# VOLUME AND BIOMASS ESTIMATION MODELS FOR *TECTONA GRANDIS* GROWN AT LONGUZA FOREST PLANTATION, TANZANIA

**JUMA RAMADHANI MWANGI**

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## ABSTRACT

Quantifying tree volume, biomass and Carbon (C) stocks potential of tree crops by using allometric models is vital for understanding the contribution of forests on climate change mitigation effort. The existing allometric models for accurate estimations of total tree volume and total tree biomass for Teak (*Tectona grandis)* has limitation of application such as models being developed from few sample trees for model development and covered narrow range of diameters and excluded trees with small and large diameters. This study was carried out to fill these gaps by developing biomass and volume estimation models for Teak that cover a wide range of diameter. A total of 51 sample trees of diameter at breast height (Dbh) between 1.00 - 83.40 cm from seven compartments with ages of 2, 5, 16, 19, 21, 34 and 42 years were used for volume and biomass model development and evaluation. The sample trees were measured for Dbh and total height then felled down through excavation and cross cut into manageable billets which measured, measured for fresh weight, mid diameter and length. The twigs and leaves of each tree were tied into bundles and weighed. A total of 16 samples per tree from stem, branches, twigs and leaves, root crown, main roots and side roots were measured for fresh weight and taken to the laboratory for dry weight determination. Different types of models for biomass (total tree biomass, total above-ground and total below-ground) and volume were developed in this study. The selection of the best model was based on high $R^2$, lower MSE and *e*%. The Akaike Information Criteria (AIC) was used as final criteria for selection of the best model in which the model with lower AIC was selected. The developed total tree biomass model for Teak was $0.7136 \times Dbh^{2.0282}$ ($R^2$ = 98%, *e%* = 0.38 and AIC = 697) and the total volume equation up to cut off point of 2 cm was $V=0.00120 \times Dbh^{1.9912}$ ($R^2$ = 99%, *e%* = 2.2 and AIC =16).

# DECLARATION

**I, JUMA RAMADHANI MWANGI,** do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

………………………………… ………………….

**JUMA RAMADHANI MWANGI** **Date**

**MSc. Forest Resources Assessment and Management**

The above declaration is confirmed by:

………………………………… ………………………

**Dr. J. Z. Katani** **Date**

**(Main Supervisor)**

…………………………………… ……………………

**Prof. S.A.O. Chamshama** **Date**

**(Co-Supervisor)**

## COPYRIGHT

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## LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| ABG | Above-ground biomass |
| AIC | Akaike Information Criteria |
| B | Biomass |
| BEF | Biomass expansion factor |
| BGB | Below-ground biomass |
| BWD | Basic wood density |
| °C | Degree Centigrade |
| C | Carbon |
| CDM | Clean Development Mechanism |
| CER | Certified Emission Reduction |
| CI | Confidence Interval |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| Dbh | Diameter at breast height |
| Eqn(s) | Equation(s) |
| Exp | Exponential |
| FAO | Food and Agriculture Organisation of the United Nations |
| $gcm\text{-}^3$ | Grams per cubic centimetre |
| GHGs | Green House Gases |
| Ht | Height |
| IJ | Joint Implementation |
| IPCC | Intergovernmental Panel on Climate Change |

| | |
|---|---|
| KH | Kwamsambia |
| KP | Kyoto Protocol |
| KS | Kihuhwi Sigi |
| LFMP | Longuza Forest Management Plan |
| LG | Longuza Bulwa |
| ln | Natural logarithm |
| m | Metre |
| Max | Maximum |
| $m^2ha^{-1}$ | Square metre per hectare |
| $m^3$ $ha^{-1}$ | Cubic meter per hectare |
| $MgCha^{-1}$ | Megagram Carbon per hectare |
| Min | Minimum |
| MPE | Mean Prediction Error |
| MSE | Mean Standard Error |
| NAFORMA | National Forest Resource Monitoring and Assessment |
| NLP | Non Linear Programming |
| P | Probability level |
| PES | Payment for Environmental Services |
| Ppm | Parts per million |
| $R^2$ | Coefficient of determination |
| RSR | Root to Shoot Ratio |
| REDD | Reduced Emissions from Deforestation and forest Degradation |
| SD | Standard Deviation |
| SE | Standard Error |

| | |
|---|---|
| SUA | Sokoine University of Agriculture |
| t $Cha^{-1}$ | tons of Carbon per hectare |
| t $ha^{-1}$ | Tons per hectare |
| TSV | Total stem volume |
| TTV | Total tree volume |
| UNFCCC | United Nations Framework Convention on Climate Change |
| V | Volume |

# CHAPTER ONE

## 1.0 INTRODUCTION

### 1.1 Background

According to FAO (2010), total forest area in the world occupies over 4 billion hectares (ha) with the five countries (The Russian Federation, Brazil, Canada, the United States of America and China) having the largest forest area accounting for more than half of the total world forest area. Forests and woodlands cover an area of about 675 million ha, or 23% of Africa's land area and about 17% of global forest area (FAO, 2011). The five countries with the largest forest area in Africa are the Democratic Republic of Congo, Sudan, Angola, Zambia and Mozambique; together they have 55% of the forest area on the continent (FAO, 2010). Tanzania has a total land area of about 88.025 million ha out of which 48.4 million ha are covered by forests and woodlands (NAFORMA, 2012). The five regions having more significant forest areas are Morogoro, Lindi, Ruvuma, Mbeya and Tabora.

The total ´planted forests' area worldwide is reported to be 264 million ha. According to FAO (2010), the area of ´planted forest´ in the global South increased more than 50% between 1990 and 2010, from 95 million to 153 million ha. According to Ngaga, (2011) the total plantation area in Africa in year 2010 was 8 036 000 ha comprising 3 392 000 ha industrial plantations, 3 273 000 ha non-industrial plantations and 1 371 000 ha unspecified plantations, which is around 4.3% of the global plantation area. Furthermore, FAO (2001) found that in Africa *Eucalyptus sp.* is the most widely planted genus covering 22.4% of all planted area, followed by *Pinus* (20.5%), *Hevea* (7.1%), *Acacia* (4.3%) and *Tectona* (2.6%). The area covered by other broadleaved and other conifers is respectively 11.2% and

7.2%, while unspecified species cover 24.7%. Private sector interest in plantation development is reported to have slowly started to emerge in East Africa (Ngaga, 2011). A good example of private Teak plantation in East Africa is one in the Kilombero Valley in Tanzania.

Large-scale establishment of exotic forest plantations in Tanzania (by then called Tanganyika) commenced under the British rule (1920-1961) and were mainly based on species and provenance trials, and successful inoculation with suitable mycorhiza (Nshubemuki *et al.,* 2001). The total gross area of forest plantations in Tanzania is estimated to be about 552 576 ha (NAFORMA, 2012). The ownership of forest plantations in Tanzania can be either government or private. Plantation forests under government ownership cover about 84,615 ha (Chamshama, 2011) and private ownership covers 450 000 ha (NAFORMA, 2012). The most important industrial plantation species are Pines (*Pinus patula, P. elliottii* and *P. caribaea*), *Cypress sp*, *Eucalyptus sp* and *Tectona grandis*.

Among all plantations in tropics, Teak (*Tectona grandis*) which is the focus of this study is highly demanded. Furthermore, Teak is the world's most cultivated high-grade tropical hardwood, covering approximately 6.0 million ha worldwide (Bhat and Hwan Ok Ma, 2004). Of this net area of Teak plantations, about 94% are in Tropical Asia, (44% in India, 31% by Indonesia alone, 19% in Thailand, Myanmar, Bangladesh and Sri Lanka) and 4.5% in Tropical Africa. The high demand for Teak is due to the excellent properties supporting wide range of uses, including flooring, decking, framing, cladding, fascias and barge boards. In the decorative line it can be used for lining, panelling, turnery, carving, furniture (both indoor and outdoor) and parquetry (Oscar *et al.,* 2006).

Among other functions, forests play a crucial role in climate change mitigation through Carbon (C) sequestration. Thus, quantification of amounts of C stored in various vegetation types has recently gained importance all over the world (Brown, 1997; Chave *et al*., 2004). The amount of C stored in the forest stand depends on its age, volume per ha and number of stems per ha (Alexandrov, 2007; Gurney, 2008). But due to variation of C storage by species and forests type, direct field measurement for estimation of biomass and total C storage for specific forest ecosystems is essential (Munishi, 2001).

## 1.2 Problem Statement and Justification

Carbon dioxide ($CO_2$) is one of the more abundant greenhouse gases (GHGs) and a primary agent of global warming (Foster *et al.,* 2007). It constitutes 72% of the total anthropogenic GHGs, causing between 9-26% of the greenhouse effect (Kiehl and Trenberth, 1997). IPCC (2007) reported that the amount of $CO_2$ in the atmosphere has increased from 280 ppm in 1750 (the pre-industrial era) to 379 ppm in 2005, and is increasing by 1.5 ppm per year. International efforts have addressed the issue of climate change across all sectors and corporations to reduce GHGs emissions (Pyo *et al.,* 2012). To achieve this, there is a need of accurately identifying emission levels of GHG across different sectors (Gibbs *et al.,* 2007).

Forests are known to store large quantities of C, which was one of the reasons to include them in the Kyoto Protocol (UNFCCC, 1997; Nabuurs, 2008). Therefore, they have the greatest potential for mitigating atmospheric $CO_2$ emissions (Brown, 1997; Munishi *et al.,* 2000; Munishi, 2001; Munishi and Shear, 2004). The amount of C stored in the forest stand depends on its age and productivity (Gurney, 2008), and species composition (Munishi, 2001; Munishi and Shear, 2004). According to Kumar (2002), a young forest, when growing rapidly, can sequester relatively large volumes of additional $CO_2$ roughly proportional to the forest growth in biomass or C stock. But due to variation of C sequestration capacity by age, species and forests type, field measurement for estimation of biomass and total C storage for specific forests ecosystem are essential (Munishi, 2001).

Allometric model for estimation of volume and biomass varies between sites and species as a function of growth conditions and tree species composition. Efforts to develop allometric equations have been increasingly in recent years in the Tropics from global to local allometric equations (Brown, 1997; Chave *et al*., 2005). The use of global allometric equations can lead to significant errors in vegetation biomass estimations compared to local equations (Brown *et al*., 1989; Chave *et al*., 2005; Heiskanen, 2006). Furthermore, developers of these equations often caution against extrapolation beyond their study areas (Navar, 2002; Chave *et al.,* 2005). In addition, the available allometric equations for quantification of root systems are limited to a few tree species and are not be available for many trees (Chavan, 2010).

In Tanzania, one model has been developed to quantify the amount of C and biomass for Teak in Mtibwa Plantation forest (O'kting'ati *et al*., 1998). Despite of the presence of allometric models for estimation of biomass in Teak in the country, yet the model cannot be used in wide range of diameter classes, ages, site classes, elevation and soil type because of the following reasons. First, the allometric model was developed from small samples (i.e. 12 sample trees). Secondly, the sample covered a narrow diameter range (17 – 42.5 cm) that excluded small or bigger trees, which means that in practice the model often must be applied beyond their valid diameter ranges. Thirdly, the model was based on plantation of 22 and 30 years of age which is about half rotation age by then. Although there are well documented biomass models for teak elsewhere e.g. general biomass model for tropical forests in which the Teak is inclusive in Africa (Brown, 1997; IPCC, 2003; FAO, 1997; Chave *et al*., 2005), India (Buvaneswaran *et al.,*2006; Siregar, 2012), Ghana (Assomaning, 2006), Australia (Eamus, 2000), their applications in Tanzania are limited due to differences associated with altitude, soil type (Brown and Lugo, 1992; Tuomisto *et al.,* 1995; Slik et *al.,* 2010; Baraloto *et al.,* 2011; Laurance *et al*., 1999), topographic position (Austin *et al*., 1996; Macauley *et al.,* 2009), disturbance regime (Lugo and Scatena, 1996), age of tree (Kumar, 2002; Alexandrov, 2007), provenance (Macauley *et al.,* 2009), and climatic conditions (Gentry, 1982; Girardin *et al.,* 2010).

This suggests the need for development of local reliable biomass models for both above and belowground for Teak that can account for the biomass variation as a function of diameters, age classes, site classes and height. The developed biomass models will enhance decisions by forest managers when developing management plan. In addition, the developed biomass models are important for the emerging C credit market mechanism such as Reducing Emission from Deforestation and Forest

Degradation (REDD+), and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks and Clean Development Mechanism (CDM). The core idea of REDD+ is the role of conservation, sustainable management of forests and enhancement of forest C stocks at multilevel (global-national-local) system through payments for environmental services (PES).

Furthermore, volume models which are able to quantify merchantable tree volume and total volume are also required when trees are warranted for commercial purposes. Similar shortcomings stated for previous developed biomass models also apply to volume models. Since the previous volume models (Malimbwi *et al.* (1998) and Van Zyl (2005)) may either underestimate or overestimate volume thus subject to uncertainty of benefits to a seller or a buyer.

This study was carried out at Longuza teak plantation which has a wide range of tree ages, site classes, diameter classes and altitudes. Studies across broad ranges of growth conditions are particularly valuable because they provide broad range of biomass and volume variations which may result into reliable biomass or volume models.

## 1.3 Research Objectives

### 1.3.1 Main objective

To develop volume and biomass estimation models for Teak at Longuza forest plantation in Tanzania

### 1.3.2 Specific objectives

i) To develop models for estimating volume of Teak.

ii) To develop models for estimation of above and below ground biomass of Teak.

iii) To compare biomass estimates computed from developed biomass model and the estimates derived from developed volume equation by Malimbwi *et al.* (1998).

iv) To determine forest structure attributes (stand volume, biomass, basal area and trees per ha)

# CHAPTER TWO

## 2.0 LITERATURE REVIEW

### 2.1 History or Introduction of Teak in Tanzania

Teak is a large sized deciduous tree indigenous to the greater part of Burma, the Indian peninsula and west parts of the Thailand and Cambodia (O'kting'ati *et al.,* 1998). It is a tree species growing in moist and dry tropical regions at elevation between sea level and 1300 m above sea level. The first recorded planting of Teak in Tanzania was done by Germans in 1898 using seeds from Calcutta which were planted at Dar es Salaam and Mhono in the Coast region (Wood, 1967). Thereafter seeds from Java, India and Thailand were distributed to many lowland stations in the country and were planted in field trial plots (Wood, 1967). Large scale planting of Teak in Tanzania started in 1960/61 at two sites, Longuza forest project in Tanga region and Mtibwa forest project in Morogoro region. The Longuza forest plantation was established by the colonial British government in 1952 as a gap planting activity to replace the exploited species in the natural forest. In 1961, the Forest Department was forced to drop the idea of gap planting and replaced it with the growing of fast growing hardwood species like Teak in order to meet the supply of wood material to satisfy the rapidly increasing local and export wood demands.

### 2. 2 The Role / Function of Forests

The forests (natural and plantations) are habitat for different biodiversity with a wide range of both socio-economic and ecological values. The forests are keys in sustaining the biodiversity of natural ecosystems and in regulating the world's climate system (Chidumayo *et al*., 2011). Moreover, forests comprise an important

C reservoir, since they store about twice the amount of C present in the atmosphere (Canadell and Raupach, 2008). Recently, adverse impacts of change in climate on the environment, human health, food security, human settlements, economic activities, natural resources and physical infrastructure are already noticeable in many countries, including Tanzania (Chidumayo *et al*., 2011). Forests contribute to climate change mitigation by removing atmospheric $CO_2$ and storing it in different C pools (*i.e*., biomass, soil, dead organic matter, litter) (IPCC, 2006).

The ultimate objective of The United Nations Framework Convention on Climate Change (UNFCCC), in which Tanzania is a member, is to stabilize the atmospheric GHG concentrations at the level that will not cause dangerous anthropogenic interference with the climate system. There are two alternatives to reduce $CO_2$: decreasing C source and increasing C sink. Forests are known to be a major C sink that store large quantities of C (650 billion tons of C, 44% in the biomass, 11% in dead wood and litter, and 45% in the soil (FAO, 2010)), which was the one of the reasons for forests to be included in the Kyoto Protocol (UNFCCC, 1997; Nabuurs, 2008). Therefore, forests have the greatest potential for mitigating atmospheric $CO_2$ emissions (Munishi *et al,* 2000; Munishi, 2001; Munishi and Shear, 2004).

Forests are major renewable natural resource on the earth and provide a wide range of economic, social, environmental, and cultural benefits. The world forest survey of 2010 has noted that the planted Teak forests are predominantly young due to increase plantations from 95 million to 153 million since 1990 (FAO, 2010). The prevailing age class distribution in the world is an indication of increased efforts to establish and manage planted Teak forests in the past 20 years and this pattern is very likely to persist in the future (FAO, 2010). Forest plantation establishment and ecosystems management practices can play a significant role in climate change mitigation if they are managed for such purposes.

## 2.3 Tree Volume

Volume estimation is necessary for understanding different utilization standards. For plantation forests, many growth and volume studies have been previously done with a focus on merchantable volume (Malimbwi, 1987; Malimbwi and Mbwambo, 1990; Malimbwi *et al*., 1998). Tree volume provides valuable information on supply of both industrial wood and hence identifying sustainable management of forests and woodland ecosystems (Chamber *et al.,* 2001, Mugasha *et al.,* 2012). Furthermore tree volume provides information about health and value of a given stand. The volume values reported by various studies at different Teak ages includes the study at 2 years old Teak by KFRI (2011) with volume value ranging from 1.87 - 6.57 $m^3$/ha, at age of 5 years by Perez and Kanninen (2005) in Costa Rica the values was 28.4 - 32 $m^3$/ha, by Perez (2005) at age of 16 volume of 420.33 – 466.35 $m^3$/ha and at 40 years by KFRI (2011) of about 236 $m^3$/ha. A study by Zambrana (1998) estimated the volume at age of 4, 10, 17 and 25 years by using volume equation to be 22 $m^3$/ha, 89 $m^3$/ha, 159 $m^3$/ha and 214 $m^3$/ha respectively. Furthermore, on study by Picado (1998) in Costa Rica estimated the volume of 48.59 $m^3$/ha, 140.04 $m^3$/ha and 198.87 $m^3$/ha at age of 8, 15 and 20 years respectively. Therefore, appropriate methods and approaches to quantify the stand volume is mandatory at different age classes and site since volume varies with location, silvicultural operation, site classes and age.

