# ALTERNATIVE ABOVEGROUND BIOMASS ESTIMATION METHODS IN MANAGED PLANTATION OF *Cupressus lusitanica* GROWN AT WONDO GENET, SOUTH CENTRAL ETHIOPIA.

MSc. THESIS

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A THESIS SUBMITTED TO THE

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FOREST RESOURCES ASSESSEMENT AND MONITORING

MARCH, 2020

## ADVISORS’ APPROVAL SHEET

This is to certify that the thesis entitled “Alternative aboveground biomass estimation methods in managed plantation of *Cupressus lusitanica* grown at Wondo Genet, south central Ethiopia” submitted in partial fulfillment of the requirements for the degree of Master's with specialization in Forest Resources Assessment and Monitoring, the Graduate Program of the Department of General Forestry, and has been carried out by Zelalem Tadele Jaben under my/our supervision. Therefore I/we recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the department.

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| ______________________ | ____________________ | _______________ |
| Name of main advisor | Signature | Date |

# EXAMINERS' APPROVAL SHEET

We, the undersigned, members of the Board of examiners of the final open defense by Zelalem Tadele Jaben have read and evaluated his thesis entitled "Alternative aboveground biomass estimation methods in managed plantation of *Cupressus lusitanica* grown at Wondo Genet, south central Ethiopia" and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirements for the Degree of Master of Science in Forestry study with specialization in Forest Resource Assessments and Monitoring.

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| Name of the Internal Examiner | Signature | Date |
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| Name of External Examiner | Signature | Date |

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Zelalem Tadele

March, 2020

# DECLARATION

I hereby declare that this thesis entitled “Alternative methods of biomass equations development for above ground and component biomass of thinned and pruned plantation of *Cupressus lusitanica* grown at Wondo Genet, south central Ethiopia” submitted in partial fulfillment of the requirements for MSc degree in Forest Resources Assessment and Monitoring at Wondo Genet College of Forestry and Natural Resources, is my own work and, it contains no materials previously published or written by another person and has not been previously submitted or accepted elsewhere to any other university or institute for the award of any other degree.

Name: Zelalem Tadele Jaben Signature: ________________

Place: Hawassa University, Wondo Genet College of Forestry and Natural Resources.

Date of submission: March, 2020

# LIST OF ABBREVIATIONS and ACRONYMS

| | |
|---|---|
| AGB | Above ground tree biomass |
| AIC | Akaike Information Criterion |
| DBH | Diameter at Breast Height (1.3m) |
| DSH | Diameter at Stump Height |
| GHG | Green House Gases |
| IPCC | Intergovernmental Panel on Climate Change |
| M | Mass |
| MAB | Mean absolute bias |
| MC | Moisture Content |
| MRV | Monitoring Reporting and Verification |
| P | Density |
| PRESS | Predicted Residual Error Sum of Square |
| $R^2$ | Coefficient of Determination |
| REDD+ | Reducing Emission from Deforestation and Forest Degradation |
| RMSE | Root Mean Square Error |
| RSE | Residual Standard Errors |
| RSS | Residual Sum of Square |
| S % | Average standard error in percent |
| SE | Standard Error |
| V | Volume |
| W | Weight |

