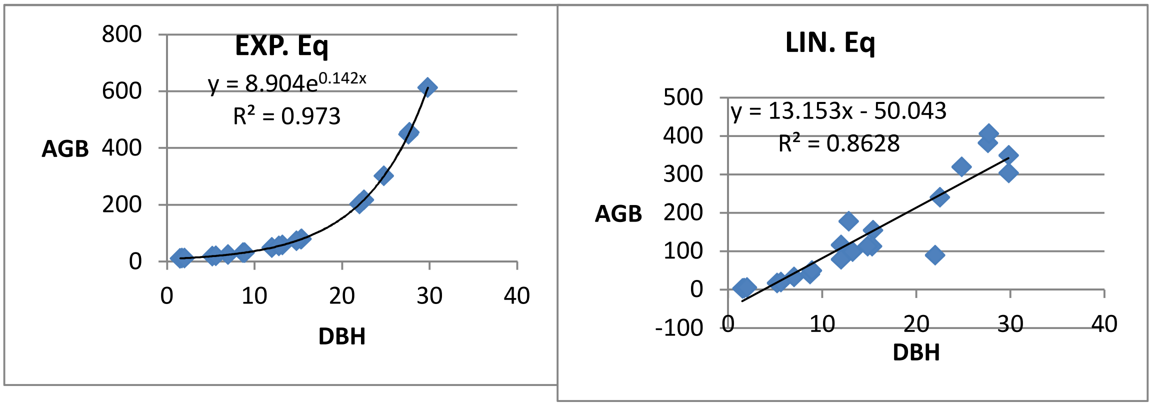
16.8	204.8925	1	11.004	1.7	4.84842	5.1	29.57862
13.3	143.2008	22	311.136	6	39.912	5.5	34.1175
29.8	503.1021	11.7	117.6464	4.4	21.86592	4.1	18.68222
35	652.86	26.4	414.6187	16.2	193.7117	2.8	5.47968
32	564.336	14.8	168.6941	19.2	251.6981	4	17.628
20	268.2	9	78.228	10.8	103.9421	4.5	22.9635
32.3	572.9276	6.4	44.70672	6.5	45.8895	3.8	15.53888
		UM 2		UM 3		UM 4	
		DBH	BIOM	DBH	BIOM	DBH	BIOM
		6.8	49.58048	7.9	63.48302	4.5	22.9635
		3.2	9.42608	1	11.008	5	28.46
		1.7	4.84162	1	11.008	7.2	54.55728
		6	39.936	2.5	2.5775	11.1	108.481
		4.4	21.88352	20.1	270.2242	6	39.936
		16.2	193.7765	7.8	62.18448	4.4	21.88352
		19.2	251.7749	5.9	38.73582	16.2	193.7765
		10.8	103.9853	5.1	29.55822	19.2	251.7749
		6.5	45.9155	5.5	34.0955	10.8	103.9853
		7.9	63.51462	4.1	18.66582	6.5	45.9155
		1	11.004	2.8	5.46848	7.9	63.51462
		1	11.004	4	17.612	11	106.976
		2.5	2.5875	4.5	22.9455	14.6	165.2139
		20.1	270.3046	3.8	15.52368	2.5	2.5875
		9.2	80.98688	1	11.008	20.1	270.3046
		8.6	72.78752	7	52.028	9.2	80.98688
		13.7	149.872	17.1	210.499	8.6	72.78752
		10.8	103.9853	9.1	79.56782	13.7	149.872
		10.4	98.08112	41.4	860.9371	10.8	103.9853
		1	11.004	32.3	572.8184	10.4	98.08112
		15.7	184.6736	13	138.248	17.5	218.1975
		15.1	173.9626	13.4	144.8203	19.3	253.808
		7.2	54.55728	12	122.268	17.6	220.1211
		1.3	8.40162	28	455.228	15.3	177.5072
		14	154.928	21.2	293.5757	17.5	218.1975
		12	122.316	14	154.872	12.3	127.0436
		1	11.004	12	122.268	8.7	74.13798
		12.3	127.0436	12.5	130.1775	7.2	54.55728
		12.3	127.0436	20.8	284.9941	7.4	57.08432
		6	39.936	12.1	123.837	15.5	181.0775
		4	17.628	4.1	18.66582	14.3	160.042
		11	106.976	9.8	89.37888	15.3	177.5072