## 2.4 Tree Biomass

Forests in particular play a key role in C cycle and in maintaining climatic balance. Forests and woodlands are important C sinks and sources containing majority of the above ground terrestrial organic C. International negotiations to limit greenhouse gases require understanding of the current and potential future role of forest C emissions and sequestration in both managed and unmanaged forests (Pan *et al*., 2011). Tanzania has reported an average C stock value of 60 t C/ha in living forest biomass (FAO, 2010). The forests in Tanzania can also be used for climate change mitigation if are well managed. The Kyoto Protocol (KP) of UNFCCC was developed as an attempt to confront and begin to reverse the rising $CO_2$ concentrations (Pearson and Brown, 2005). The KP was adopted in 1997 and entered into force in 2005 with establishment of innovative mechanisms to assist developed countries to meet their emissions commitments (UNFCCC, 2007). The Protocol created a framework for the implementation of national climate policies, and stimulated the creation of the C market and new institutional mechanisms that could provide the foundation for future mitigation efforts (Geoff, 2009). The Protocol has flexible mechanisms through which developed countries can achieve their emissions reduction commitments (Chidumayo *et al.,* 2011). These include Emissions Trading, Joint Implementation (JI) and the CDM. Of interest to African forestry is the CDM which allows developed countries to invest in green projects that reduce C emissions in Africa and other developing countries (UNFCCC, 2007).

The CDM is an arrangement under Article 12 of the KP of the UNFCCC (UNFCCC, 2007). The purpose of the CDM was to assist developed countries in achieving sustainable development and in contributing to the ultimate objective of the convention, and to assist developed countries in achieving compliance with their quantified limitation and reduction commitments (UNFCCC, 2007). This allows developed countries with a GHGs reduction commitment and developing countries to jointly undertake emission reduction project activities in developing countries that contribute to sustainable development and result in certified emission reduction (CER) (UNFCCC, 2007). The C market aims to decrease emissions of GHGs which scientific evidence shows in all likelihood to be contributing to global warming and climate change. The selling of C credit obtained from afforestation and reforestation project was seem to be one of the incentives to motivate local community to be involve in climate change mitigation. C credits earned via conservation are best suited for trade in the voluntary C market where buyers place high value on the sustainability of a project, often paying a premium for C removal which provides benefits for rural livelihoods. C credits are the unit of trade used in the C market, where one C credit represents one ton of $CO_2$ that has been removed from the atmosphere or has been prevented from entering the atmosphere (IPCC, 2003). However, the key requirement of C trading mechanism is the availability of individual tree biomass equations to facilitate the computation of baseline and the change of C. The Voluntary Carbon Standard (VCS) follows the format of CDM but does not require authorization by the host country which greatly reduces transaction costs. Currently there are few projects (example Kilombero Teak Company) registered under CDM in Tanzania with challenge of quantifying C using a general equation developed from other nations.

## 2.5 Methods of Estimating Tree Volume and Biomass

### 2.5.1 Tree volume estimation

There are two methods for tree volume estimation in forest plantations namely destructive methods and non-destructive methods. Destructive method is very common approach for estimating volume of standing trees. This method involves felling of sample trees measuring the length and mid diameter of the different components of the harvested trees like tree stem and branches (Malimbwi *et al*., 1998). Due to differences in allometry and tree architecture, species specific volume models are often preferred (e.g. Ketterings *et al.,* 2001). The total tree and merchantable volume in the study area had been developed by Malimbwi *et al.* (1998). However, accurate computation of volume at the final harvest depends largely on the availability of individual tree volume equations. With increasing demand and availability of Teak, it is essential to develop appropriate volume allometric models in order to quantify the amount of poles, lumber, firewood and other wood products in terms of volumes for efficient pricing and utilization of wood from juvenile wood to mature wood. Volume estimation models provide valuable information on supply of both industrial wood and hence identifying sustainable management of forests and woodland ecosystems (Chamber *et al.,* 2001, Mugasha *et al.,* 2013a). Malimbwi *et al.* (1998) developed equation for estimation of Teak volume with a narrow range of tree diameter (5 – 65 cm).

Non-destructive method involves the multiplication of the tree basal area by the tree height and form factor (e.g. Munishi and Shear, 2004). Form factor is one method for harmony a relation between tree form and volume and is defined as the ratio of tree real volume to volume of one geometrical form such as cylinder, cone and or truncated cone that its diameter and height are near to tree (diameter of geometrical from is equal to diameter at breast height and its height is equal to tree height). Volume obtained from this way has the advantage of getting quick results but suffer the problem of accumulated error resulting from the prediction of height. The study on form factor was done by Malimbwi *et al.* (1998) at Mtibwa and Longuza forest plantation during development of volume equation. Also, a number of studies have reported standing volume of teak by using non destructive and destructive methods. For example teak standing volume estimated by volume equations have been reported by Hamzah and Mohamed (1994) for Mata Ayer in Malaysia; by Chakrbarti and Gaharwar (1995) for Karnataka, Madhya Pradesh, by Moret *et al.* (1998) for Venezuela; by Nunifu and Murchinson (1999) for northern Ghana and by Phillips (1995) in Sri Lanka.

### 2.5.2 Tree biomass estimation

There is no single method for estimating biomass stocks, but there are number of methods depending on the scale accuracy considered (Gibbs *et al.,* 2007). There are two main common methods for estimation of biomass namely ground based and remote-sensing. Ground based biomass can be either aboveground or both above and below ground biomass estimation. The above and below ground biomass estimation can either be destructive or non-destructive methods. The non-destructive method estimates biomass as a product of volume and wood basic density where tree volume is a function of basal area and tree total height. Non-destructive method also may involve remote sensing technology. The remote sensing methods provide broad geographic coverage; they are reliant on good quality of ground-truthing data for calibration and verification (Mitchard *et al.,* 2011).

The destructive sampling involves falling and excavating of tree, crosscutting into manageable size, weighing the billets as well as roots, taking samples for oven dry to fresh weight determination and finally establishing the relationship between dry weight of tree and easily measurable tree parameters such as basal area, diameter at breast height (Dbh), height or both. The destructive method is believed to produce high accuracy in estimating the tree biomass (Brown, 1997; Seifert and Seifert, 2013). Also, it has been established that site and species specific biomass estimates, obtained from locally developed equations provide estimates of C with greater certainty (IPCC, 2006); that is why biomass equations for specific species and site specific need to be developed.

#### 2.5.2.1 Biomass estimation from allometric equation

The most common procedure used for estimating individual tree biomass is to relate biomass and easily measurable tree parameters by means of regression equation (Brown, 1997). Biomass non-linear or linear equations are usually fit using least squares estimates of regression parameters where the candidate models are selected first. Before a model is accepted for further analysis, its variance ratio must be significant at the chosen level of probability and plot of residuals must have constant variance and no bias. Similarly a plot of measured against estimated biomass should show no bias. However, according to Canadell *et al.* (1996), Levang-Brilz and Biondini (2002) and Jackson *et al.* (1996) there are no current models for predicting belowground biomass based on measurements of aboveground biomass across diverse species. Allometric models for estimation of biomass and C stored in different forests and woodlands are still uncertain in developing countries due to lack of specific allometric models for biomass estimation (Chave *et al.,* 2005; Houghton, 2005). Also, it has been established that site and species specific biomass and C stock estimates, obtained from locally developed equations provide estimates of greater certainty (IPCC, 2006). There has been an effort to establish the Teak allometric model in Tanzania. A study conducted by O'kting'ati *et al.,* (1998) on the potential of *Tectona grandis* at Mtibwa to act as a C sink found that *Tectona grandis* stored between 595 ton $CO_2$/ha and 844 ton $CO_2$/ha. The strength of the study conducted by O'kting'ati *et al.,* (1998), is that biomass estimates were based on site and species specific equations; both belowground (roots) and aboveground tree components (stem, branches, twigs and leaves) were included in the study. Biomass and C stocks estimation equations developed for *Tectona grandis* in Mtibwa forest plantations by O'kting'ati *et al.* (1998) have a number of shortcomings. First, they were developed from a small sample (i.e. 12 sample trees), cover narrow range of diameters (17 - 42.5 cm), data covering limited variation regarding growth condition, silvicultural treatments and exclude large trees as well small trees (young trees). According to Brown and Lugo (1992) the regression equations must include wide range of tree size to represent all variation of biomass from the smallest tree diameter to the largest tree diameter. From these facts, site specific and species specific is needed covering wide range of tree size to quantify the biomass of Teak in Tanzania. These equations are of great importance for the estimation of tree biomass and then to estimate forest C stock and C stock changes. The quality of these equations is crucial for ensuring the accuracy of forest biomass and C estimates in the plantation.

#### 2.5.2.2 Biomass estimation from tree volume

The total biomass estimated from tree volume uses basic wood density (BWD), biomass expansion factor (BEF) and root to shoot ratios (RSR). These parameters are essential in estimating the total tree biomass without destroying trees. The BWD defined as the ratio of oven dry mass and its fresh stem wood volume without bark (IPCC, 2006). The BWD is an essential component for estimating forest C stocks as it varies among tree genus and species (Chave *et al.,* 2006). The BWD of Teak was determined by O'kting'ati *et al.* (1998) in Mtibwa forest plantation and Sibomana *et al.* (1997) in Longuza forest plantation. The study by O'kting'ati *et al.* (1998) was based on Teak aged 22 and 30 years with BWD of 0.52 - 0.54 $gcm^{-3}$. The study by Sibomana *et al.* (1997) in Longuza forest plantation at age of 14 years recorded BWD of 0.525 – 0.587 $gcm^{-3}$. Another study by Izekor *et al*. (2010*)* in Malaysia at age of 15, 20 and 25 years found the value of BWD of 0.48 $gcm^{-3}$, 0.56 $gcm^{-3}$and 0.65 $gcm^{-3}$ respectively indicating the BWD varying with age, site class, location, soil type, silvicultural operation and slope. Consequently, IPCC recommended development of BWDs that reflected the influence of regions and ages (IPCC, 2006).

The BEF is computed by dividing total biomass of aboveground tree components (stem, branches and twigs) to biomass of stem (Brown, 1997). Essentially, BEF is used to estimate biomass of other parts which are not covered during biomass measurement. The BEFs from inventories in tropical Asia, America, and Africa were reported to be 1.1 and 2.5 (Brown and Lugo 1992;, 1997). The BEF differs between sites (Wirth *et al*., 2004) and ages (Lehtonen *et al.,* 2004). The mean value for the BEF of Teak was ranging from 1.4 - 1.8 (Sengura and Kanninen, 2004). The value for BEF given by Guendehou *et al.* (2012) at Teak of 3 - 15 years was between 1.28 and 1.46. From these studies it is very clear that BEF varies with age and site and hence it is better to find the BEF across various ages found in the study area.

The RSR is obtained by dividing biomass of total belowground tree components to biomass of total aboveground tree components. The value of RSR of Teak reported by Brown (1997) is 0.20 and Perez and Kanninen (2003) ranges from 0.11 - 0.23 for 20 years old teak. This finding showed the variation of RSR with tree age with the highest value for young age and the lowest value for old Teak. Although other authors, such as Cairns *et al.* (1997) and Mokany *et al.* (2006) did not find any differences between groups of species in RSR (softwood and hardwood) and they give a value of 0.26. Pearson and Brown (2005) observed that the RSR varies with age in which the young tree had shown to have large value of RSR in comparison to the old tree. Further study by Hase and Forster (1983) observed that the RSR decreased in value with increase in tree age from 0.42 at age of 4 years to 0.20 at age 9 years. In Tanzania no studies had been done for computation of RSR across various ages of Teak.

## 2.6 Other Stand Parameters

The estimation of other forest parameters are often carried out to describe characteristics of forest plantation during study time. Basal area is a useful measure of stocking. Basal area is defined as the sum of cross-sectional area measured at breast height of all trees in a stand, expressed as $m^2ha^{-1}$. Furthermore, basal area provides other information needed for tending operations such as whether or not thinning should be conducted. A study conducted by Sunanda and Jayarame (2006) at age of 2 and 42 years observed the basal area was ranging from 0.3 $m^2ha^{-1}$ to 51.98 $m^2ha^{-1}$ on young Teak of one year to old Teak stand. Further, study by Robertson and Reilly (2005) on performance of 14 and 16 year old Teak found the basal area ranging from 8.4 to 14.2 $m^2ha^{-1}$ at age of 14 years and from 9.1 to 14.5 $m^2ha^{-1}$ at age of 16 years. The number of stems per hectare, (N) is a useful parameter for defining stocking if it is accompanied with information on age, mean height or diameter. The manipulation of the number of stems per ha through thinning can be used to control the growth of individual trees for provision of tree sizes for specific utilization standards (Malimbwi, 1997).

# CHAPTER THREE

## 3.0 MATERIALS AND METHODS

### 3.1 Location of the Study Area

Longuza Forest Plantation has total area of 2 449 ha. Out of this area 1809.8 ha is plantation forest and 639.2 ha is under natural forest. It is situated 17 km from Muheza town and 52 km from Tanga port on the Eastern foothills of the East Usambara Mountains, which is Amani Nature Reserve and part of the Eastern Arc Mountains between latitudes 4º55' and 5º10' South and Longitudes 38º 40' and $39^0$ 00' East. The mean annual rainfall for Longuza plantation is about 1500 mm with a mean annual temperature of about $27^0$C (Van Zyl, 2005; Ngaga, 2011).

Longuza Forest plantation lies at altitudes between 160 and 560 meters above sea level (Sibomana *et al.* 1997; Van Zyl, 2005; Ngaga, 2011). The plantation is covered geologically by the Usambara rocks which are Pre – cambian and assigned to old Usagara basement complex system. The crystalline rocks underwent several cycles of folding, metamorphism and finally migmatization (Van Zyl, 2005; Ngaga, 2011). The soil is dominated by loam soil which is easily accessible to cultivation (Malimbwi *et al*, 1998; Ngaga, 2011). The dominant species in natural vegetation include *Khaya anthotheca, Newtonia paucijuga, Albizia gummifera, Combretum schumanni, Brachystegia* sp., *Isoberlinia* sp., *Pterocarpus angolensis, Milicia excelsa*, *Antiaris* sp., *Zanha* sp., *Sterculia* sp. and *Acacia* sp. (Sibomana *et al.* 1997; Van Zyl, 2005).

## 3.2 Structure of the Plantation

### 3.2.1 Management units

The forest plantation is managed in units of different sizes, ages and species, which are known as compartments. There are three ranges/blocks namely Kihuhwi/Kwamsambia (KH); Kihuhwi - Sigi (KS) and Longuza/Bulwa (LG). Each range/block is subdivided into compartments and these compartments are numbered 1, 2, 3 etc. The planted area for Teak is about 1709.8 ha and the rest of planted area is planted with *Teminalia sp., Cedrella sp.*, *Mellia azadirach* and *Milicia excela* (LFMP, 2013). The plantation is divided into three site classes namely KS being site class I of about 553.2 ha, KH in site class II of about 592.6 ha and LG in site class III having 564 ha. Each range/block was subdivided into compartments having trees with different ages. There are research plots established by TAFORI and SUA located within the forest plantation. These include Kihuhwi seed stand of about 31.6 ha planted in 1906, International teak provenance at Kihuhwi/Sigi planted in 1960, hardwood arboretum situated in Bulwa having 68 different trees species and spacing trial planted in 1996 and 1998 respectively.

### 3.2.2 Age distribution and status of the plantation

The Teak plantation is dominated by Old aged Teak (Over half of the area). The age distribution of the plantation is not normal, which means the forest age is not normally distributed. The plantation has more area (more than half of the area planted Teak) for old trees greater than 20 years than young trees. Most of the compartments have trees with good form except, those compartments which were not tended in the past due to lack of funds. The health of forest stand is good except there are few deaths of trees in some compartments due to maturity.

## 3.3 Data Collection

### 3.3.1 Reconnaissance survey

Reconnaissance survey was carried out for deciding number of plots per each compartments and to eliminate those compartments which were impractical or unfeasible.

According to Chave *et al.* (2004), the number of sampling plots should be determined based on area and homogeneity of vegetation. So in this study; stratified sampling design was used in which the plantation was classified into six strata according to age and site classes. These strata were 1-5 years, 6-10 years, 11-15 years, 16 -20 years, 21-25 years and greater than or equal to 26 years. All strata were having all site classes (KS site class I, KH site class II and LG class III) found in the plantation.

Random sampling was employed in the selection of strata because there were several compartments having the same characteristics of interest in the study area. The total number of plots in each stratum was determined by estimating basal area using relascope in which a minimum of 15 sweeps were done in each stratum and the number of plots was obtained using equation 1.

$$n = cv^2t^2/E^2 \qquad \textit{(Equation 1)}$$

Where:

$n$ = number of plots; $cv^2$ = coefficient of variation (standard deviation/sample mean); $t$ = value of t obtained from n-1 degrees of freedom of the preliminary study at 5 % probability in the t table and $E$ = sampling error of 10 %.

In KS compartment 3ci, due to small number of surviving trees and concentrated to only small area of the compartment (1.3 ha), the use of sweeps resulted into overlapping of the sweeps which give greater number of plots while the area is small. Therefore, the use of the following formula was applied to get total number of plots in that compartment:

$$N = (A \times E) \div a \qquad \textit{(Equation 2)}$$

Where:

n = Number of plots, A = Area of the compartment, E = Sampling error (10 %) and a = plot size. In this study the allowable error of 10 % was used to get number of sample plots. The total number acquired from this compartment was 3 plots at 10 % allowable error.

### 3.3.2 Data for biomass and volume

For the compartments having the same age, only one compartment was selected randomly so as to get a representative for a particular stratum. Systematic sampling was used whereby the first plot was selected randomly and the rest were laid out systematically at regular or equal intervals. The plot (circular of 0.025 ha or 8.92 m radius for volume and biomass stock estimation) was laid along transects lines at regular intervals at inter plot distance ranging from 60 m to 140 m and distance between transect lines ranged from 70 m to 180 m depending on the area of the strata. The circular plots were preferred because they are quick to establish and efficient in allowing accurate area sampling with minimal effort. In this study, the number of plots adopted aimed for a sampling error of 10 % at a 95% confidence level and 98 plots were surveyed in seven compartments (KS 3ci (1.3 ha), KS3cii

(3.1 ha), KS 5 (53.7 ha), KH1A (60.9 ha), KH9 (10.9 ha), LG58B (4.4 ha) and LG11A (10 ha)) covering the youngest stand (2 years) up to the oldest stand (46 years) found in the forest plantation. In each plot, all trees were measured for Dbh and only three trees (large, medium and small diameter) were measured for total height. Other recorded data describing the plot were: altitude, slope, soil type, plot coordinates and age (see Appendix 1 data collection form).