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# ABSTRACT

*Forest biomass is estimated through direct and indirect methods. The indirect method is less costly and efficient. Biomass equation is one of the indirect methods to estimate biomass using certain parameters. However, very few biomass equations have been developed for limited tree species in Ethiopia and hence, generic biomass equations are usually used. This may under or overestimate the biomass. Besides, the accuracy of biomass estimate using the different methods was inadequately studied. Therefore, the general objective of this study was to evaluate the performance of semi-destructive and generic method in reference to destructive method for Cupressus lustanica grown at Wondo Genet, South central Ethiopia. For the semi destructive method 30 sample trees (10 from each age group) were selected from three ages (5, 12 and 24). Sample trees were measured for their biometric parameters such as diameter at breast height (DBH), diameter at stump height (DSH), and total height (H). For the sampled trees 10% of the total branch counts were trimmed for further parametric measurements. Based on the collected data 6 models were fitted using R 3.2.3 (R Development core team 2019). The best biomass equations were selected on the basis of different performance statistics (Bias, RMSE, PRESS, AIC, D and R2). The best performing total above ground biomass equation by semi-destructive method was* $Y = 0.07407x\ D^{1.01228}\ x\ H^{1.5674}$ *(*$R^2 = 0.94$ *, p =3.882e-12). Estimation performance test was conducted for the semi-destructive model (this study) and generic model (Vigil, 2010) by using the destructive model (Leakemariam, et al., 2013) as a reference. Pair wise t-test was used to test the significance of the variation on above ground biomass estimation. The semi destructively developed and generic above ground biomass models underestimated by 18.7% and 39.4% respectively. The result of the pair wise t-test showed that the difference was insignificant for the semi destructive method (P=0.9059), while it was significant for the generic model (P= 0.0294) in reference to the destructive method. It was concluded that semi destructive method can estimate the above ground biomass of Cupressus lustanica as good as the destructive method. This can make the process of biomass equation development less costly and environmentally friendly.*

Keywords/Phrases: Biomass equations, Biomass, component biomass, Semi destructive method

# 1. INTRODUCTION

## 1.1. Background

The concentration of carbon dioxide (the major GHG) and other greenhouse gases in the atmosphere has considerably increased over the last century. Carbon dioxide is accumulating in the atmosphere at a rate of 3.5 Pg per annum, the largest proportion of which emit from burning of fossil fuels and conversion of tropical forests to agricultural production (Paustian *et al*., 2000). Forest plays a major role in climate change mitigation by sequestering carbon from the atmosphere through photosynthesis.

*Cupressus lustanica* is the most widely planted coniferous species in Ethiopia. It was introduced to Ethiopia probably before 1950 from different countries (Pukala and Pohjonen, 1993). Later on it is distributed to different parts of the country through afforestation and reforestation activities. It is commonly used in Ethiopia for sawn building timber, construction beam, furniture production. More over the species is used as a live fence, hedge and windbreak. Biomass is an important variable in different forestry and ecological researches. It is defined as oven dried or fresh mass of an organic matter found both above and below ground (Lehtonen *et al*., 2004). Tree biomass is a crucial variable that helps to understand the potential of a forest for climate change mitigation (GTOS, 2009). Since forest inventories are conducted to gather information of standing trees. Tree biomass estimation is usually done using different biomass equations. These biomass equations are mathematical models constituting easily measurable tree parameters. The choice of biomass equation has its own influence on biomass and carbon estimation (Chave *et al.*, 2014).

Inappropriate choice of biomass equation may lead to over or under estimation of both biomass and carbon stock. Most biomass models currently in use are mixed species that ignores species diversity and variation between species trait (Namvt *et al.*, 2016). Commonly biomass equations are developed either by destructive or nondestructive methods. The destructive method involves felling an appropriate number of trees and measuring their field and oven dry weight. Even though, it is the most accurate method it is costly and impractical especially when dealing with heterogeneous forest (Basuki *et al.,* 2009). This “destructive” method is commonly used to validate other less intensive and costly methods, such as the estimation of biomass and carbon stock using non-destructive in-situ measurements and remote sensing (Wang et al., 2003).

The semi-destructive method attempts to estimate biomass from easily measurable tree variables with less destruction to the tree. This method works by constructing functional relationship between tree biomass and other tree variables like DBH, height and wood density without any destructive sampling.

## 1.2. Statement of the problem

The need for reliable estimation of total biomass has led to development of various biomass estimation methods. For instance, REDD+ requires the standard and reliable information of forest carbon stock. Besides, the development of species specific biomass equation is important for sustainable forest management and productions. Biomass equations that relate a tree biomass to different measurable variables is used to estimate tree biomass and carbon stock (Brown, 1997; Gibbs *et al.,* 2007). The models should also be applicable in the process of MRV (Monitoring Reporting and Verification).