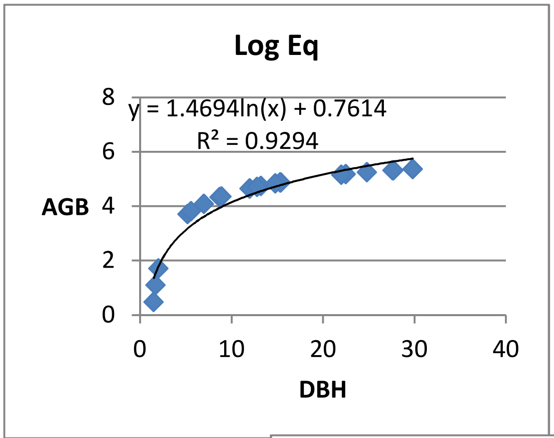
13	138.3	8.4	70.07232	18.4	235.7419
15	172.2	4.5	22.9455		
18	227.88	9.4	83.73392		
4	17.628	15.9	188.2318		
6	39.936	14.6	165.1555		
3	7.44	7.4	57.05472		
1	11.004	15.5	181.0155		
17.2	212.4653	14.3	159.9848		
UM 2		UM 3			
DBH	BIOM	DBH	BIOM		
3	7.44	15.3	177.446		
12	122.316	18.4	235.6683		
12	122.316	2.8	5.46848		
4	17.628	13.2	141.5213		
11	106.976	1	11.008		
5	28.46	6.5	45.8895		
1	11.004	6.3	43.47918		
5.2	30.70368	6.8	49.55328		
6.1	41.11902	7.8	62.18448		
3	7.44	5.9	38.73582		
21	289.356	5.1	29.55822		
12	122.316	5.5	34.0955		
19.8	264.0701	4.1	18.66582		
2	2.104	2.8	5.46848		
3	7.44	4	17.612		
4	17.628	4.5	22.9455		
2	2.104	3.8	15.52368		
2	2.104	20.9	287.1298		
16	190.116	2.2	-0.25552		
1	11.004	19	247.652		
16.8	204.9125	2	-2.112		
13.3	143.2208	8.9	76.82262		
29.8	503.1221	1.4	-7.52688		
35	652.88	1.2	-9.28032		
32	564.356	16.5	199.2495		
20	268.22	12.6	131.7787		

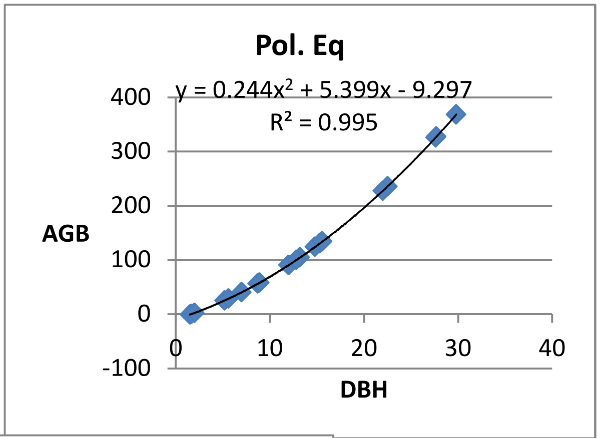
APPENDIX 7a: Total tree biomass (TTB) as a function of DBH