### 3.3.3 Destructive sampling for biomass and volume models

A total of 51 trees were selected purposively for model development and validation (Table 1). The selected trees cover the diameter distribution in Longuza forest plantation from 1 cm to 83.4 cm. The selection of trees for destructive sampling was based on measured diameter for all the trees in the 98 sample plots. The inventory data were distributed into eight diameter classes starting from 1-10 cm, 10.1-20 cm, 20.1-30 cm, 30.1-40 cm, 40.1-50 cm, 50.1- 60 cm, 60.1-70 cm and greater than 70.1 cm. The number of trees sampled was determined based on the ratio of trees within each diameter class, while for the larger diameter of > 50 cm, at least five to six trees were sampled.

**Table 1: Statistical summary for number of sample trees (n), diameter at breast height (Dbh) and height (ht) of sample trees**

| n | Dbh (cm) | | | | Ht (m) | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Min. | Max. | SD | Mean | Min. | Max. | SD |
| 51 | 37.40 | 1 | 83.4 | 24.53 | 25.65 | 1.5 | 37.50 | 11.00 |

In each diameter class, trees were selected to cover all three site classes found in the plantation e.g. diameter class ranging from 1 - 10 cm had a total of 8 trees with distribution of three trees from site class I, three trees from site class II and two trees from site class III. The trees for destructive sampling were measured for Dbh, total height and root collar diameter (15 cm height from the ground) before felling and then felled. Total tree bole height was measured again on the felled tree to ensure accuracy. The standing height before felling was used as independent variable in model development. Stems (including branches) were trimmed and cross cut into manageable billets ranging from 27 cm to 270 cm depending on taper and weight. The branches were classified into three classes (Large branch with mid diameter > 10 cm, medium branch size with mid diameter < 10 cm to > 5 cm and small branch with mid diameter ≤ 5 cm to 2 cm). In order to minimize the effect of taper, the billets with almost equal bottom and top diameters were measured for mid diameter. Three small samples i.e. one at Dbh, one in the middle of the tree and last one near the top of the stem from bark to pith were extracted. Three samples i.e. one from large branch, one from medium branch and one from small branch were extracted. Twigs and leaves were collected and tied into bundles and were weighed for fresh weight. Two small samples (of about 2 cm thickness) and one sample with three to four leaves were taken.

For below ground components (see Figure 1) once excavated, the main belowground components were treated as follows:

(a) Stump/root crown was cleaned from soil, weighed for fresh weight and two samples were taken for dry weight determination in the laboratory.

(b) All broken roots (roots not excavated) were measured for base diameter at breakage point on the root crown.

(c) From each sample tree, 3 main roots (small, medium and large) were selected and traced to minimum diameter of 1 cm. The sampled roots were detached from root crown and base diameters were measured and weighed. All sampled roots were weighed for fresh weight. When main roots enter obstacles (stone or another tree), the end point diameter was measured. One sample from large root, one sample from medium root and one sample from small root were taken for oven dry weight determination in the laboratory. For main root with side roots, three side roots were selected and traced to minimum diameter of 1 cm and weighed for fresh weight while other side roots were measured for base diameters. Three samples from side roots covering small, medium and large roots if present were taken for oven dry weight determination in the laboratory.

All billets from stems, branches, sample roots and tied bundle of twigs and leaves were measured for weight. Also samples from stem, branches, twigs and leaves as well as from belowground were labelled and measured for fresh weight using electronic balance. Finally all samples were taken for further analysis in the laboratory.

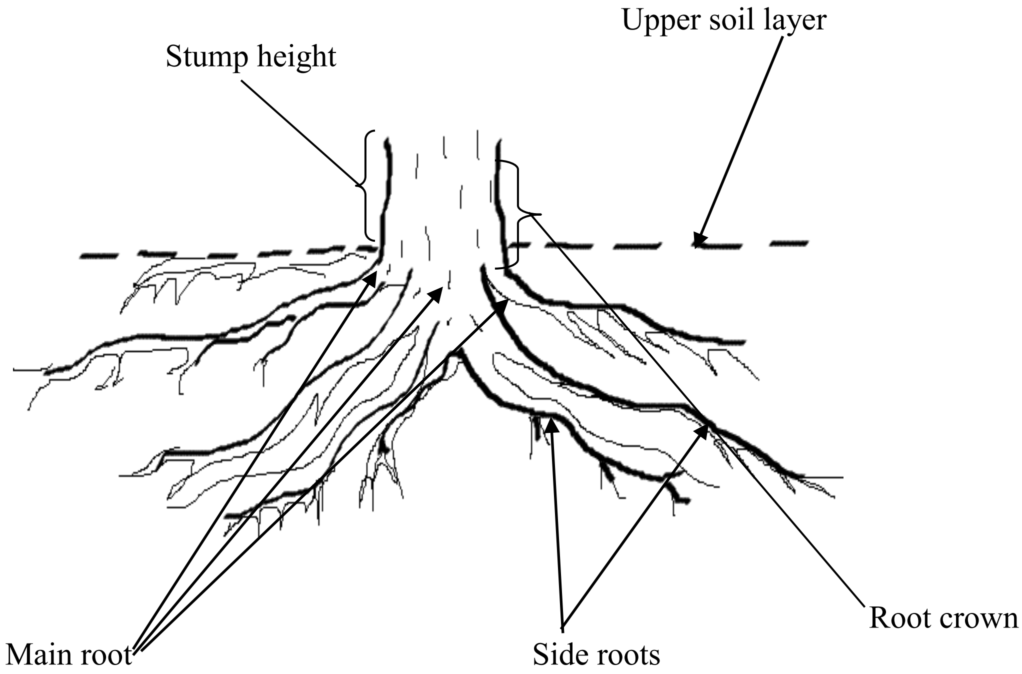



**Figure 1: The tree below ground components**

### 3.3.4 Laboratory work

The collected samples except parts with some leaves were soaked for about eight to ten days until they attained constant weight. Then fresh volume of each sample was determined by water displacement method. Water displacement method minimizes the error in estimating the volume of the disk. The samples for stem and branches were put in oven and dried to constant weight at 103 °C for 72 to 96 hours and then measured for dry weight. The root samples were oven dried to constant weight at 78 °C to 80 °C for 72 hours. The twigs and leaves were dried at 60 to 65 °C for about 48 hours and measured for dry weight.

## 3.4 Data Analysis

### 3.4.1 Tree volume data preparation

The individual billet volume of respective tree section (stem and branches) were calculated using Huber's formula (Loetsch *et al.,* 1973). The sum of all billets of similar tree component were computed. The tree top volume was determined by using cone formula. Because it was difficult to measure the volume of twigs (< 2 cm in diameter), the total tree volume equation did not consider the volume of twigs. Total individual tree volume was obtained as the sum of tree stem, branches and cone volume as follows:

$V_{tot} = V_{stem} + V_L\text{-}branch + V_m\text{-}branch + V_S\text{-}branch + V_{cone}$ *(Equations 3)*

Where:

$V_{tot}$ = Total tree volume ($m^3$), $V_{stem}$ = volume of a stem ($m^3$), $V_L$-*branch* = volume of large branch ($m^3$), $V_m$-*branch* = volume of medium branch ($m^3$), $V_S$-*branch* = volume of small branch ($m^3$) and $V_{cone}$ = volume of tree top ($m^3$).

Individual total tree volume (stem + branch) and stem volume (stem without branches) was computed at three minimum diameter limit i.e. 2 cm, 5 cm, and 10 cm.

### 3.4.2 Tree biomass data preparation

The biomass of each tree sections (stem, branch and twigs and leaves) was calculated as a product of its total fresh weight with its respective ratio of oven dry weight to fresh weight. The total tree aboveground biomass was computed as the summation of dry weight from stem, branch, and tied bundle of twigs and leaves.

For belowground section, the ratio of oven dry to fresh weight from side roots was multiplied by fresh weight of total side root. The models were developed using their total side root biomass through regressed with their base diameter using PROC NLIN, a procedure in SAS software (SAS Institute Inc., 2004) to compute models parameters. There are two forms of models subjected to this stage having only diameter as parameter for finding its parameter estimates. The best model was selected by examining p-values (significant at p-value < 0.05), the mean square error (MSE), the coefficient of determination ($R^2$) and percentage mean prediction error (*e %*). The side roots model developed was used to estimate unexcavated side roots from sampled side roots. The side root model was:

$$\boldsymbol{B = 0.1482D^{1.4822}} \qquad \textit{(Equation 4)}$$

Where:

*B* = Side root biomass (Kg); *D* = Side root base diameter (cm) (e% = 2.56, MSE = 0.76 and $R^2$ =0.71).

The total main root biomass was obtained as the summation of side root biomass (excavated and unexcavated) and the biomass of the sampled main root. Similar procedure was done for the best model selection as for side root. The main root model was used to estimate the biomass of unexcavated roots from root crown. The main root model was:

$$\boldsymbol{B = 0.1005 \times D^{1.6468}} \qquad \textit{(Equation 5)}$$

Where:

B = Main root biomass (Kg); D = Main root base diameter (cm) (e% = 0.30, MSE = 11.73 and $R^2$ =0.81). All *e*% for both side root and main root were found to be non significant at 5%.

The total below ground biomass was given as the summation of biomass from three sampled main roots biomass (all side roots, three sample roots), biomass from unexcavated main root roots and biomass from root crown.

### 3.4.3 Model development, selection and evaluation

The four general forms of models (two model forms include Dbh only and two other models include both Dbh and height) were fitted to tree volume and biomass. The model forms were as follows:

$B/V = a \times Dbh^b$ *(Equation 6)*

$B/V = a + b \times Dbh + c \times Dbh^2$ *(Equation 7)*

$B/V = Exp\ (a + b \times ln\ (ht \times Dbh^2))$ *(Equation 8)*

$B/V = a \times Dbh^b \times ht^c$ *(Equation 9)*

Where:

*B* = Biomass (Kg), *V* = Volume in ($m^3$), *Dbh* = diameter at breast height (cm), *ht* = total tree height (m) and *a*, *b* and *c* are model parameters.

Volume of 51 (see Appendix 2) were used for volume model development and similar trees biomass (above ground and below ground) was used for biomass model development. All tree volumes and tree biomass were fitted by using PROC NLIN, a procedure in SAS software (SAS Institute Inc., 2004) to compute models parameter. The candidate model was selected by examining p-values (significant at p-value < 0.05), the mean square of the error (MSE), the coefficient of determination ($R^2$), percentage mean prediction error (*e %*) and by plotting the residuals (observed minus predicted values) against Dbh. For the good candidate model, the mean prediction error should not differ from zero so that the prediction is unbiased.

The study aim to select two candidate models i.e. one candidate model with Dbh only and the other candidate model with Dbh and ht.

The candidate models were further evaluated by using Akaike Information Criteria (AIC) which takes account of number of parameters the model has and the equation is given as follows:

$$AIC=-2logL+2p \qquad \textit{(Equation 10)}$$

Where:

$p$ = parameters and $L$= Log of likelihood

The AIC is used as final decision for selection of the best model in this study (Chave *et al.,* 2005; Basuki *et al.* 2009; Marshall *et al.* 2012; Mugasha *et al.* 2013b). The best model was the one with lowest AIC in comparison with other models under evaluation.

### 3.4.4 Height diameter model development

In this study three trees (large, medium and small diameter) were measured for height as sample trees in each plot. Six general models from Mugasha *et al.* (2013b) (see Appendix 3) which were non-linear models for *ht-dbh* relationship were fitted. The NLIN procedure (Non Linear Programming) in SAS software (SAS Institute Inc., 2004) was used to estimate the model parameters. The model selection and evaluation follows similar approach as for volume and biomass model. The best height model is given by:

$$ht = 1.3+29.1579\times[exp\ (-3.0280\times exp\ (-0.1078\times Dbh))] \qquad \textit{(Equation 11)}$$

Where:

*ht* = total tree height (m) and *Dbh* = Diameter at breast height (cm)

(e % = 0.90, MSE = 10.75, $R^2$ = 0.902)

The best height estimation model was used to estimate the unmeasured tree height in the sample plot. The height computed was used in computation of biomass using the biomass model with both model parameters (Dbh and ht).

### 3.4.5 Evaluation of previous merchantable volume to estimate tree biomass

In order to arrive at total tree biomass for teak, normally it has been computed as a function of merchantable volume, basic wood density (BWD), biomass expansion factor (BEF) and root to shoot ratio (RSR). The equation is as follows:

$$TB = V \times BWD \times BEF \times (1+RSR) \qquad \textit{(Equation 12)}$$

Where:

*TB* = total biomass (kg); *V* = merchantable stem volume ($m^3$) ($-0.0761 + 0.000906 \times Dbh^2$) (Malimbwi *et al.,* 1998),

*BWD* = basic wood density computed as ratio of oven dry weight to green volume of samples of wood discs ($kgm^{-3}$);

*BEF* = biomass expansion factor (computed by dividing total biomass of aboveground tree components (stem, branches and twigs) to biomass of stem),

*RSR* = root-to-shoot ratio computed as a ratio of biomass of total belowground tree components (root crown, main roots and side roots) to biomass of total aboveground tree components (stem, branches and twigs).

The tree biomass estimated from equation 12 was compared to observed biomass using *Z* test.

### 3.4.6 Computation of other forest parameters

***Basal area***

Basal area $m^2ha^{-1}$ (G) in this study was determined by using the equation:-

$$G = \frac{\sum^{n}(\sum^{m_i} g_{ij} / a_{ij})}{n_i} \quad \text{(Equation 13)}$$

Where G = Average basal area per ha, $g_{ij}$ = Basal area in the $j^{th}$ diameter class of the $i^{th}$ plot, $m^2$, $m_i$ = number of diameter classes in the $i^{th}$ plot, 1 …*i*…*n*, *n* = number of plots 1….*i*….*n*, *a* = area of subplot j in $i^{th}$ plot plot. Whereas basal area per tree (g $m^2$) was calculated from the equation:-

$$g = 0.0000785 d_i^2 \quad \text{(Equation 14)}$$

Where g = basal area per tree and d = diameter at breast height (Dbh)

***Stocking***

In each plot, the number of stems $ha^{-1}$ (N) was determined. This was done by dividing the total plot number of stems by the plot area. The mean number of stems was obtained by dividing the sum of stems $ha^{-1}$ for all plots by the number of plots. The following formula was used (Philip, 1994):

$$N = \sum(n_i / a_i) / n \quad \text{(Equation 15)}$$

Where N = Number of stems $ha^{-1}$, $n_i$ = Tree counts in the $i^{th}$ plot, $a_i$ = Area of the $i^{th}$ plot in ha, *n* = Total number of sampled plots.

***Stand biomass and volume***

The best performing volume and biomass models were used to compute respective stand attribute. The measured Dbh and ht variables from ht regression equation were used to compute volume, biomass and carbon stock at plot level. Total volume and biomass stocks for all trees in a plot were added to get volume and biomass stocks per plot. Volume and biomass per ha was obtained by converting total tree volume and biomass in a plot by dividing it by plot area (ha).

Biomass (kg/ha) was further divided by 1000 to get tons of biomass per ha ($tha^{-1}$). Biomass was converted to C by assuming 0.50 % of biomass is C (Basuki *et al.* 2009; Macauley *et al.,* 2009; Marshall *et al.,* 2012; Fahey *et al.,* 2010; Henry *et al.,* 2010; Henry, 2011; Mshana, 2013).

# CHAPTER FOUR

## 4.0 RESULTS AND DISCUSSION

This chapter presents the research findings with respect to research objectives. This includes findings on development of models for estimating volume of Teak; development of models for estimation of above and below ground biomass of Teak; comparing biomass estimates computed from developed biomass model and the estimates derived from previous developed volume equation and determination of forest structure attributes (stand volume, biomass, basal area and trees per ha).

## 4.1 Tree Volume Models

Tree volume models developed include the total tree volume (stem + branch), stem and branches where the diameter of stem or/and branches were set to minimum of 2 cm, 5 cm, and 10 cm. The motive of developing wide range of models (by differing the minimum diameter limit) was to satisfy different needs of the final user of teak components. Parameter estimates and model performance criteria are presented in Table 2. The candidate model was selected by examining p-values (significant at p-value < 0.05), the low mean square of the error (MSE), the high coefficient of determination ($R^2$), low percentage mean prediction error (*e %*) and normal distribution of the residuals (observed minus predicted values) against Dbh. *P-value* for equations 6 and 8 were found to have significant parameter estimates while equations 7 and 9 were found with some or all of the parameter estimate which were not significantly for all tree sections. Although MSE, MPE% and $R^2$ did not vary significantly among the models. The residual plot of the selected model for total tree, total stem and merchantable volume also did not show any adverse pattern suggesting that the model had a good fit (Figure 2 and Appendix 4). In most cases addition of tree total height in the model as an explanatory variable improved the model fit.