The main method of developing biomass equation is destructive harvest. In this method trees are felled and measured to generate dataset helping to develop biomass equations. Though the destructive method is the best method to estimate biomass, it is not acceptable to apply in conservation forest and on rare species, and the method is costly and environmentally unfriendly. As an alternative to this the semi-destructive method is also used for the development of biomass equation. This method involves measurement of standing trees through harvesting part of the branches of sampled trees without total felling. In addition to the destructively and semi-destructively developed biomass equations generic biomass equations are also used for biomass estimation. But the biomass estimation by both the semi-destructively developed and generic biomass equation could cause under or overestimation. Nevertheless, empirical evidence is lacking on the variation and accuracy of the various biomass estimation methods. Therefore, this study was opted to evaluate the performance of semi-destructive and generic methods in reference destructive method of biomass estimation for *Cuppressus lustanica* grown in South Central Ethiopia.

## 1.3. Objective

### 1.3.1. General objective

The overall objective of this study was to evaluate performance of semi-destructive and generic biomass estimation methods in reference to destructive methods for managed (pruned and thinned) *Cupressus lusitanica* grown at Wondo Genet, south central Ethiopia

### 1.3.2. Specific objectives

- Developing biomass equations for total aboveground and component's biomasses of *Cupressus lusitanica* through semi-destructive method.
- Compare and contrast the performance of the semi destructive models over the generic and destructive models.

## 1.4. Significance of the study

Usually tree biomass models are used for the biomass and carbon stock estimation of a tree and forest. In most cases these biomass models are developed by destructive method which is difficult because of its time and labor intensive activities. In addition to that the destructive method is sometimes not applicable in some areas where tree cutting is not allowed and for trees that are in the red list. From the scientific point of view the findings of this study will contribute to making the development of biomass models easier and less costly and less destructive. This can play its own role on improving the estimation of biomass and carbon stock of a forest. It can benefit any interested bodies that work on the use and development of biomass models by making the work less costly and time saving without compromising the estimation quality of the model.

# 2. LITERATURE REVIEW

## 2.1 Ecological and morphological characteristics of *Cupressus lustanica.*

*Cupressus lustanica* was first introduced to Ethiopia in 1950 (Negash *et al.,* 1995; Pukala and Pohjonen, 1993). The genus Cupressus is native to warm temperate climate in the norther hemisphere. It is found around the Mediterranean in North America and Asia (Cros e*t al.,* 1999).Cupressus lustanica is native to Mexico, Guatemala and Honduras. It is widely grown in the altitudinal range between 1800 and 2600 m.a.s.l. In suitable conditions it can grow up to 30m high and 1.2 m diameter. It prefers moist soil for better growth (Cros *et al.,* 1999). The morphological characteristics of Cuppressus lustanica are easily identifiable. It has rough and subcylindarical branchelets that are aligned radially. The leaves are green and blue green in color. It is a monoecious species and for first round seed bearing it takes three to four years (Johnson and Karrfalt, 1996). Cupressus lustanica has an ability to adapt to wide range of ecology and it grows well in the mid altitude range but as it extends to high altitudes the growth will be stunted (Tesfaye and Petty, 1999)

## 2.2. Tree above ground biomass

A tree above ground biomass is the whole plant material that is found above the ground of a tree including stem/trunk, branch, seed and leaf/foliage. Estimation of tree biomass might be required for different purposes like research, management, for studies of energy and nutrient flow in an ecosystem. Nowadays biomass of a tree or a forest is mostly estimated for the issues related with carbon and climate change. Biomass can be estimated both for a single tree and the whole forest area. For a single tree biomass estimation the part of the tree can be divided in to two as above ground and below ground biomass.

The above ground biomass includes all the tree parts that are found above the ground i.e. stem, branch, bark, leaf, seed and fruit. The below ground biomass is composed of the root including the fine roots (Brown, 2002).

### 2.3. Biomass estimation methods

Estimation of tree biomass is essential in the assessment of forest condition, structure and carbon stock (Chavé *et al.*, 2005). As asserted by Brown and Lugo (1992), most researchers have relied on tree biomass inventory as a reliable way of estimating forest biomass because it accounts for the largest fraction of biomass in forest ecosystem. In many cases of biomass estimation only the above ground biomass is estimated because of the difficulty of estimating the below ground biomass. For a given forest biomass estimation the forest could be divided into different sections as overstory, shrub, lianas and others and the estimation of biomass for each sections will be done following different procedures and principles. Generally the biomass of tree could be estimated through two methods i.e. direct and indirect method.