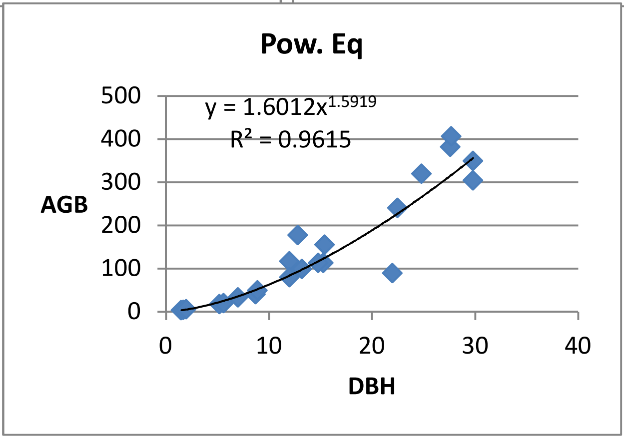


APPENDIX 7b: Aboveground biomass (AGB) as a function of DBH

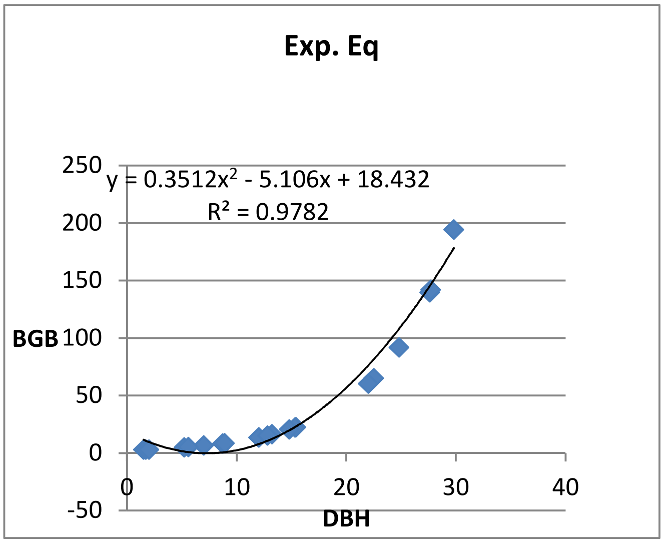


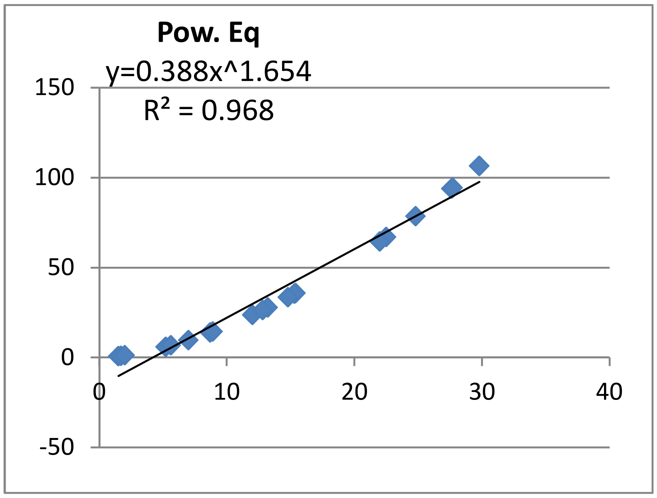

Log Eq
y = 1.4694ln(x) + 0.7614
R² = 0.9294
AGB
0
2
4
6
8
0
10
20
30
40
DBH

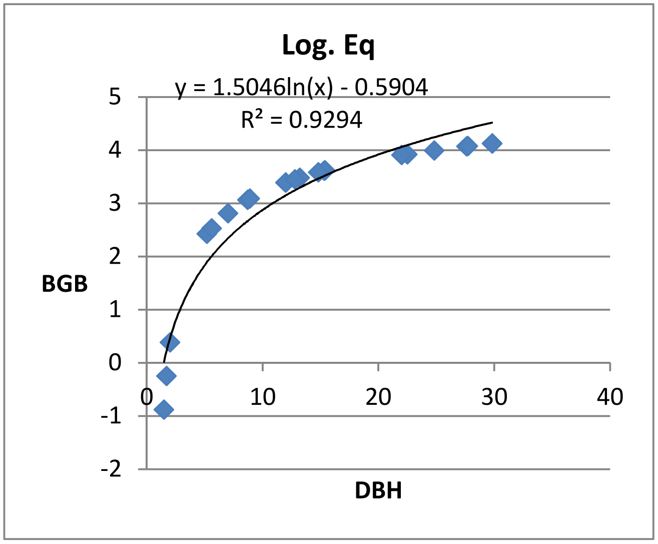

Pol. Eq
y = 0.244x² + 5.399x - 9.297
R² = 0.995
AGB
-100
0
100
200
300
400
0
10
20
30
40
DBH

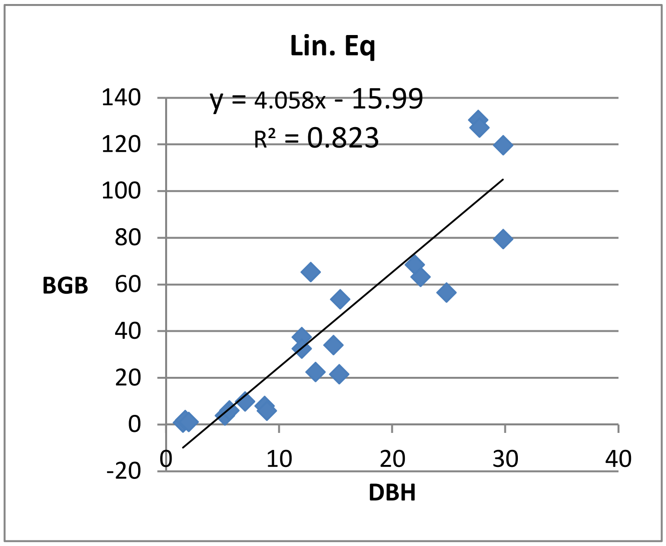

Pow. Eq
y = 1.6012x^1.5919
R² = 0.9615
AGB
0
100
200
300
400
500
0
10
20
30
40
DBH