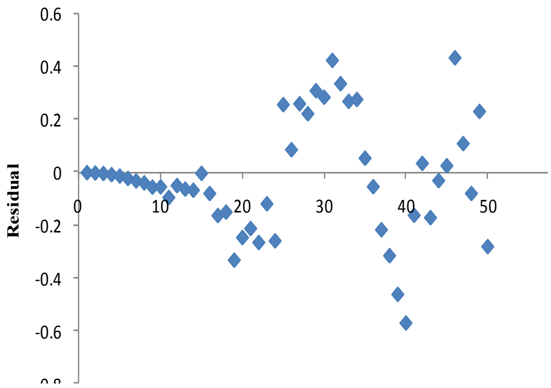
**Table 2: Volume model parameters and performance criteria for various tree components**

| Tree sections | Eqns | Parameter estimates | | | Performance criteria | | | |
|---|---|---|---|---|---|---|---|---|
| | | a | b | c | $R^2$ | MSE | MPE% | AIC |
| **TTV up cut off 2 cm** | **6** | **0.00120*** | **1.9912*** | **-** | **0.991** | **0.0482** | **2.200** | **15.9338** |
| | 7 | -0.0711* | 0.0032 | 0.011 | 0.992 | 0.0484 | 0.300 | 16.9422 |
| | **8** | **-8.8746*** | **0.8793*** | **-** | **0.988** | **0.0648** | **0.101** | **7.1410** |
| | 9 | 0.0007* | 1.9368 | 0.261* | 0.992 | 0.0471 | 1.400 | 17.4414 |
| **Total stem volume** | **6** | **0.00247*** | **1.7541*** | **-** | **0.976** | **0.0747** | **2.886** | **1.43686** |
| | 7 | -0.1572 | 0.0183 | 0.0006* | 0.976 | 0.0767 | 0.043 | 16.6684 |
| | **8** | **-7.9275*** | **0.7775*** | **-** | **0.980** | **0.0625** | **1.628** | **5.3236** |
| | 9 | 0.00047* | 1.5854 | -0.660 | 0.980 | 0.0635 | 1.518 | 17.0426 |
| **TTV up cut off 5 cm** | **6** | **0.00114*** | **1.9988*** | **-** | **0.991** | **0.0512** | **1.358** | **12.8966** |
| | 7 | -0.0678 | 0.0026* | 0.0011* | 0.991 | 0.0514 | 0.672 | 15.7340 |
| | **8** | **-8.9321*** | **0.8829*** | **-** | **0.988** | **0.0661** | **1.080** | **0.1120** |
| | 9 | 0.00064 | 1.9397 | 0.235 | 0.991 | 0.0498 | 1.349 | 17.353 |
| **TSV up cut off 10 cm** | **6** | **0.00233*** | **1.7663*** | **-** | **0.968** | **0.0938** | **0.947** | **21.7528** |
| | 7 | -0.4827* | 0.0321* | 0.0005* | 0.970 | 0.0898 | 0.259 | 20.8692 |
| | **8** | **-8.0059*** | **0.7837*** | **-** | **0.973** | **0.0787** | **1.908** | **14.3858** |
| | 9 | 0.00043 | 1.5961* | 0.677* | 0.973 | 0.0804 | 1.689 | 16.1882 |
| **TTV up cut off 10 cm(Merchantable volume)** | **6** | **0.00105*** | **2.0049*** | **-** | **0.987** | **0.0630** | **3.079** | **-0.5091** |
| | 7 | -0.2508 | 0.0102 | 0.001 | 0.987 | 0.0613 | 0.026 | 0.5914 |
| | **8** | **-9.0374*** | **0.8865*** | **-** | **0.984** | **0.0738** | **1.508** | **-3.8277** |
| | 9 | 0.00049* | 1.9292 | 0.302 | 0.988 | 0.0602 | 1.582 | 0.9690 |

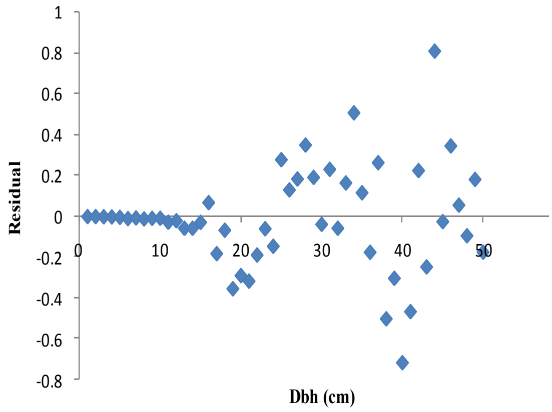
*= Significant at 5%. Where; TTV = Total tree volume, TSV = Total stem volume. Selected model for each tree sections is one bolded

Then the candidate models were evaluated using AIC and the lowest AIC was the best model among the tested models subjected to evaluation. In all cases model 6 for single variable (Dbh) and 8 for two variable (Dbh and ht) were shown to have the lowest AIC and therefore they were selected. The best equation among of the two is equation 8 by having the lowest AIC value.

## Total tree volume up cut off diameter of 2cm

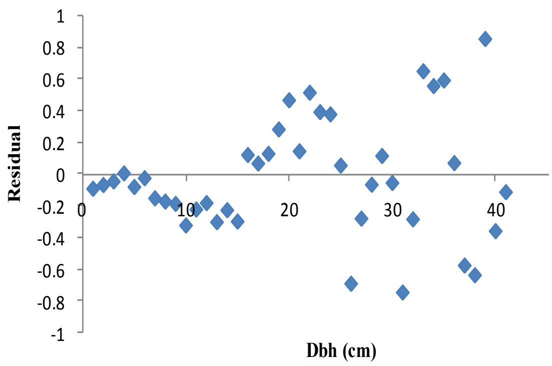



Equation 6 $V=0.0012\times Dbh^{1.9912}$

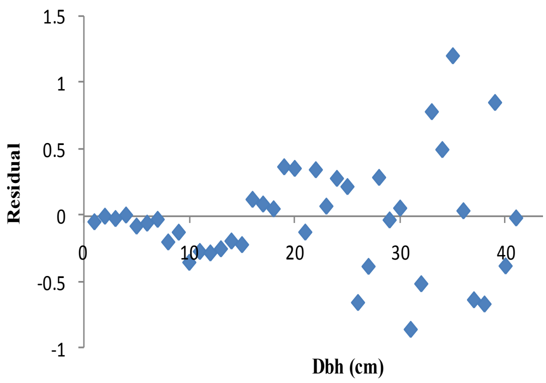



Equation 8 $V=Exp(-8.8746+0.8793\times ln(ht\times dbh^2))$

## Total stem volume

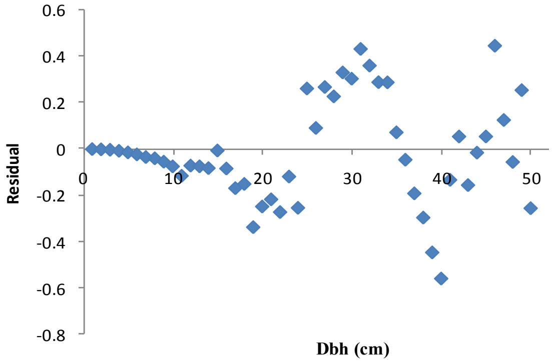



Equation 6 $V=0.00247\times Dbh^{1.7541}$

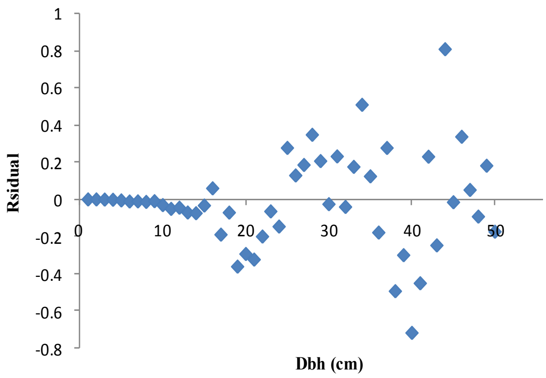



Equation 8 $V=Exp(-7.9275+0.7775\times ln(ht\times dbh^2))$

## Merchantable volume




Equation 6 $V=0.00105\times Dbh^{2.0049}$




Equation 8 $V=Exp(-9.0374+0.8865\times ln(ht\times dbh^2))$

**Figure 2: Residuals plot for total tree volume, total stem volume and merchantable volume model selected for evaluation**

***Comparison of developed total volume models with other general model***

The developed model were compared with model developed by Malimbwi *et al.* (1998), Van Zyl (2005), Hall (1933), cited by Van Zyl (2005) and Phillips (1995) (Table 3, Figure 3).

**Table 3: The comparison of total tree volume with other general total tree volume**

| Total tree volume comparison ($m^3$/ha) | Model abbreviation | Amount exceeds | % Excess | Model author(s) |
|---|---|---|---|---|
| **Total tree volume model** | **$0.00114 \times D^{1.9988}$** | **0.69** | **0.61** | **Developed model** |
| Total tree volume model | **$V = Exp(-8.685+2.479 \times \ln(D))$** | 15.65 | 13.69 | Phillips, 1995 |
| Total tree volume model | **$V = Exp(-9.918+1.8889 \times \ln(D)+1.009 \times \ln(ht)$** | 4.14 | 3.61 | Van Zyl, 2005 |
| Total tree volume model | **$0.0456 - 1.2356 \times \ln(D)+11.8011 \times \ln(ht)$** | 5.09 | 4.45 | Depuy and Mille, 1993 |
| Total tree volume model | **$V = 0.000024 \times D^{2.35}$** | 11.38 | 13.38 | Malimbwi et al., 1998 |

The model developed by Malimbwi *et al.* (1998) shown in the Figure 3 tends to underestimate the total tree volume at diameter range of 28 cm to 75cm with MPE of 11.38% see Table 2.

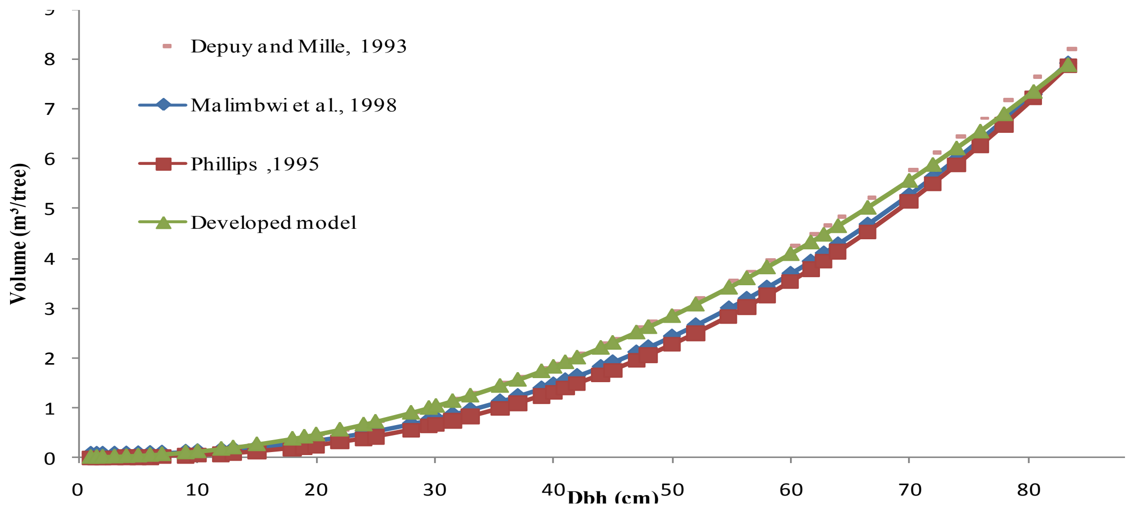



**Figure 3: Comparison of developed total tree volume model with other teak total tree volume models developed by Malimbwi *et al.* (1998), Philips (1995) and Depuy and Mille (1993)**

The different pattern between the models developed in this study and those from previous studies by Malimbwi *et al.* (1998), Phillips (1995); Hall (1933), cited by Van Zyl (2005) and Van Zyl (2005) was mainly due to methodological approach with regard to the minimum diameter set for stem and branches. Furthermore the difference in age also contributed to the difference as shown in Figure 3. Models developed by Phillips (1995) and Van Zyl (2005) underestimated volume by 13.69% and 3.67% respectively. The developed model had least MPE showing that developed model provides best estimate for total volume which was followed by model developed by Van Zyl (2005).

***Comparison of developed merchantable volume models with other model***

For merchantable volume, often the minimum diameter is set at 10 cm for branches and stem. The volume excludes the cone volume of less than 10 cm minimum diameter. The developed merchantable volume model was compared with the merchantable volume model developed by Malimbwi *et al.* (1998) and Perez and Kanninen (2003) see Figure 4. The model developed by Malimbwi *et al.* (1998) was found to underestimate the merchantable volume for the trees with diameter greater than 20 cm by 17.38% see Table 4.

**Table 4: The comparison of merchantable volume and other merchantable volume models**

| Model abbreviation | Amount exceeds | % Excess | Model author(s) |
|---|---|---|---|
| **$V = 0.00105\times D^{2.0049}$** | **1.29** | **1.21** | **Developed model** |
| **$V = (-0.0884 + 0.0297\times D)^2$** | 27.32 | 25.51 | Perez and Kanninen, 2003 |
| **$V = -0.0761+0.000906D^2$** | 18.61 | 17.38 | Malimbwi et al., 1998 |

The difference between the developed model and the model developed by Malimbwi *et al.* (1998) was because of age and diameter used to develop the model in this study. The MPE found when using Perez and Kanninen (2003) was about 25.51% in comparison to the MPE of 1.21% provided by developed merchantable volume.

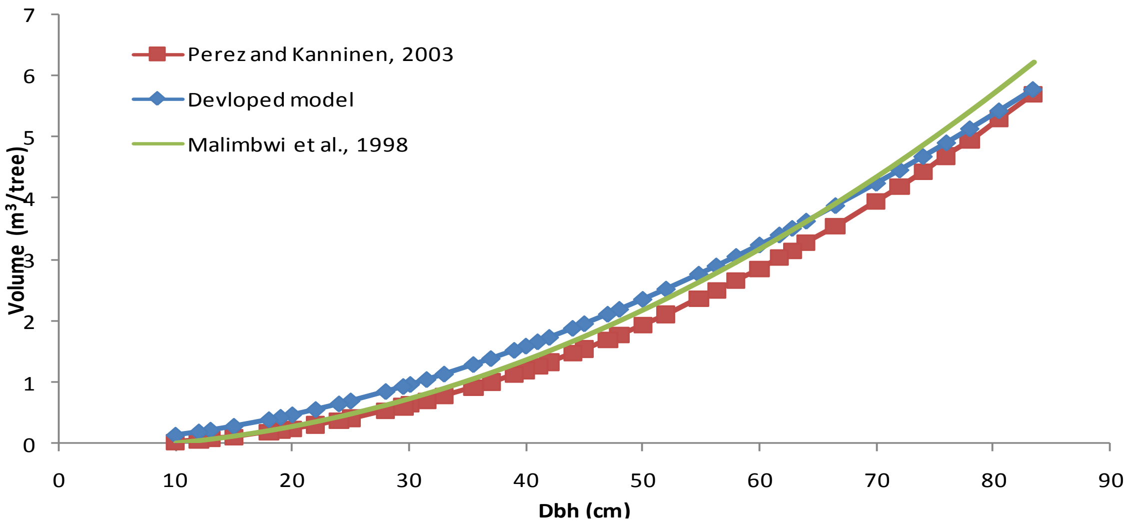



**Figure 4: The comparison of developed model for merchantable volume with other Teak merchantable volume model developed by Malimbwi et al. (1998) and Perez and Kanninen, (2003)**

## 4.2 Tree Biomass Models

The models developed in this study include the total tree above-ground biomass model (stem biomass and branch) and total tree below-ground biomass model. The total tree above-ground biomass model includes stem biomass and branch biomass. The total tree below ground biomass model includes side root biomass and main root biomass.

### 4.2.1 Total tree above ground biomass model

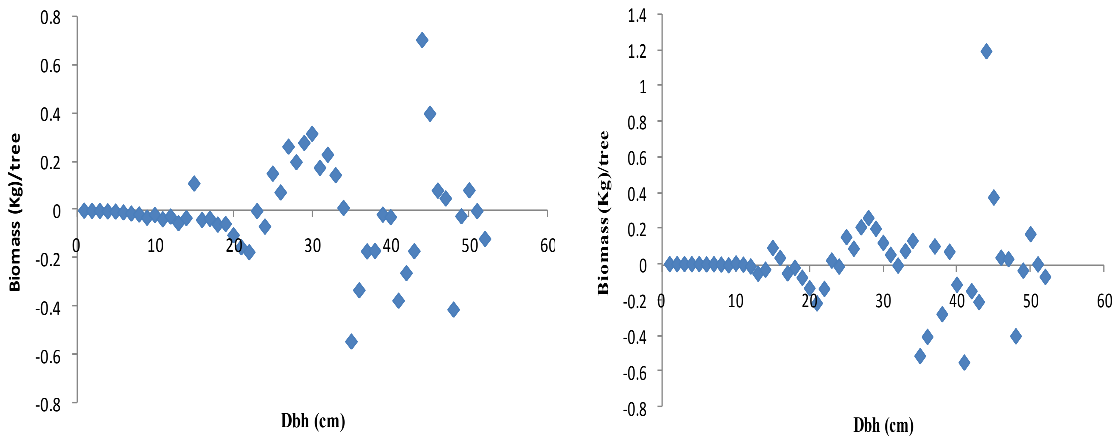
The result for above-ground biomass models are presented in Table 5. The candidate model for above ground biomass was selected by examining p-values (significant at p-value < 0.05), the low mean square of the error (MSE), the high coefficient of determination ($R^2$), low percentage mean prediction error (*e%*) and normal distribution of the residuals (observed minus predicted values) against Dbh.

**Table 5: Biomass model parameters and their performance criteria**

| Tree section | Equation | Parameter estimates | | | | | Performance criteria | |
|---|---|---|---|---|---|---|---|---|
| | | a | b | c | $R^2$ | MSE | MPE% | AIC |
| **Total Above-ground biomass** | **6** | **0.5043*** | **2.0636*** | **-** | **0.977** | **42857.1** | **0.2300** | **677.13** |
| Total above-ground biomass | 7 | -4.557 | -1.8448 | 0.689* | 0.977 | 43807.0 | 0.0070 | 679.36 |
| **Total above-ground biomass** | **8** | **-2.7944*** | **0.9016*** | **-** | **0.966** | **62908.7** | **0.0141** | **676.32** |
| Total above-ground biomass | 9 | 1.2136* | 2.1598 | -0.363 | 0.978 | 41806.4 | 0.0291 | 696.32 |
| **Total tree biomass** | **6** | **0.7136*** | **2.0282*** | **-** | **0.976** | **65817.4** | **0.3800** | **696.58** |
| Total tree biomass | 7 | -17.02 | 0.3016 | 0.812* | 0.976 | 67178.2 | 0.4500 | 700.56 |
| **Total tree biomass** | **8** | **-2.4305*** | **0.8878*** | **-** | **0.968** | **89804.8** | **0.0260** | **714.12** |
| Total tree biomass | 9 | 1.2097* | 2.0855 | 0.22 | 0.977 | 66170.3 | 0.0430 | 719.81 |

*= Significant at 5%. Selected for each tree sections is one bolded

The selected candidate models were equations are 6 and 8. The *p-value* for equations 6 and 8 were significant for all parameter estimates while equations 7 and 9 were not significant at 5% level for some of the parameter estimates. The $R^2$ is 0.976 for equation 6 and 0.968 for equation 8 with MSE of 65817.4 and 89804.8 respectively. Furthermore, plot of residual values of total above-ground biomass for all tested forms of models are shown in Figure 5 and Appendix 5. The selected models (equation 6 and 8) have their scatter plots normally distributed.




Eqn 6 $B=0.5043\times\mathbf{Dbh}^{2.0636}$ Eqn **8** $B=Exp(-2.794+0.901\times\ln(\mathbf{ht}\times\mathbf{Dbh}^2))$

**Figure 5: The residual plot for total tree above ground biomass models under evaluation**

The equations subjected to further evaluation were equations 6 and 8 in order to get their AIC values because their *p-values* for all parameter estimates were significant at 5%. The best equation between the two equations subjected to evaluation for estimation of total above-ground biomass as shown by equation 8, having lowest *e%* (0.014) and AIC (676.32) in comparison with equation 6 having *e%* and AIC of 0.23 and 677.13 respectively (see Table 4). However equation 6 can be used if there is only data for Dbh.

***Comparison of developed total above ground biomass model and other general models***

The developed model for total above ground biomass was compared with other models developed for the same species and with other general model for tropical forests in Africa see Table 6. In general, both models for total above ground biomass estimations tended to have identical trend, with minor mean difference of 7.38%.