#### 2.3.1. Direct or Destructive method

In the direct method the biomass of a tree is estimated by destructively harvesting the whole plant material and measuring its mass or weight (Gibbs *et al.*, 2007). In this method the trees are destructively harvested and separated into different parts like stem, branch, leaf, seed and flower and then each part will be weighed for its fresh weight. From the total plant parts small samples with known fresh weight will be taken in to the laboratory and oven dried to estimate the moisture content of the tree. Once the moisture content is known by multiplying the total fresh weight of the tree by its moisture content the dry biomass of the tree can estimated (Liu and Westman, 2009), Even though the direct method is the most accurate method for biomass estimation because of its destructive nature it is not usually applied, instead other indirect methods are used (Montès *et al.*, 2000; Wang *et al.*, 2003). This method is usually applied in the development of biomass equations (Devi and Yadava, 2009; Navár, 2009).

### 2.3.2. Indirect or Non-destructive method

#### 2.3.2.1. Remote sensing

Remote sensing method is the most cost effective and practical method for the estimation of biomass over large area. Remote sensing is the process of acquiring information from a distant without direct contact with the source or area being examined (Vashun and Jayakumar, 2012). Although the remote sensing method is not able to measure the biomass of a tree or forest the radiometry is sensitive to the shadow, texture and different vegetation structures like crown area and tree density. (Baccini *et al.*, 2008) The remote sensing technologies used for biomass estimation are classified into three broad groups as passive optical, LIDAR and radar. The passive optical technology estimates the biomass by recording the interaction between the sun radiance and vegetation cover. (Bombelli *et al*., 2009).The radar (Radio Detection and Ranging) technology it is a remote sensing method where radio signals are used to determine the biomass of an object. The radar technology operates day and night passing through the cloud. LIDAR (Light Detection and Ranging) is an active remote sensing technology, where the instrument itself emits laser and record the backscattering from the vegetation. (Rosette *et al*., 2012).

#### 2.3.2.2. Biomass Equations/Allometry method

In the indirect method tree biomass is estimated by using biomass models or biomass equations. The term Allometry refers to the scaling relationship between the size of a body part and the size of the body as a whole, as both grow during development (Brown, 1997; Chave *et al.*, 2005). The basic principle of Allometry is identifying the relationship between some independent variable of the tree with the biomass of the whole tree. These models or equations estimates the biomass of a tree from different easily measurable tree variables like height, diameter at breast height, diameter at stump height and other. This method is suitable for estimating biomass of different forest types and ecologies including protected areas (Liu and Westman, 2009).

## 2.4. Types of biomass models

### 2.4.1. Generic biomass models

Biomass estimations are largely the result of a common equation applied over a given area (Houghton, 2003). Usage of biomass model is a standard method for the estimation of biomass of a given forest. The advantage of using generic biomass model is that they are developed by including trees from wide diameter range and species diversity and this can potentially increase the accuracy of the estimation. Instead of developing species specific biomass model for all species usage of generic models is suitable in the biomass estimation of forests having high species diversity (Brown, 2002). Apart from their advantage generic biomass models have a disadvantage on the accuracy of estimates when they are compared with species specific models because the biomass of plant will vary based on the species, ecology and age which the generic biomass fail to fulfill for all species (Litton *et al.*, 2006)

### 2.4.2. Species specific model

Species specific biomass equations are equations that are developed for a single selected species and these equations are specific to species, age, diameter and management practices. Equations that are developed elsewhere cannot accurately estimate the local biomass of tree due to difference in tree architecture (number of stems, type of branch), age, diameter, climate and management interventions. Management practices can highly influence the biomass production of a tree. For example pruning can decrease the biomass of tree without affecting the DBH.

In addition to pruning thinning and coppicing can affect the biomass accumulation of tree. So in order to accommodate the difference in biomass estimation between different tree species, species specific biomass equations should be developed for different localities (Brown, 2002; Chave *et al.*, 2014; FAO, 2010; Kairo *et al.*, 2009).