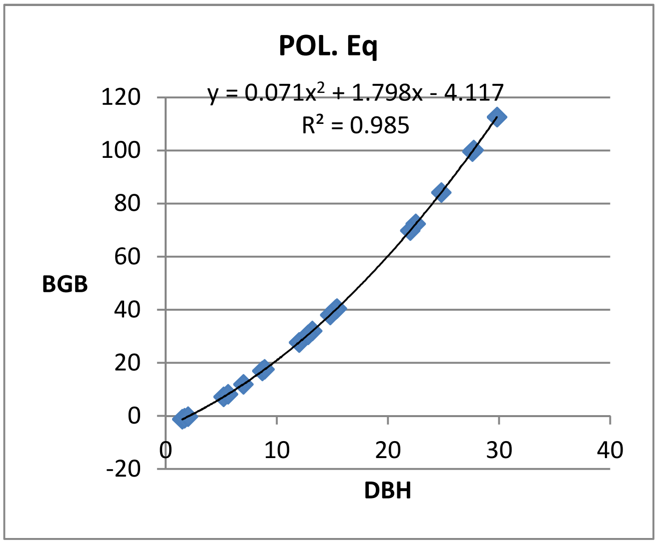
APPENDIX 7c: Bellow ground biomass (BGB) as a function of DBH