**Table 6: The comparison of total above ground biomass and other general above ground biomass models**

| Model abbreviation | Amount exceeds | % Excess | Model author(s) |
|---|---|---|---|
| $B = 0.5043 \times D^{2.0636}$ | 117.345 | 0.18 | Developed model |
| $B = 0.054 \times D^{2.579}$ | 7594.85 | 11.53 | Anwari, 2012 |
| $B = 0.04506 \times D^{2.082}$ | 2326.76 | 3.53 | Eamus, 2000 |
| $B = 0.1636 \times D^{2.32}$ | 4921.07 | 7.47 | Brown, 1997 |
| $B = Exp(-2+2.42\times\ln(D))$ | 10094.12 | 15.33 | Chave *et al.,* 2001 |
| $B = 0.066 \times D^{2.565}$ | 1364.79 | 2.07 | Assomaning, 2006 |
| $B = 0.153 \times D^{2.382}$ | 7613.97 | 11.56 | IPCC, 2003 |

However, the maximum difference between 2 and 46 years of age was 15.33%. The comparison of the biomass model developed by Eamus (2000); Brown (1997); IPCC (2003); Assomaning (2006) and Siregar (2012) with the developed model study is shown in Figure 5 .The biomass models developed by IPCC (2003) and Assomaning (2006) tend to underestimate the biomass by 11.56 % and 2.07 % respectively when tested using the independent dataset (Table 6). Figure 6 reveals that the IPCC (2003) and Assomaning (2006) overestimate the tree biomass for large trees while it underestimates the biomass for small diameter trees.

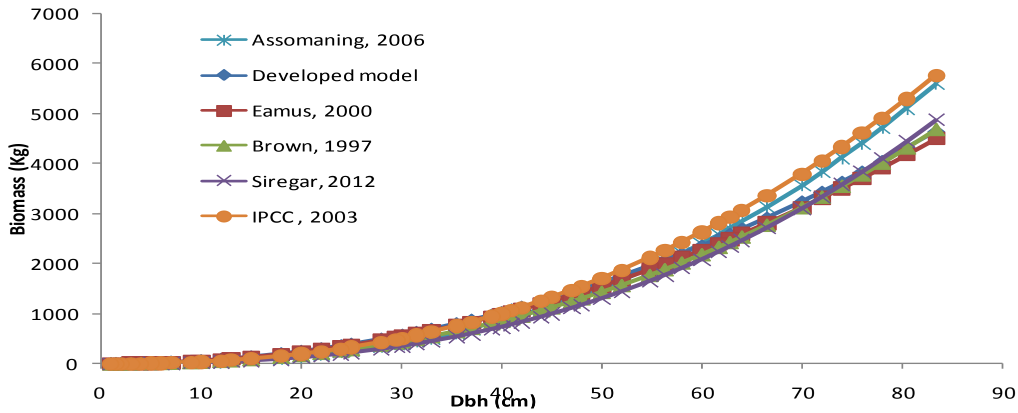



**Figure 6: The comparison of developed total above ground biomass model with other Teak total above ground biomass models developed by Eamus (2000); Brown (1997); IPCC (2003); Assomaning (2006) and Siregar (2012)**

Also the biomass models developed by Eamus (2000), Brown (1997) and Siregar (2012 overestimated the biomass by over 3.53%, 7.47% and 11.53% respectively when tested to the independent data set. The further differences shown in Figure 5 reveal that models developed by Siregar (2012); Brown (1997) and Eamus (2000) were closer to the developed model for above-ground biomass, although both models tended to underestimate large trees and overestimate the small diameter trees. The reason for different values displayed in the model could be the range of diameter used to develop the model. For example the Siregar (2012) model was for Teak aged 1-15 years old with diameter ranging from 4.8 cm to 26.2 cm. In addition to that, both previously developed models did not include large trees. Furthermore, the difference may be due to management practices between the study sites, difference in tree height and the site quality. From this observation can be concluded that above ground biomass model from one location cannot be simply used in another location even when the areas are ecologically comparable.

### 4.2.2 Total tree belowground biomass model

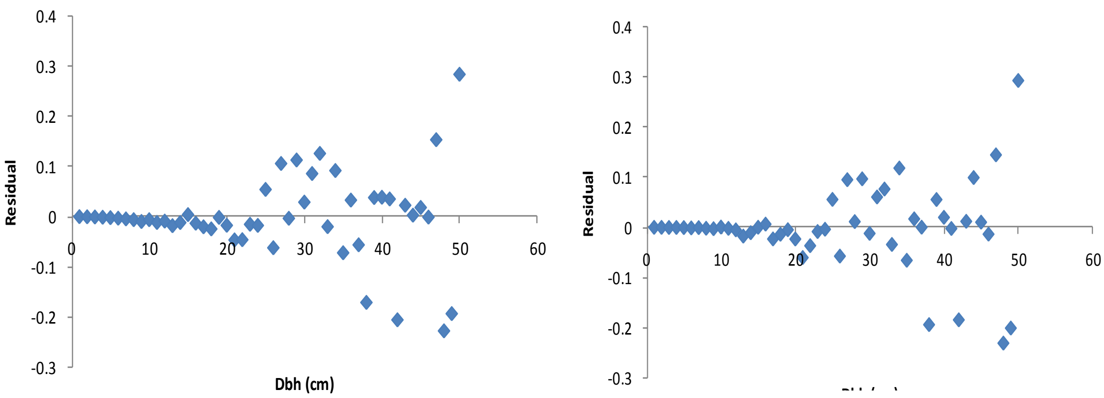
The total tree belowground biomass models include the biomass from side root, main roots and root crown. The results for total tree below ground biomass models are presented in Table 7.

**Table 7: Below ground model parameters and performance criteria**

| Equations | Parameter estimates | | | Performance criteria | | | |
|---|---|---|---|---|---|---|---|
| | a | b | c | $R^2$ | MSE | MPE% | AIC |
| **6** | **0.2479*** | **1.8712*** | **-** | **0.92** | **7269.00** | **0.4765** | **580.00** |
| 7 | -12.47* | 1.543 | 0.1238 | 0.92 | 7410.40 | 0.4429 | 578.33 |
| **8** | **-3.409*** | **0.8262*** | **-** | **0.92** | **7241.00** | **0.2692** | **580.22** |
| **9** | 0.0854* | 1.7601 | 0.4317 | 0.92 | 7288.30 | 0.0346 | 577.50 |

*= Significant at 5%. Selected for each tree sections is one bolded

The candidate models (equation 6 and 8) selected for below ground biomass have significant parameter estimates while 7 and 9 were having some of the parameter estimates which were not significant at 5% and hence were not considered for evaluation.  The equation with single variable found to perform better than the one equation with two variable (Dbh and ht) as indicated in residual plot for normal distribution (Figure 7 and Appendix 5). Equations 6 and 8 were further evaluated using AIC in order to get the best model. After evaluation using AIC, the best model obtained for total tree below-ground biomass model is given by equation 6 with single variable. The results indicate that the total tree below-ground biomass were explained well by Dbh than by both Dbh and ht (Table 7). The best model for total tree below ground biomass model is equation 6 for single variable (Dbh) and equation 8 for two variable (Dbh and ht) model. The best equation among of the two is equation 6 by having the lowest AIC value.




Eqns 6 $B = 0.2479Dbh^{1.8712}$ Eqns 8 $B = Exp(-3.4093 + 0.8262 \times ln(ht \times Dbh^2))$

**Figure 7: The residual plot for total tree below ground biomass model**

***Comparison of below ground biomass model with other biomass models***

The developed model was compared with other models developed for the same species and also with other tropical forests developed by other studies in India. The MPE estimates for each of the compared models are presented in Table 8.

**Table 8: The comparison of total tree below ground biomass model with other studies**

| Model abbreviation | Amount exceeds | % Excess | Model author(s) |
|---|---|---|---|
| $B = 0.2479 \times D^{1.8712}$ | **70.4938** | **0.48** | **Developed model** |
| $B = Exp(-1.0587+0.8836 \times ln(D))$ | 5464.43 | 36.95 | Assomaning, 2006 |
| $B = 0.006 \times D^{2.702}$ | 4043.64 | 27.33 | Siregar, 2012 |
| $B = 0.097 \times D^{2.023}$ | 4034.27 | 27.26 | Buvaneswaran *et al.* 2006 |

Furthermore, the developed models were compared with total tree below-ground biomass model from other researchers that uses the ratios of above ground to below ground biomass and results are shown in Figure 8.

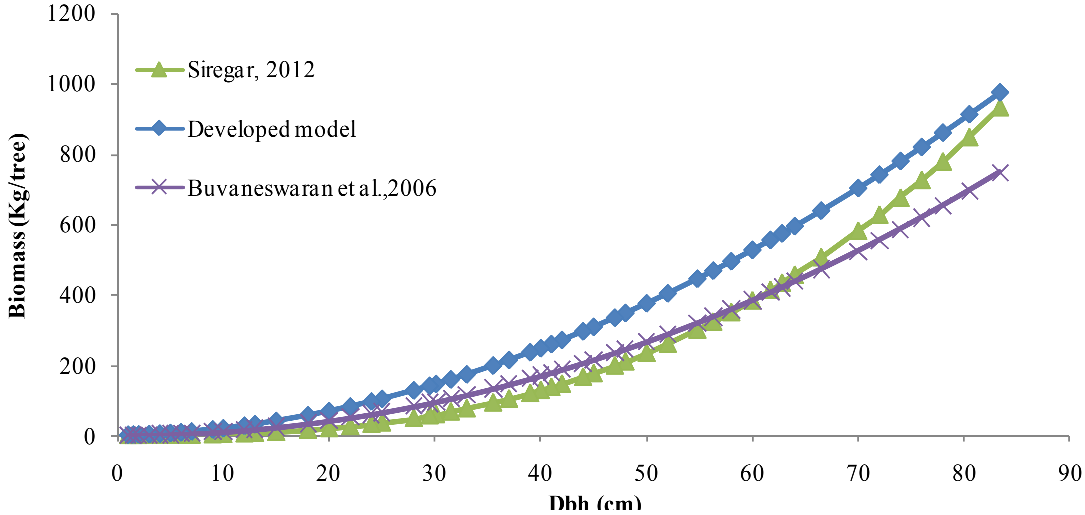



**Figure 8: Comparison of developed model for belowground biomass with other Teak total belowground biomass model given by Siregar, (2012) and Buvaneswaran *et al.* (2006)**

The models developed by Assomaning (2006) and Buvaneswaran *et al.* (2006) showed to underestimate the below-ground biomass in the study area (Figure 7). Assomaning (2006) had a MPE of about 36.95 % and Buvaneswaran *et al.* (2006) had 27.33 % (Table 8). The MPE by Assomaning (2006) and Buvaneswaran *et al.* (2006) were high as protocol by Huang *et al.,* (2003) requires bias % of < $\pm$ 10 % at 95% confidence level provided no adverse pattern is displayed. The variation displayed by these models might be due to the range of diameter and number of sample trees used to develop the model, site condition, management practices, height difference and other environmental factors.  Also similar findings of variation in biomass estimated using site specific models were observed to vary with altitude and soil type (Slik et *al.,* 2010; Baraloto *et al.,* 2011), topographic position (Macauley *et al.,* 2009), age of tree (Alexandrov, 2007), provenance (Macauley *et al.,* 2009) and climatic conditions (Girardin *et al.,* 2010) also might be contributed to the variation found in this study.

Furthermore, the ratios proposed by Carns *et al.* (1997) tend to overestimate total tree below-ground biomass in the study area as compared with the developed model. The developed model had good fit to below-ground biomass data than other models developed by other studies in other areas. From this finding it is clear that the site and species specific models are more appropriate in estimating the biomass in particular area than general models that cover wide area and not site specific. This is in line with the finding reported by Chave *et al.* (2004); IPCC (2007); Somogy *et al.* (2008); Litton and Kauffinan, 2008; Navar, 2009 and Keith *et al.* (2009) who pointed out that site and specific models provide accurate estimated of biomass than the general models.

### 4.2.3 Total tree biomass model

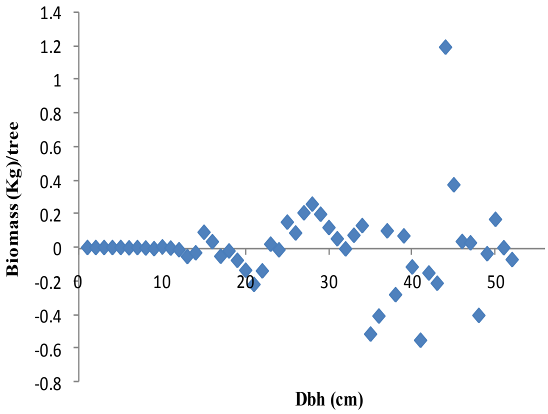
The result for total tree biomass is presented in Table 9. The candidate models (equation 6 and 8) were have significant parameter estimates while 7 and 9 were having some of the parameter estimates which were not significant at 5% and hence were not considered for evaluation. Single variable candidate model had $R^2$ of about 0.976, e % of 0.38 and 65817.4 as MSE while for two variable model had $R^2$ of about 0.968, e% of 0.026 and 8980.8 as MSE (Table 9).

**Table 9: Total below ground model parameters and performance criteria**

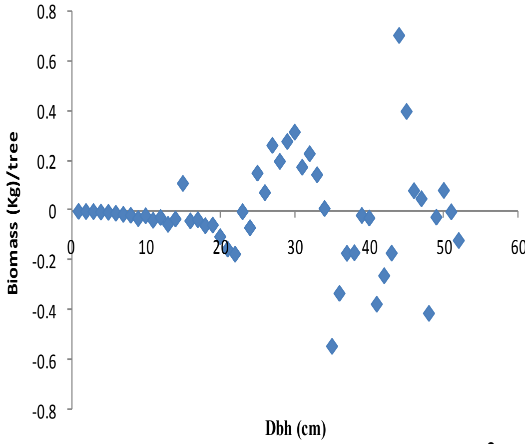
| Equation | Parameter estimates | | | Performance criteria | | | |
|---|---|---|---|---|---|---|---|
| | a | b | c | $R^2$ | MSE | MPE% | AIC |
| **6** | **).7136*** | **2.0282*** | **-** | **0.976** | **65817.4** | **0.3800** | **696.58** |
| 7 | -17.02 | 0.3016 | 0.812* | 0.976 | 67178.2 | 0.4500 | 700.56 |
| **8** | **2.4305*** | **0.8878*** | **-** | **0.968** | **89804.8** | **0.0260** | **714.12** |
| 9 | l.2097* | 2.0855 | 0.22 | 0.977 | 66170.3 | 0.0430 | 719.81 |

*= Significant at 5%. Selected for each tree sections is one bolded

The residual plot show normal distribution of residuals for equation with single variable and performs better than the equation with two variables (Figure 9 and Appendix 5). The equations 6 and 8 are further evaluated using AIC in order to get the best model for total tree biomass. The best equation between the two is single variable model (equation 6) as it has lower AIC (696.58) value in comparison with the two parameter model (714.12).




**Eqns 6 B=0.7136×Dbh$^{2.0282}$**




**Eqns 8 B=Exp(-2.4305+0.8878×ln(ht×Dbh$^{2}$)**

**Figure 9: The residual plot for total tree biomass model**

***Comparison of total tree biomass model and other general models***

The developed total tree biomass was compared with other Teak models developed by other studies. The large differences was found in total tree biomass estimates for individual trees when comparing the biomass estimates of the allometric model developed in this study with generalized tropical tree models (Chave *et al.,* 2001; Buvaneswaran *et al.,*2006; Siregar, 2012) across a range of 52 – 83.4 cm Dbh (Figure 10). All generalized models greatly overestimated biomass of larger Dbh (≥ 52 cm) and tended to greatly underestimate biomass for smaller trees Dbh (< 45cm).

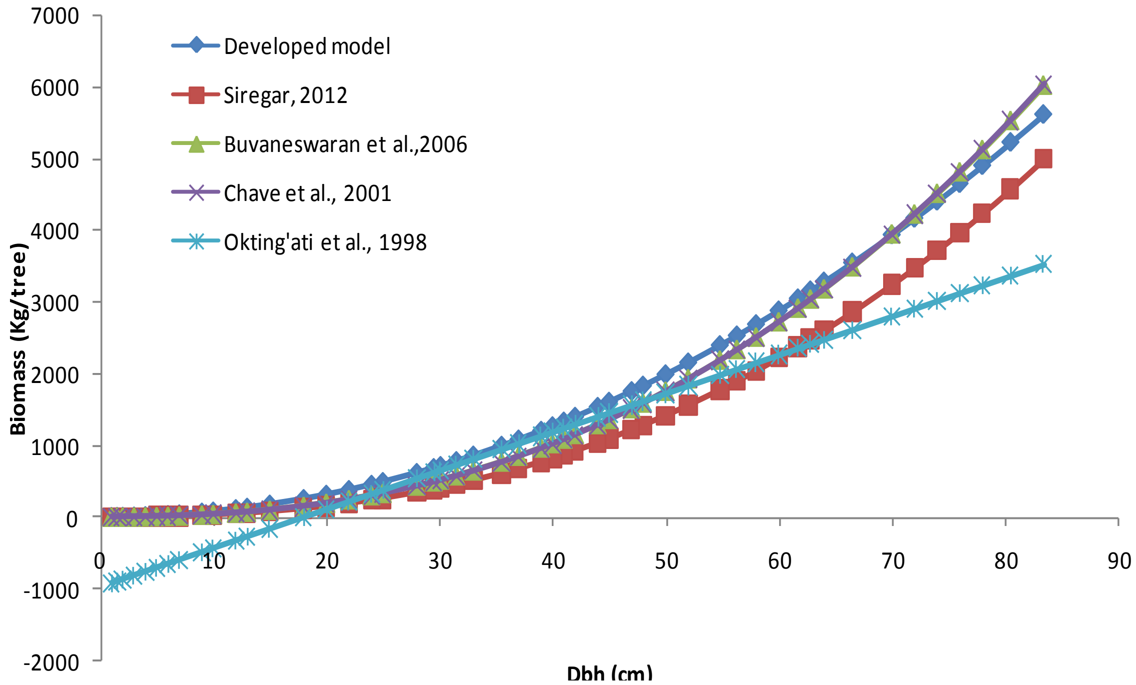



**Figure 10: The comparison of developed models for total tree biomass with other Teak total tree biomass models developed by Chave *et al.* (2001); Buvaneswaran *et al.* (2006); Siregar (2012)**

Table 10 shows the MPE of tested models in which the largest MPE is shown by Siregar (2012) (23.11%), followed by IPCC (2003) (8.9 %) and the lowest being Eamus (2000) (3.53 %). Differences in site conditions, stocking and management are probably accounting for these slight variations in the biomass distribution between the compared studies. Furthermore the model developed by Brown (1997) for wet climates displayed the MPE of 4 – 12% and at Dbh > 25 cm greatly underestimated biomass.