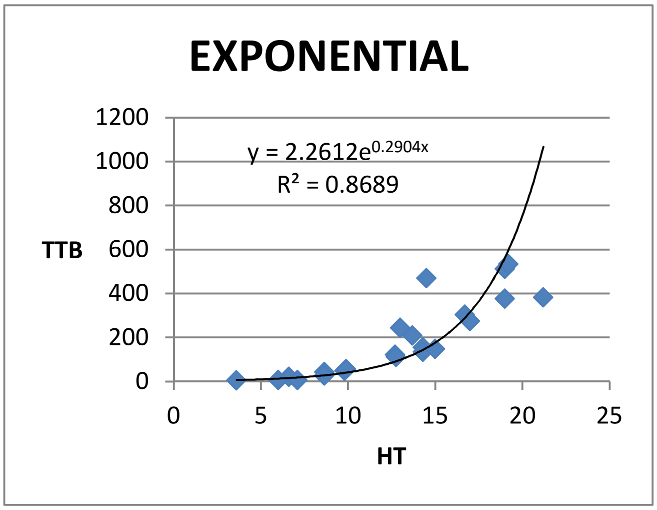


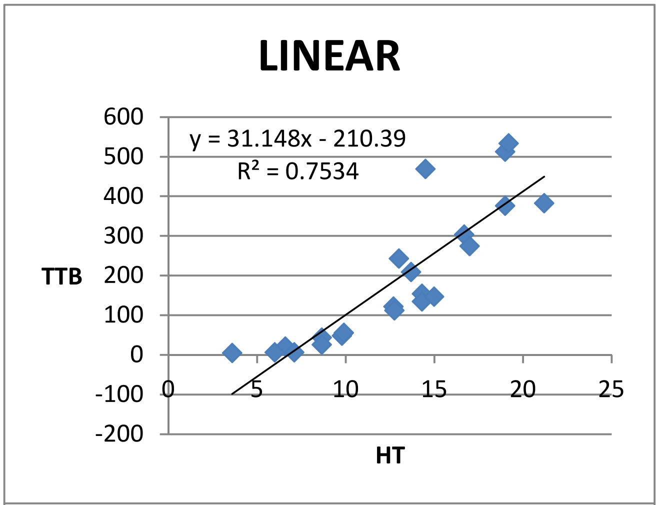


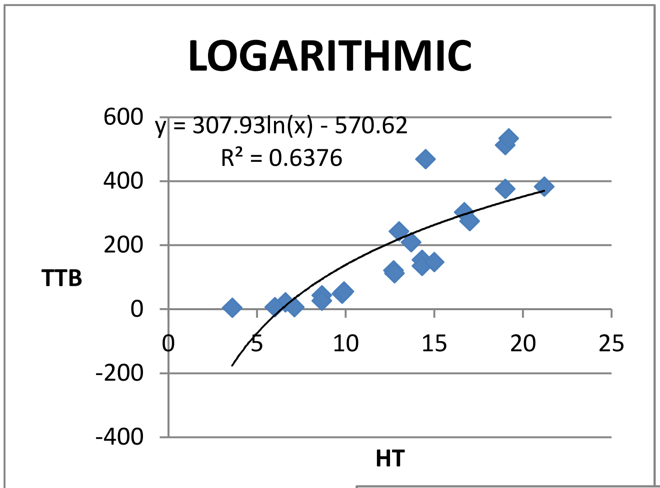


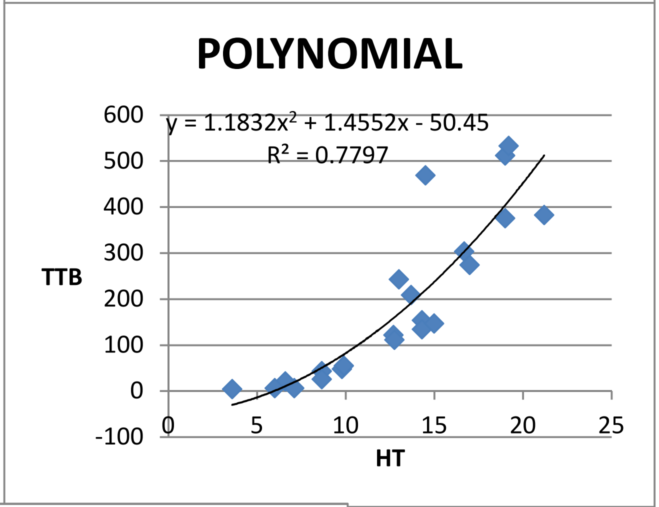


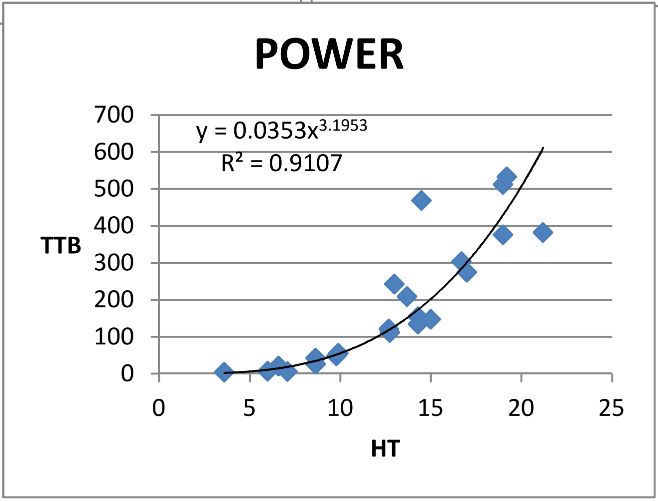
APPENDIX 7d: Total tree biomass (TTB) as a function of Ht











APPENDIX 8: Analysis of variance and t-test summaries

APPENDIX 8a: Analysis of variance

Attribute	Source of variation	SS	df	MS	f	p-value	f_{crit}
RS	Between AEZs	0.055	3	0.018	2.38	0.09	2.93
	Within AEZs	0.221	29	0.008			
	Total	0.276	32				
RS (Tree sizes)	Between groups	1249.904	32	39.05949	0.27	0.99	1.79
	Within groups	4689.6	33	142.1091			
	Total	5939.503	65				
R/H	Within AEZs	0.221	29	0.012	2.16	0.11	2.93
	Within AEZs	0.276	32	0.006			
	Total	0.202	32				
R/H (Tree sizes)	Between sizes	0.051618	1	0.05	12.8	1.5E-12	0.001
	Within sizes	0.124933	31	0.004			
	Total	0.176552	32				
TTB comparison	Between AEZs	117135.3	3	39045.1	2.21	0.09	2.61
	Within AEZs	18746907	1061	17669.09			
	Total	18864042	1064				
RH (small sizes verses medium sizes)	Between pairs	0.241	15	0.005	1.58	0.22	2.72
	Within pairs	0.162	11	0.003			
	Total	0.403	26				
RH (Small sizes verses large sizes)	Between pairs	0.241	15	0.005	8.80	0.02	5.86
	Within pairs	0.11	4	0.000			
	Total	0.351	19				
RH (Medium sizes verses large sizes)	Between pairs	0.161	11	0.003	5.57	0.06	5.93
	Within pairs	0.11	4	0.000			
	Total	0.171	15				

APPENDIX 8b: Biomass t-tests Summaries

Attribute	Mean biomass		df	MS	r	t	p-value	t_{crit}
AGB	Rurangwe	42.33	10	1336.34	0.89	0.54	0.30	2.23
	Owate	39.55	10	929.69				
BGB	Rurangwe	135.35	10	10310.42	0.98	-.71	0.06	2.23
	Owate	153.88	10	16486.59				
TTB	Rurangwe	188.01	10	25207..83	0.98	-.42	0.34	2.23
	Owate	192.21	10	19949.09				
Equations comparison	Owate (TTB)	119.25	10	5905.55	0.94	1.54	0.34	1.83
	Kuyah (TTB)	143	10	21256.1				