**Table 10: The comparison of total tree biomass and other general models**

| Model abbreviation | Amount exceeds | % Excess | Model author(s) |
|---|---|---|---|
| **$B = 0.7136 \times D^{2.0282}$** | **194.39** | **0.24** | **Developed model** |
| **$B = 0.04506 \times D^{2.082}$** | 2326.76 | 3.53 | Eamus, 2000 |
| **$B = 0.142 \times D^{2.409}$** | 4477.89 | 5.55 | Buvaneswaran *et al.* 2006 |
| **$B = 0.153 \times D^{2.382}$** | 7181.32 | 8.90 | IPCC,2003 |
| **$B = -963 + 53.9D$** | 27042.59 | 33.53 | Okting'ati *et al.* 1998 |
| **$B = 0.093 \times D^{2.462}$** | 18638.76 | 23.11 | Siregar, 2012 |

Another study, by O'kting'ati *et al.* (1998) in Mtibwa forest plantation found that *T. grandis* had a biomass less by 33.53% compared to measured biomass in the field. Differences in growth and thinning schedule contributed to variation in results between two study sites (Longuza and Mtibwa). The pattern shown by O'kting'ati *et al.* (1998) is due to differences in diameter used in developing the model. The samples used in development of O'kting'ati *et al.* (1998) model covered a narrow diameter range (17 – 42.5 cm) that excluded small or bigger trees. Another reason for the difference in biomass value estimated by the O'kting'ati *et al.* (1998) model and those from this study is probably because of the plantation studied by the researcher was 22 and 30 years of age while the present study covered age up to 46 years.

### 4.2.4 Other biomass models

The other biomass models covering different tree components are represented in Table 11. The candidate models selected for stems and branches were equation 6 and 8 because they were having significant parameter estimates while 7 and 9 were having some of the parameter estimates which were not significant at 5% and hence were not considered for evaluation (Table 11). Their scatter plots for selected and unselected models see Appendix 6.

**Table 11: Biomass model parameters and performance criteria for other tree components**

| Tree section | Equation | Parameter estimates | | | Performance criteria | | | |
|---|---|---|---|---|---|---|---|---|
| | | a | b | c | $R^2$ | MSE | MPE% | AIC |
| **Branch biomass** | **6** | **0.0009*** | **3.2115*** | **-** | **0.868** | **18337.2** | **0.1300** | **628.07** |
| Branch biomass | 7 | 60.6180* | -9.7904 | 0.282* | 0.859 | 19901.2 | 0.0100 | 639.72 |
| **Branch biomass** | **8** | **-10.211*** | **1.3933*** | **-** | **0.841** | **21979.8** | **0.0015** | **613.74** |
| Branch biomass | 9 | 0.0783 | 3.7451 | 0.006* | 0.8840 | 16414.0 | 0.2300 | 630.09 |
| **Stem biomass** | **6** | **0.9740*** | **1.836*** | **-** | **0.963** | **36561.0** | **0.7400** | **669.19** |
| Stem biomass | 7 | -56.034* | 6.6151 | 0.40 | 0.963 | 37327.4 | 0.0030 | 671.18 |
| **Stem biomass** | **8** | **-1.951*** | **0.8065*** | **-** | **0.960** | **39300.8** | **0.5640** | **662.80** |
| Stem biomass | 9 | 0.6089* | 1.7855 | 0.19 | 0.964 | 37011.4 | 0.7070 | 671.90 |

*= Significant at 5%. Selected for each tree sections is one bolded

The best equation among of the two subjected to the evaluation were equation 8 for both stem biomass model and branch biomass model.

There were no studies or literature found to compare with the developed models. The two variable model gives the best fit to the biomass data than single variable model. The problem with combined variable model is that requires the measurement of total tree height which is often erroneous and tedious for standing trees in plantation with dense canopy. Since the Kyoto protocol clearly affirms the importance of increasing our understanding of forest carbon budget and the role of forests in offsetting global carbon emission. This study has contributed in that direction.

## 4.3 Comparison of Biomass Estimating Approaches

The result for comparison of the biomass estimates using two approaches is presented in Table 13. The biomass estimated using merchantable volume model developed by Malimbwi *et al.* (1998) in the study area was compared with the biomass estimated using developed total tree biomass model in this study. The biomass from volume equation involves the multiplication of BWD, BEF and RSR values. The average BWD, BEF and RSR in this study was used in the computation of tree biomass used in comparison.

***Basic wood density***

The result for BWD in the study area is presented in Table 12. The BWD in the study area was shown to increase with increase in age. The site class also was influencing the basic wood density especially for site class one. The basic wood density for site class one was lower than for site class three of the same age. The reason for lower BWD is due to the fast growth of teak in site class I that lowering the wood strength properties than that of site class three. The middle age plantations (16, 19, 21 and 34 years see Table 12) in the study area were not much affected by site class. The reason for this might be due to slow growing rate in middle age trees as compared to the growing rate in the younger trees. Wood basic density was observed to varies within the tree itself in which at the top was lower than at base of the tree and middle of the tree.

**Table 12: Site class and Basic wood density**

| Age | Site class I | Site class II | Site class III |
|---|---|---|---|
| 2 | 0.24 | 0.315 | 0.37 |
| 3 | 0.30 | 0.321 | 0.38 |
| 5 | 0.31 | 0.36 | 0.40 |
| 16 | 0.41 | 0.48 | 0.55 |
| 19 | - | - | 0.52 |
| 21 | - | 0.52 | - |
| 33 | 0.54 | - | - |
| 41 | - | 0.53 | - |
| 42 | - | 0.62 | - |
| 46 | 0.58 | - | - |

The value obtained in this study was ranging from 0.24 - 0.62 g/cm$^3$ with an average of 0.52 g/cm$^3$. This result was in agreement with other finding in different localities such as Moya (2003), which reported the range of 0.38-0.65 g/cm$^3$ in 10 years Teak, Chauhan *et al.* (2006) that ranges from 0.47-0.585 g/cm$^3$ in 6-20 years teak, O'kting'ati *et al.* (1998) which ranges from 0.52-0.54 g/cm$^3$ in 22 years and 30 years Teak. Other studies for tropical tree species in Africa also show similarity in woody density obtained in present study. For example, Sibomana *et al.* (1997) with value ranging from 0.525-0.587 in 14 years teak; Brown (1997) with value ranging from 0.5-0.79 g/cm$^3$. However, the variations might be attributed by site quality, silvicultural operation and other environmental factors. The BWD in the study area was significantly influenced by age, site quality, tree condition, and topography and tree height. The finding reveals that the site quality had influence on basic wood density. Basic wood density was varying according to site classes but also by location on the stem. The site class three at young age was shown to have high basic wood density than that found in site class one.

***Root to shoot ratio***

The RSR in the study was ranging from 0.16 - 0.52 with average of 0.26 and with highest value showed by young stand (Table 13). The high contribution of root to shoot ratio might be due to young teak had more biomass on leaves than in stem and other parts. This indicates that at younger age teak grows faster while it slows down afterwards since there was progressive decrease in the value of the ratio with increase plantation age.

**Table 13: Root to shoot ratio in the study area**

| S/number | Dbh classes (cm) | Number of tree per class | Average root to shoot ratio |
|---|---|---|---|
| 1 | 1 – 10 | 10 | 0.34 ± 0.05 |
| 2 | 11 – 20 | 4 | 0.27 ± 0.03 |
| 3 | 21 – 30 | 5 | 0.25 ± 0.02 |
| 4 | 31 – 40 | 5 | 0.24 ± 0.03 |
| 5 | 41 – 50 | 7 | 0.24 ± 0.04 |
| 6 | 51 – 60 | 6 | 0.24 ± 0.04 |
| 7 | 61 - 70 | 7 | 0.22 ± 0.04 |
| 8 | 71 - 80 | 5 | 0.21 ± 0.03 |
| 9 | 81 - 90 | 2 | 0.20 ± 0.05 |
| **Average** | | **6** | **0.26 ± 0.02** |

It has also been revealed that though teak grows at faster rate during early years and growth rate slows down afterwards, at the age of thirty four it produces considerably higher biomass. This finding of root to shoot ratios was closer to the other findings on teak given by Brown (1997) with root to shoot ratio of 0.20 for hardwood; Perez and Kanninen, (2003) with range of 0.11 to 0.23 for 20 years old Teak; Derwisch *et al. (*2009) ranges from 0.46 to 0.42; Leavy *et al.* (2010) with 0.36 and IPCC (2006) for hardwood was 0.25 This indicates that the young teak had more biomass in root than in shoot since their ratio were high in comparison with old Teak. The high biomass in root for young teak optimize nutrients uptake to favour fast grow for young teak.

***Biomass expansion factor***

BEF in the study area is ranging from 0.90 - 1.6 with average of 1.26. The highest biomass expansion factor was shown by young Teak. The old Teak had lower BEF than young age because large tree their contribution was reduced by volume contribution from branches. The biomass expansion factor was seems to be affected by site class since the site class I was seems to had high biomass expansion factor than site class III. The mean value for the BEF given in this study correspond to the average value of 1.4 to 1.8 given by Sengura and Kanninen (2004) for the same species. The value for the BEF is also within the range from 1.28 to 1.46 given for the similar forest type (similar species) by Guendehou *et al.* (2012) at teak of 3 to 15 years. BEF was observed in the study site tend to increase with decrease in age of the teak. Also the variation in BEF observed in study site and in comparison with other studies is caused by silvicultural operations such as thinning, the different environment, climatic factor or other management activities since were highly influenced by branching pattern of a tree.

***Comparison of two approach of biomass estimation method using t test***

A t-test was done to test if estimated biomass from volume equation is similar to biomass stock estimated using developed biomass equations in this study. The results for t test show that the two methods (biomass estimates from biomass model and biomass from volume equation) were statistically different at probability of 0.05 since the probability value obtained was greater than 0.05 showing that biomass estimates from the two methods were not the same (Table 14).

**Table 14: Results of comparison between two methods for biomass estimates**

| Variable | z value | Pr. value |
|---|---|---|
| Biomass from volume equation and Biomass from biomass model (one tail) | 1.6449 | 0.0844* |
| Biomass from volume equation and Biomass from biomass model (two tail) | 1.9599 | 0.1688* |

*=Statistically different at 5% level.

The result for *Z*- test show that the two methods (developed total biomass model and Observed biomass) were not statistically difference at probability of 0.05 since the probability value obtained was less than 0.05 showing that the two methods were almost the same.

The two methods are statistically significantly different at 5% since the computation of biomass from volume in young stand tends to overestimate the biomass because of using constant (BWD and BEF) that lead to difference in biomass between two methods (Appendix 2). The use of mean BWD which was larger than the actual basic wood density found in the young stands might be the reason why the volume method for biomass estimation tends to overestimate the biomass of young stand in the study area. The BWD in the study area was increasing with increasing age and the use of any constant BWD in any calculation causes systematic error in biomass or C estimation. Also BEF tend to decrease with increase in age of Teak in the study area and the use of mean BEF in biomass computation also contributed to errors in final answer of biomass of a tree.

## 4.4 Forest Stand Parameters

### 4.4.1 Stand volume

The estimation of volume is very important for sale, because it is one of the essential elements of wood value. The volume estimated in the plantation can be the basis of the commercial transaction between buyers and plantation managers. It is also useful in forest management and monitoring to know how much the stock volume is present in forest stand.

***Volume by age***

The computed stand volume in the study area are presented in Table 15. The best developed model with single variable for volume was used to compute volume in the study area. The estimation by age class provides a better understanding of the plantation if it was normal as well as if other silvicultural activities were implemented.

**Table 15: Total tree biomass, volume, stem/ha and above-ground biomass by age**

| Age. | 2 | 5 | 16 | 19 | 21 | 34 | 42 |
|---|---|---|---|---|---|---|---|
| Volume | 6.14 ± 1.11 | 174.98 ± 17.02 | 443.34 ± 23.01 | 405.46 ± 26.72 | 464.73 ± 33.00 | 431.21 ± 32.88 | 471.51 ± 38.28 |
| ABG | 2.80 ± 0.14 | 86.90 ± 6.22 | 235 ±1 0.30 | 216.08 ± 10.18 3 | 313.74 ± 12.42 | 234.50 ± 14.78 | 262.70 ± 16.28 |
| Carbon | 1.40 ± 0.07 | 43.45 ± 3.11 | 117.54 ± 5.15 | 108.04 ± 5.09 | 156.87 ± 6.21 | 117.25 ± 7.39 | 131.35 ± 8.14 |
| TTB* | 3.80 ± 0.70 | 113.14 ± 11.16 | 296.66 ± 15.35 | 272.02 ± 17.78 | 313.74 ± 21.86 | 354.34 ± 27.11 | 323.80 ± 26.28 |
| Carbon | 1.90 ± 0.35 | 56.57 ± 5.58 | 148.33 ± 7.68 | 136.01 ± 8.89 | 156.87 ± 10.93 | 177.17 ± 13.56 | 161.90 ± 13.13 |
| Basal | 0.404 ± 0.073 | 11.67 ± 1.14 | 29.82 ± 1.55 | 27.29 ± 1.79 | 31.34 ± 2.21 | 29.11 ± 2.22 | 31.94 ± 2.58 |
| Stem/ha | 496 ± 140 | 1568 ± 108 | 654 ± 90 | 576 ± 119 | 427 ± 134 | 320 ± 49 | 194 ± 41 |

*= (TTB) Total tree biomass

The volume in study area was increasing with increasing in age and but affected by thinning at later stage. For example, the study observed that volume in the study area was increasing with increasing age but at age of 19 years, the volume decreases due to thinning done at age of 18 years. Then there was progressive increase in volume up to the age of 21 years and then decreases due to thinning again. Finally the volume starts to increase up to the age of 42 years. From this trend the observed increase in volume following thinning could be attributed to more space and enhance growth in diameter of the trees.

The minimum volume in the study area was found at age of 2 years that ranges from 5.13 – 7.25 $m^3$/ha with 494 stem per ha. The volume at this age was comparable with other studies carried out in teak of almost the same age. The finding by KFRI (2011) in India at age of 3 years the value was ranging from 1.87 - 6.57 $m^3$/ha. The findings reveal that at the study site the teak grow better than those found by KFRI (2011) which was associated with higher age than those in the study area.

At the age of 5 years the volume obtained was ranging from 157.96 - 192 $m^3$/ha. This value was higher than that found by Perez and Kanninen (2003) in Costa Rica (28.4 to 32 $m^3$/ha) and this difference was due to low number of stems/ha at this age in Costa Rica which was about 611 to 667 stems per ha. Furthermore, the study conducted by Perez (2005) in teak of 4 years found that the volume was about 190 $m^3$/ha which was similar to the volume found in this study at age of 5 year. This variation from Perez (2005) may be contributed by silvicultural operations, site quality, climatic condition or other environmental factors between two sites in which the site by Perez (2005) was seen to be good since they differ even in age.

At age of 16 years the volume was found to range from 420.33 – 466.35 $m^3$/ha. This value was higher than value of volume value found by Henry *et al.* (2011) at spacing of 1.98 by 1.98 m at the age of 17 years. This variation was mainly contributed by number of stems/ha present at this age. According to Tanzania Technical order No 1 of 2003 the required number that was supposed to be at this age was about 300 stems/ha while at the study area the stems was almost more than twice (654 stems/ha) the number required to be in this age. The similar variation was observed in the study conducted by Perez (2005), Petsri *et al*. (2007), Kauli *et al.* (2010), Takahashi (2012), Smith *et al.* (2011) and Hiratsuka (2008). The variation was mainly contributed by delay of thinning operation in the study site.

The results at age of 42 year teak in this study were comparable to other studies reported in other forests with similar species. At the age of 42 years the volume obtained in this study was twice the volume reported by KFRI (2011) at age of 40 years. The value at this age is comparable to the study conducted by Evans and Turnbull (2004) in India at age of 60 – 80 years which gives the volume of about 240 – 680 $m^3$/ha. The site quality and number of stem/ha might have contributed to these differences.

***Volume by Dbh classes***

The volume computed by diameter class is shown in Table 16 and the classes start from 1-5 cm as first diameter class and greater than 60 cm as the last diameter class found in the plantation. The volume in the first Dbh class is ranging from 0.4966 – 0.5766 $m^3$/ha with the largest Dbh class ranging from 199.40 – 266.88 $m^3$/ha. The volume in the first Dbh class was low regardless of the high stem /ha. This is probably caused by small size of Dbh that resulted to low contribution to the volume by individual tree. The summation of volume in the third and fourth diameter classes was 22.13 $m^3$/ha. This value is comparable with the study conducted by Prasad *et al.* (2008) for the same (species) with Dbh class of 10.1 - 20 cm giving the volume of 284.7 $m^3$/ha. However, the volume obtained in the study site was lower than that reported by Prasad *et al.* (2008) due to number of stem/ha found in these classes. The summation of volume contributed by individual tree was not large enough due to low number of stem/ha. In the study area for age of 2 and 3 years the number of stems was lower than that required by Tanzania Technical Order No 1 of 2003. Also low value of volume might be contributed by difference in climatic condition, site, soil and other silvicultural operation in these two sites. Furthermore, the diameter ranging from 10.1 - 20 cm was average diameter for the tree which overdue to receive first thinning, hence the lower volume in the study area may be contributed by delay of first thinning. The study conducted by Gajaseni and Jordan (1990) in Northern Thailand in these diameter class found the volume to be about 37.8 $m^3$/ha with number of stem of around 205 stems/ha.

**Table 16: Biomass, volume, basal area and stem per ha in by Dbh class**

| Dbh classes | Volume ($m^3$/ha) | Biomass (Tons/ha) | Stocking (Stem/ha) | Basal area ($m^{2/}$ha) |
|---|---|---|---|---|
| 1-5 | 0.54 ± 0.04 | 0.33 ± 003 | 219 | 0.04 ± 0.002 |
| 5.1- 10 | 3.03 ± 0.11 | 1.94 ± 0.07 | 334 | 0.20 ± 0.01 |
| 10.1- 15 | 6.875 ± 0.19 | 4.48 ± 0.13 | 239 | 0.46 ± 0.01 |
| 15.1- 20 | 15.26 ± 0.49 | 10.08 ± 0.33 | 100 | 1.02 ± 0.003 |
| 20.1- 25 | 23.97 ± 0.50 | 16.37 ± 0.41 | 159 | 1.61 ± 0.03 |
| 25.1- 30 | 35.61 ± 0.62 | 24.73 ± 0.57 | 136 | 2.40 ± 0.04 |
| 30.1- 35 | 49.72 ± 0.95 | 36.53 ± 1.19 | 92 | 3.35 ± 0.06 |
| 35.1- 40 | 64.30 ± 1.16 | 48.72 ± 1.58 | 58 | 4.34 ± 0.08 |
| 40.1- 45 | 82.99 ± 1.57 | 61.23 ± 2.13 | 47 | 5.61 ± 1.07 |
| 45.1- 50 | 104.12 ± 1.97 | 74.05 ± 2.58 | 31 | 7.05 ± 0.13 |
| 50.1- 55 | 131.06 ± 5.72 | 93.14 ± 5.21 | 7 | 8.89 ± 0.39 |
| 55.1- 60 | 152.10 ± 2.24 | 105.09 ± 1.58 | 12 | 10.32 ± 0.30 |
| >60.1 | 233.14 ± 16.89 | 162.49 ± 23.97 | 8 | 15.86 ± 3.99 |

The number of stem/ha was almost the same but the volume differ and the reason could be partly associated with many trees in the study area lying at Dbh class of 10.1 - 15 cm and few trees in Dbh class of 15.1 - 20 cm. Lower number of trees in the near upper bound of the diameter class that contributed to the lower volume in comparison to volume found in Thailand under the same diameter class. The volume in the study area at diameter of 50.1- 60 cm was 283.1585 $m^3$/ha with stems/ha of about 8. The volume was similar to that in diameter class of 10 - 20 cm by Prasad *et al.* (2008). The volume by Prasad *et al.* (2008) (669.01 $m^3$/ha) is thrice the volume in the study area in the class of 50 - 60 cm. The lower value in the study area was probably attributed by the thinning for compartment aged 19 years.

#### 4.4.2 Stand biomass

The estimates of biomass and C stock are important for management issues such as forest productivity and scientific purposes especially in the regulation of atmospheric C concentrations. In addition, the computation of biomass is a key variable in the annual change of GHG taken by trees through C sequestration. Also estimating tree biomass and its components are essential for assessing structural and functional attributes of forest plantation in the study site.

***Biomass by age class***

The result for biomass by age is presented in Table 15. The allometric equation developed in this study with single parameter (Dbh) for ABG was used to estimate the biomass of a tree. The above ground biomass in the study area was ranging from 2.66 - 278.98 t/ha with C stock of 1.33 - 139.49 t/ha. The value found in this study at age of 2 years was low when compared to the study carried by Bohre *et al.* (2013) in the same age who found relatively higher above-ground biomass of about 10.43 t/ha. The different in biomass value may be due to low number of stems per hectare in the study area. In the study site number of stem/ha was relatively lower than required by Tanzania Technical Order Number 1 of 2003. But these values in the study area was nearly the same (2.9 t/ha) to the finding of Petsri *et al. (*2004) at age of 3 years. This indicates that site quality in the study area had contributed more accumulation of biomass at age of 2 years in comparison to the above finding (Petsri *et al. (*2004)). Also study by Sing *et al.* (2013) at age of one year teak had about 3.8 t/ha with 1183 stems/ha while Sebastian, (2008), Takahashi (2012) and Henry *et al.* (2011) at age of 3 years had about 3.8 t/ha which is higher than value found in the study area. The reason for this increase in biomass was due to higher number of stem/ha as compared to the study area especially for Sing *et al.* (2013) and difference in age since biomass was increasing with increasing in age in the study area. The biomass was observed in study area to be highly influenced by number of stems/ha. In comparison to the study by Sebastian (2008), Petsri *et al. (*2004) and

Sing *et al.* (2013) the number of stems/ha was almost thrice the number of stems/ha in the study area that resulted to more biomass to such particular areas. Similar difference was also observed in study by Petsri *et al.* (2007) in Philippine at age of one year where the value was higher than value found in the study area at age of 2 years. Furthermore, finding by Siregar (2012) in Indonesia under small scale plantation was about 19.44 t/ha with 1000 stem/ha which was eight times the biomass obtained in the study area under similar age. Similar reason for difference in biomass applied for Siregar (2012) showing the effects of stem/ha to increase the biomass. Furthermore the effect of height was shown to increase the biomass which means the short tree had lower biomass compared to the same aged tree which is higher than others.

The value at age of 5 years in the study site was ranging from 80.68 - 93.12 t/ha. The result can be compared with the biomass value found by Sreejesh *et al.* (2013) which was 51.2 t/ha, Mbaekwe (2008) by 54.01 t/ha, Henry *et al.* (2011) and Takahashi (2012) at age of 6 years was 28.6 t/ha which was lower than in the study area. These variations were highly contributed by site quality since the compared result was lower in biomass despite of their higher age than stand of study site. Furthermore the climatic condition, soil, height difference between compared studies and other environmental factors may have contributing to the difference in biomass. The result in the study areas was in line with study conducted by Petsri *et al.* (2007) and Siregar (2012) at age of 6 years in which the value was 93.7 t/ha with 1111 stems per ha. The small difference may be due to difference in number of stems/ha at age of 5 years in which was about 1568 stem/ha in comparison of 1111 stem/ha at age of

6 years. The difference in biomass seems to be influenced more by good site quality since value obtained in the study was almost equal to value of biomass found in other area with one year's older than in the study area. The value obtained in study at age of 5 years was the same to value obtained by Takahashi (2012) at age of 20 years which was about 86.9 t/ha which proves that the quality between two sites were highly different in which one of the site was best than other.

At age of 19 years the results agree with value of teak found by Kraenzel *et al.* (2003) in Panama at 20 years Teak which was about 120 t c/ha. This indicates that the site quality in the study area was better than the site quality in Panama. Furthermore, at old age (46 years) Teak in the study area had biomass ranging from 246 – 278.98 t/ha which was in line with the study conducted by Brown *et al.* (1989) in tropical forest which gives the range of 238-314 t/ha in Cameroon. Also Glenday (2008) found the value for above-ground biomass for hardwood was ranging from 203-357 t/ha in which the value found in the study lay within the range. This value can be compared to value found by Lu (2006) in low land forest which ranges between 260 - 267 t/ha. The good site quality, silvicultural management and other environmental factors might contribute to good performance of teak in study site.

***Biomass by Dbh classes***

The biomass above-ground biomass in the study area by Dbh class is shown in Table 16. The biomass obtained in the lower diameter class (1- 5 cm) was 0.33 t/ha with 219 stems/ha and maximum diameter class (> 60 cm) was 162.49 t/ha with 8 stems/ha. The result by Gajaseni and Jordan (1990) for similar species under Dbh class of 21-30 cm of about 22.72 t/ha with 49 stems/ha was similar to the value of biomass found in this study at Dbh class of 25.1 – 30 cm although the number of stem/ha was lower than in the study area.

***AGB biomass distribution in the tree***

The individual trees and stands of forests grown can sequester substantial amount of C. The distribution of biomass in tree differs in stems, branches, leaves as well as roots as shown in the Figure 11. Large part of biomass was stored in stems followed by roots, then branches and lastly twigs and leaves. All sampled trees their average tree biomass for each component was used in drawing the figure below. The Figure 11 below shows the percentage contribution to the total tree biomass in which the stem contribute about 62.5%.

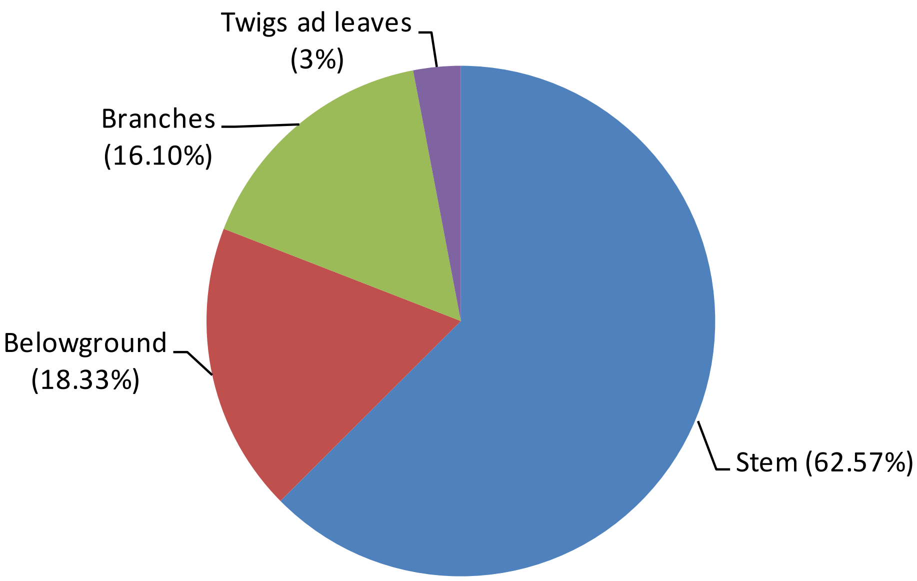



**Figure 11: Biomass distributions in the tree parts**

Similar results of biomass distribution were observed by Takahashi (2012) in the same species where the stems contributing about 69.2%, leaves by 1.9%, branches by 14.8% and 14.1% in root. Also similar results were observed by Baishya *et al.* (2009) in which their contribution were 61% in stem, 4% in leaves, 20% in branches and 15% in roots. These values of biomass in leaves in the study areas were decreasing with increase in age in which the young Teaks have more biomass in leaves in comparison with other tree part. Hence, young stand has greater amount of its biomass being stored in leaves compared to the old stand which has greater share in stem. Also the same trends of distribution of biomass in young age to contribute more biomass in leaves was shown by O'kting'ati *et al.* (1998), Perez (2003), Bohre *et al.* (2013) and Sreejesh *et al.* (2013) that ranges from 1.08 to 60.18%.

### 4.4.3 Stem per ha

The stem per ha was ranging from 192 - 1568 by considering by age (see Table 15) and from 8 - 334 stem per ha by Dbh classes (see Table 16). The lowest stems per ha is shown by compartment of 42 years and high stems per ha is shown by compartment of 5 years (Table 15). The stem per ha for compartment aged 2 years was low due to poor survival and there were no beating up.

Results indicate that the mean stems per ha values were decreasing with age which is due to thinning and mortality. The stem per ha in 2 years ranges from 356 to 634 which was the lowest in comparison to the allowed stem per ha at 2 years by Tanzania Technical Order Number one of 2003 that requiring 1600 stems per ha. The stem/ha at age of 2 years if compared by Sing *et al.* (2013) of Teak of one year with stems per ha of about 1183 was low due to survival rate and some trees were probably cleared by farmers practicing taungya system in the study site. Also, the findings by Siregar (2012) in a stand with 1000 stem/ha were higher than stem/ha obtained in a study area.

At the age of 5 years the stem per ha was also high in comparison to the study conducted by Siregar (2012) and Petsri *et al.* (2007) (1190 stems/ha) on teak of 6 years. This indicate that the amount of stem/ha required by Tanzania Technical Order Number one of 2003 of about 1600 stems per ha was almost equivalent to 1568 stem/ha at age of 5 years.  The greater number was highly contributed by survival rate especially in age 5 years.

Furthermore the effects of low number of stem/ha was observed in age 19 years where the stem/ha had decreased the total tree biomass in the study area (Table 15). The lower number of stem/ha was caused by thinning done at age of 18 years.

### 4.4.4 Basal area per ha

The basal area ranges from 0.41 - 31.94 $m^2$/ha from 2 years to 42 years (see Table 15) and ranges from 0.04 - 15.86 $m^2$/ha by considering Dbh classes (Table 16). The low basal area in 2 years was contributed by low number of stem per ha present in the compartment. The basal area for 16 year was high in comparison with that of 19 years since the number of stem present was high for 16 years teak. The findings reveal that the basal area increases with increase in age except for the aged teak intervened by thinning operations. Also the basal are by Dbh class increases with the increase in Dbh class i.e. the higher the Dbh class the higher the basal area.

Basal area was highly influenced by stems per ha in the study area. At age of 2 and 42 years the basal area was similar to the finding by Sunanda and Jayarame (2006) that ranges from 0.3 - 51.98 $m^2$/ha on young teak of one year to old teak stand. But this result was low in comparison to the study by Brown (1997) and Perez and Kanninen (2003) at Teak of one year in which the basal area was 1.2 $m^2$/ha. The variation of the basal area was caused by low number of stems/ha in the study area at year 2.

At age of 5 years, the basal area (17.33 $m^2$/ha) was comparable to the study by Perez (2003) at age of 6 year with basal area of 18.2 $m^2$/ha. Other basal area were taken as average of 19, 21 and 34 years in the study area having 27.92 $m^2$/ha and this value is comparable to Shamaki and Akindele (2013) average at age of 19 years and 20 years having 27.29 $m^2$/ha.

# CHAPTER FIVE

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

The volume and biomass equations developed in this study can be used by the interested institutions, organisations and academics for research purposes as well as relevant authorities particularly National Carbon Monitoring Centre for estimating the current standing stock of the biomass resource and whether the standing woody biomass can meet local demands and international standard. Total above-ground biomass model, total below-ground biomass model, total tree biomass model and total tree volume were developed in this study. However, model validation must be done for different area with different soil, topography and altitude to make these models applicable to the area of interest.

The equation with single parameter (Dbh) for both volume and biomass tends to overestimate the biomass and volume especially for young stand more than old stand, so it is better to estimate the young stand volume and biomass by using equation with two parameters (Dbh and ht). The use of model with single parameter (Dbh) can be applied when simplified approaches are necessary, such as in participatory methods of C monitoring, as Dbh is easily measured by even non-professional actors. The findings show that biomass equations incorporating height are the most likely to be accurate because it provides values similar to those obtained through the full enumeration of trees. The results for biomass estimates showed that teak plantations can be very effective on reducing the atmospheric $CO_2$ concentrations besides the role that they play in wood production for commercial purposes. Furthermore, study findings shows that older trees sequester large quantity of C stocks compared to younger trees and silvicultural operation in the study area tends lower the biomass and volume at time of operation.

Total tree biomass stocks estimated using two methods (developed biomass equations and volume equation, BD, BEF and R.S) are statistically not significantly different. Aboveground tree components store substantially higher C stocks (81.33%) compared to belowground tree components (18.67%). Older trees store substantially larger quantities of C in stem compared in comparison to younger trees which have more C on roots. Also study reveals that biomass and C requested in trees depends on tree age, site conditions, forest management such as thinning operation and biological characteristics of tree.

## 5.2 Recommendations

### 5.2.1 The need to use single parameter and two parameter models for biomass and volume estimation

The equation developed for both volume and biomass in this study are specific for Longuza Forest plantation for tree with Dbh of 1cm to 83.4 cm. The integration of Dbh and ht dimensions in the estimation of volume and biomass provide high accuracy estimate than single parameter estimates. The problem associated with two parameter models is that the total tree height measurement is often erroneous and tedious for standing trees in the plantation with dense canopy. Hence, the use of single parameter models (Dbh) became necessary, as Dbh is easily measured by even non-professional actors.

### 5.2.2 The need to conduct studies on plantation soil biomass

The study estimated tree component biomass in the plantation, further research is needed to know the contribution of the soil organic C and herbaceous layers in Teak plantation.

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# APPENDICES

**Appendix 1: Data collection form**

Plot number ……………Compartment age……… Compartment area………………………

Location: **Easting**………………**Northing**…………………Elevation………Soil …………

Topographic ………Disturbances…………………Any near vegetation ………………

GPS type……………GPS error……….. Arc type…………………… Others............

| S/N | Tree | diameter | Height | Remarks |
|---|---|---|---|---|
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# Appendix 2 Tree sample data

| Tree no | Tree age(Years) | Measured Biomass(Kg) | Estimated biomass by regression (Kg) | Estimated biomass by Volume (Kg) | Dbh (cm) | Ht (m) | BWD ($gcm^{-3}$) |
|---|---|---|---|---|---|---|---|
| 1 | 46 | 5989.41 | 5622.94 | 5040.75 | 83.4 | 36.5 | 0.62 |
| 2 | 46 | 5015.99 | 5233.47 | 4692.08 | 80.5 | 37 | 0.61 |
| 3 | 41 | 4271.11 | 4909.09 | 4401.4 | 78 | 36.5 | 0.6 |
| 4 | 42 | 4859.23 | 4657.16 | 4175.46 | 76 | 36.5 | 0.59 |
| 5 | 41 | 4492.21 | 4411.95 | 3955.39 | 74 | 36.5 | 0.59 |
| 6 | 41 | 4590.78 | 4173.46 | 3741.19 | 72 | 36 | 0.58 |
| 7 | 46 | 4648.67 | 3941.69 | 3532.86 | 70 | 29.5 | 0.58 |
| 8 | 42 | 3405.38 | 3552.24 | 3182.4 | 66.5 | 35.5 | 0.58 |
| 9 | 46 | 2821.02 | 3286.62 | 2943.07 | 64 | 33 | 0.58 |
| 10 | 42 | 2823.59 | 3162.84 | 2831.45 | 62.8 | 37 | 0.57 |
| 11 | 41 | 3061.36 | 3051.48 | 2730.99 | 61.7 | 35.5 | 0.57 |
| 12 | 41 | 2903.11 | 2883.36 | 2579.22 | 60 | 32.5 | 0.56 |
| 13 | 41 | 2353.05 | 2691.78 | 2406.1 | 58 | 35.5 | 0.56 |
| 14 | 41 | 2308.12 | 2534.17 | 2263.56 | 56.3 | 28.5 | 0.56 |
| 15 | 41 | 2101.21 | 2399.11 | 2141.31 | 54.8 | 34.5 | 0.56 |
| 16 | 46 | 1542.22 | 2157.01 | 1921.95 | 52 | 32 | 0.56 |
| 17 | 41 | 2093.83 | 1992.08 | 1772.3 | 50 | 29.5 | 0.56 |
| 18 | 46 | 1959.45 | 1833.78 | 1628.52 | 48 | 33.5 | 0.55 |
| 19 | 41 | 2113.03 | 1757.13 | 1558.83 | 47 | 37.5 | 0.55 |
| 20 | 46 | 1870.74 | 1608.79 | 1423.86 | 45 | 34.5 | 0.55 |
| 21 | 41 | 1882.96 | 1537.11 | 1358.57 | 44 | 36.5 | 0.54 |
| 22 | 46 | 1790.82 | 1398.71 | 1232.39 | 42 | 33 | 0.54 |
| 23 | 42 | 1528.46 | 1332 | 1171.51 | 41 | 28.5 | 0.54 |
| 24 | 21 | 1636.58 | 1266.93 | 1112.09 | 40 | 32 | 0.53 |
| 25 | 16 | 1216.25 | 1203.52 | 1054.14 | 39 | 29.5 | 0.53 |
| 26 | 46 | 1288.4 | 1081.64 | 942.64 | 37 | 29.5 | 0.53 |
| 27 | 19 | 910.95 | 994.55 | 862.86 | 35.5 | 27 | 0.53 |
| 28 | 41 | 840.71 | 857.64 | 737.24 | 33 | 27.5 | 0.53 |
| 29 | 19 | 562.65 | 780.42 | 666.26 | 31.5 | 26.5 | 0.52 |
| 30 | 19 | 513.74 | 711.68 | 603 | 30.1 | 31.5 | 0.52 |
| 31 | 41 | 564.25 | 683.2 | 576.77 | 29.5 | 29.5 | 0.52 |
| 32 | 21 | 558.03 | 614.58 | 513.5 | 28 | 28.5 | 0.52 |
| 33 | 42 | 406.52 | 488.38 | 396.86 | 25 | 23.5 | 0.52 |
| 34 | 19 | 395.98 | 449.57 | 360.92 | 24 | 27.5 | 0.52 |
| 35 | 33 | 325.64 | 376.84 | 293.43 | 22 | 18.5 | 0.51 |
| 36 | 33 | 427.12 | 310.6 | 231.81 | 20 | 27 | 0.51 |
| 37 | 19 | 208.65 | 220.84 | 203.2 | 19 | 20.5 | 0.5 |
| 38 | 33 | 198.86 | 212.37 | 176.06 | 18 | 24 | 0.5 |
| 39 | 5 | 103.56 | 173.3 | 103.44 | 15 | 23 | 0.46 |
| 40 | 2 | 96.39 | 129.64 | 62.36 | 13 | 19 | 0.46 |
| 41 | 5 | 63.16 | 110.22 | 44.02 | 12 | 12.5 | 0.46 |
| 42 | 5 | 52.32 | 76.15 | 11.74 | 10 | 12 | 0.45 |
| 43 | 3 | 22.88 | 61.5 | -2.1975 | 9 | 9.5 | 0.44 |
| 44 | 5 | 14.98 | 36.94 | -25.672 | 7 | 9 | 0.43 |
| 45 | 3 | 10.25 | 27.02 | -35.208 | 6 | 6.5 | 0.42 |
| 46 | 2 | 7.74 | 18.67 | -43.277 | 5 | 9 | 0.41 |
| 47 | 2 | 5.56 | 11.87 | -49.879 | 4 | 7 | 0.39 |
| 48 | 2 | 2.09 | 6.62 | -55.014 | 3 | 5 | 0.38 |
| 49 | 2 | 0.75 | 2.91 | -58.682 | 2 | 4 | 0.34 |
| 50 | 2 | 0.21 | 1.62 | -59.966 | 1.5 | 2 | 0.25 |
| 51 | 2 | 0.06 | 0.7136 | -60.883 | 1 | 1.5 | 0.24 |

**Appendix 3: Tree height model forms and the selected model**

The tree model forms were found in in Mugasha *et al.,* 2013b

1. $ht = 1.3+a[\exp(-b/(dbh+c))]$
2. $ht = 1.3+a[1-\exp(-b.dbh)]^c$
3. $ht = 1.3+a[1-\exp(-b.dbh^c)]$
4. $ht = 1.3+a[\exp(-b.\exp(-c.dbh))]$
5. $ht = 1.3+[dbh/(a+b.(dbh))]c$
6. $ht = 1.3+a/(1+b.\exp(-c.dbh))$

Where,

*Ht* =height measured in (m)

Dbh=diameter at breast height in (cm) and a, b and c were model parameters (constant)

These forms of models were given by Ratkowsky (1990), Richards (1959), Yang *et al.* (1978), Winsor (1932), Nilsson *et al.* (2010) and Pearl and Reed (1920) respectively

**Result for height model**

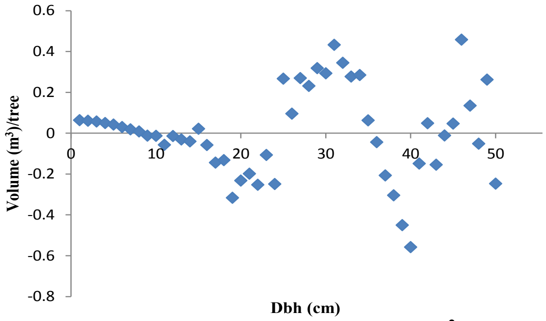
**Height model parameters and performance criteria**

| Eqns | Parameter estimates | | | Performance criteria | | | | |
|---|---|---|---|---|---|---|---|---|
| | a | b | c | $R^2$ | MSE | *MPE* | *MPE%* | AIC |
| 1 | 39.2288 | 14.9268 | 2.5806 | 0.8971 | 11.3328 | 0.000842 | 0.0842 | 1519.4716 |
| 2 | 30.3254 | 0.0727 | 1.4858 | 0.9014 | 10.8568 | 0.001825 | 0.1825 | 1507.1134 |
| 3 | 29.6127 | 0.0233 | 1.3081 | 0.9021 | 10.7832 | 0.001254 | 0.1254 | 1505.1154 |
| ***4**** | ***29.1579*** | ***3.0280*** | ***0.1078*** | ***0.9024*** | ***10.7467*** | ***-0.00092*** | ***-0.092*** | ***1504.1772*** |
| 5 | 1.3779 | 0.2161 | 2.3972 | 0.8966 | 11.3847 | 0.002125 | 0.2125 | 1520.7878 |
| 6 | 28.2797 | 10.5611 | 0.1682 | 0.9000 | 11.0098 | -0.00340 | -0.340 | 1511.144 |

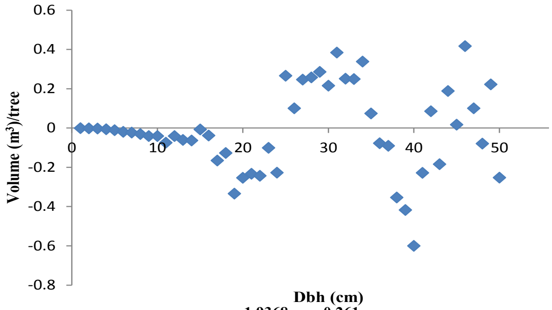
* = The best model low AIC in comparison with the other models

## Appendix 4: Scatter plots for unselected volume model

### Total tree volume model up to cut off point of 2 cm

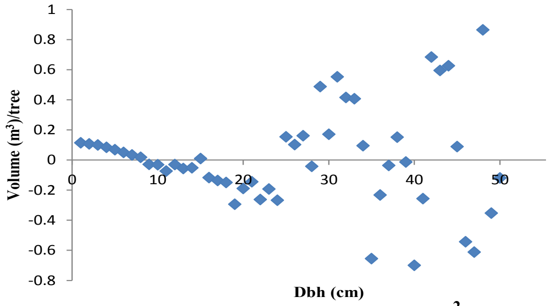



**Eqns 7 $V=-0.0711+0.0032\times dbh+0.0112\times dbh^2$**

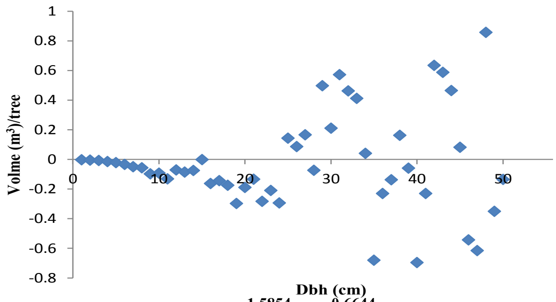



**Eqns 9 $V=0.00069\times Dbh^{1.9368}\times ht^{0.261}$**

### Total stem volume model

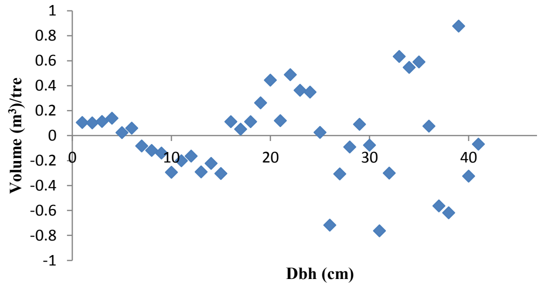



**Eqns 7 $V=-0.1572+0.0183\times dbh+0.0006\times dbh^2$**

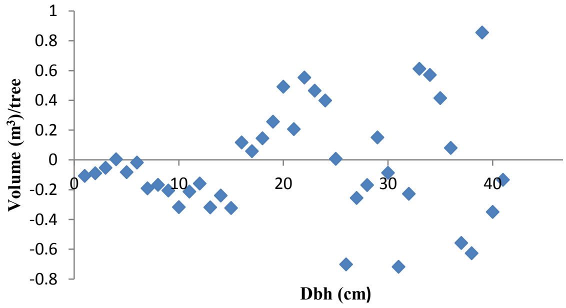



**Eqns 9 $V=0.00047\times Dbh^{1.5854}\times ht^{-0.6644}$**

### Total volume up 10 cm top diameter stems and branches volume model (Merchantable volume)



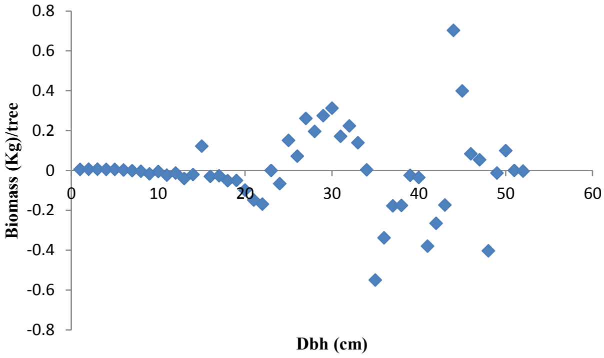

**Eqns 7 $V=-0.2508+0.0102\times dbh+0.00097\times dbh^2$**



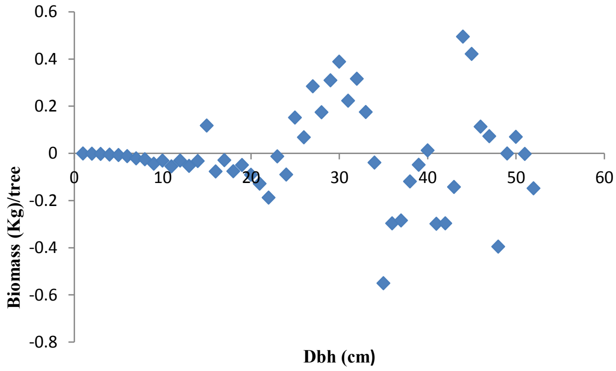

**Eqns 9 $V=0.00049\times Dbh^{1.9292}\times ht^{0.3024}$**

## Appendix 5: Scatter plots for unselected biomass model

### Total tree above ground biomass model

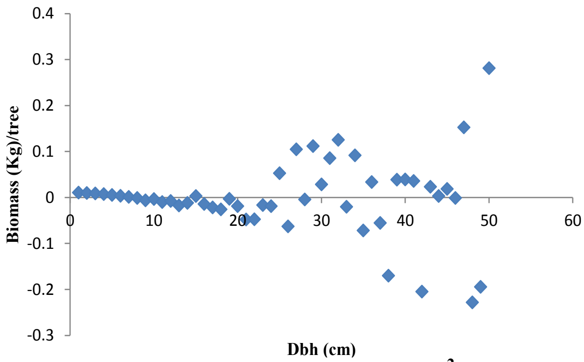



**7 B=-4.5573+-1.8448×dbh+0.6886×dbh$^2$**

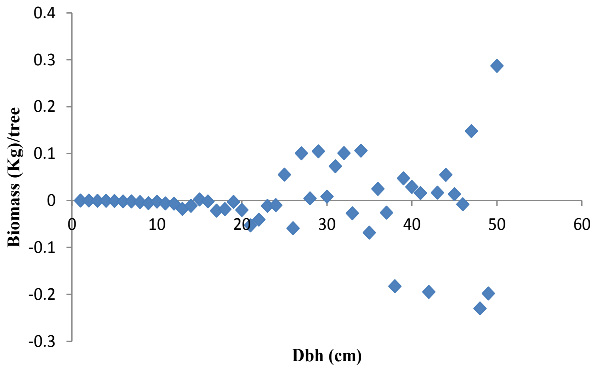



**Eqns 9 B=1.2136×Dbh$^{2.1598}$×ht$^{-0.3616}$**

### Total below ground biomass model

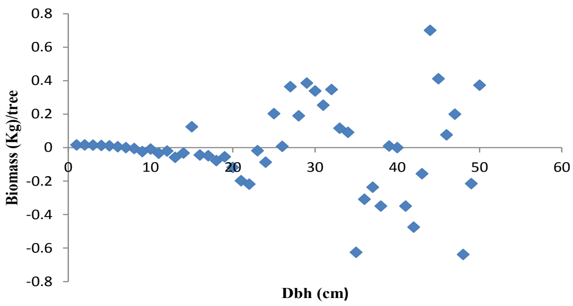



**Eqns 7 B=-0.5352+0.3146×dbh+0.0202×dbh$^2$**

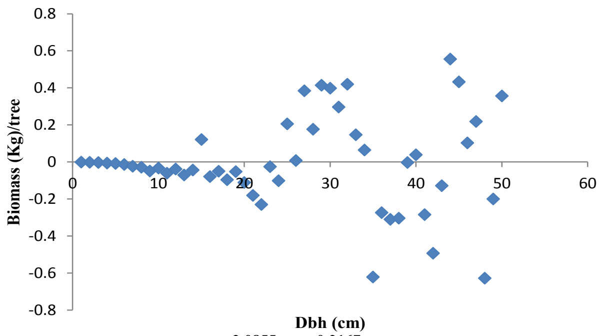



**Eqns 9 B=0.0854×Dbh$^{1.7601}$×ht$^{0.4317}$**

### Total tree biomass model



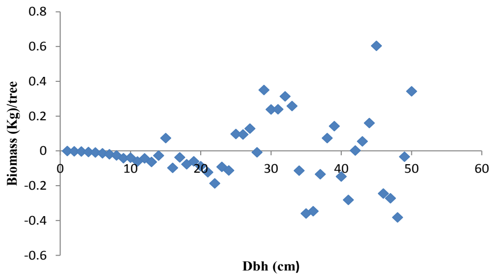

**Eqns 7 B=-17.024+-0.3016×dbh+0.8123×dbh$^2$**



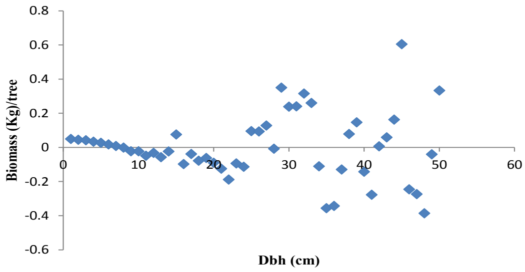

**Eqns 9 B=1.2097×Dbh$^{2.0855}$×ht$^{-0.2167}$**

## Appendix 6: Scatter plot for stem biomass model and branch biomass models

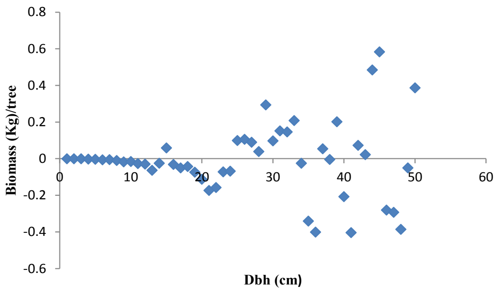
### Stem biomass model



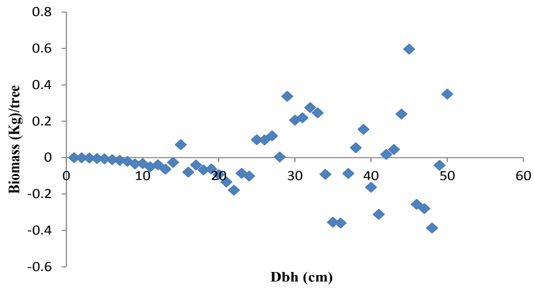

**Eqns 6 B=0.9740×dbh$^{1.8369}$**




**Eqns 7 B=-56.034+6.6151×dbh+0.4036×dbh$^{2}$**

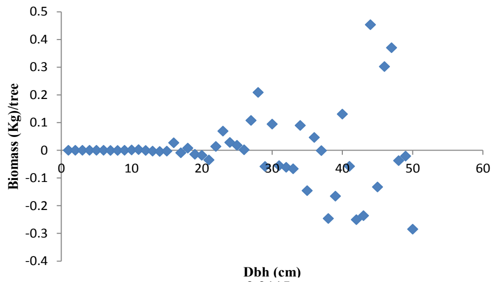



**Eqns 8 B=Exp (-1.951+0.8065×ln (ht×dbh$^{2}$)**

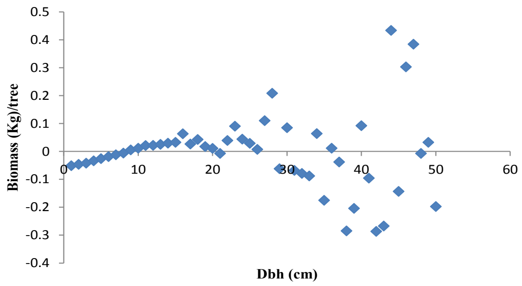



**Eqns 9 B=0.6089×Dbh$^{1.7855}$×ht$^{0.1933}$**

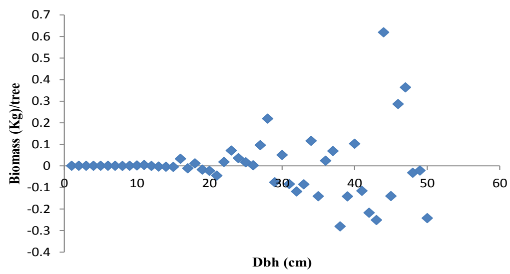
### Branch biomass models



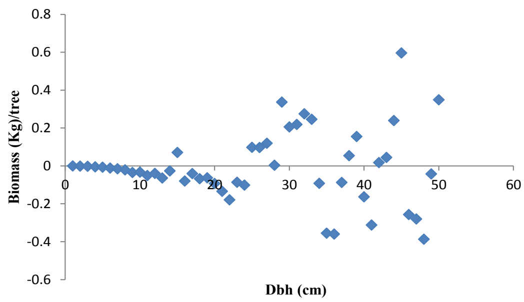

Eqns **6 B=0.p-0009×dbh$^{3.2115}$**




**Eqns 7 B=60+-9.7904×dbh+0.2815×dbh$^{2}$**




**Eqns 8 B=Exp (-10.211+1.3933×ln (ht×dbh$^{2}$)**




**Eqns 9 B=0.0783×Dbh$^{3.7451}$×ht$^{0.0062}$**