## 2.5. Development of biomass equation

### 2.5.1. Basic steps in development of biomass equations

There are several things that have to be considered in the development of biomass equation. The first one is the purpose or the objective of the model should be known. The second will be deciding what data is required for the development of the equation to achieve the previously set objectives. The other thing that has to be considered is the geographical extent and tree species for which the model will be applied. Most commonly estimates are applied to determine the biomass density of tree biomass (Basuki *et al.*, 2009).

Estimates of carbon stock are generally produced by first measuring the total biomass of the population. The first is to estimate wood volume for each tree using a volume equation, convert wood volume to mass using an estimate of timber density, and then convert wood mass to total tree biomass using biomass expansion factors. Biomass is calculated through the application of biomass equations to direct tree measurements (Brown, 1997). Measured DBH are utilized to calculate the volume of the base of the tree to the first main branch. This volume of biomass (VOB) was then expanded to account for biomass of other aboveground components, and converted to biomass following the formula of Brown 1997):

$AGB = V_{OB} \times P \times BEF$

Where: AGB = Above Ground Biomass (t/ha),

VOB = average above ground volume of trees per area (m3/ha),

P = average wood density,

BEF = biomass expansion factor.

### 2.5.2. Destructive method of biomass equation development

The basic idea of destructive method is simply to remove or cut and weigh all the biomass of the tree. In this method the tree is cut and sectioned into different parts like stem, branch and leaves. Each parts of the tree will be weighed separately for its fresh biomass, from each section of the felled tree samples will be taken and weighed for its fresh biomass and taken into laboratory for its dry biomass estimation by oven drying method. The dry weight of the whole tree will be estimated from the moisture content of the dried samples and the fresh biomass of the whole tree.

From the oven dried biomass of the tree and different easily measurable tree variables like DBH, height and wood density a regression model (biomass equation) will be developed and this biomass equation will be used for the biomass estimation of other trees nondestructively (Chave *et al.* 2014; Keith *et al.*, 2000).

## 2.6. Biomass equation validation process

Biomass equations play a fundamental role in the estimation of volume, biomass and nutrient cycling of tree and shrub. Even though allometric models play basic role in the estimation of biomass of a tree inappropriate use and development of this models will lead to wrong results and finally wrong decisions. In the development process for the selection of the best fitting model there are different statistical indicators used (Houghton, 1999; Lu, 2006; Negash *et al*., 2013). Some of these are R-squared ($R^2$), Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Residual standard errors of estimation (RSE), Root mean square error (RMSE) and Mean absolute bias (MAB). R-squared is a statistical measure that represents the proportion of the variance for a dependent variable that's explained by an independent variable.

The residual standard error of estimation (RSE) describes on average how much the prediction or the response value deviates from the regression line. It is calculated as square root of residual sum of square (RSS) divided by degree of freedom (DF). Akaike Information Criterion (AIC) estimates the quality of each model relative to each other. The best model should have the highest R2 value and the lowest RSE and AIC value (Chavé *et al*., 2014; Chavé *et al*., 2005; Gibbs *et al*., 2007).

## 2.7. Challenges of developing biomass equations

### 2.7.1. Errors on equation development

Direct biomass estimation involves difficult tasks and its destructive nature makes it practically impossible, so the use of biomass models in the estimation of tree biomass is inevitable. Mostly this biomass models are developed by destructively sampling few trees from different classes which leads to different errors. Majorly there are three stages in the development allometric which causes error and this are sampling error, measurement error and model misspecification (Chavé *et al*., 2014).

#### 2.7.1.1. Sampling error

Different studies have shown a varying range of sampling error in biomass estimation. In addition to this, in the model development the percent-age sampling error for individual trees differs from the percent sampling error for the total biomass of trees (Jeremy, 1996). If sample selection has been restricted to trees with symmetric and undamaged crowns, to fully stocked stands, or to the most accessible portions of the landscape, then the sampling error estimated in model development may not correspond to the error incurred when the model is extrapolated to the full population of trees or stands (Chavé *et al*., 2014).

#### 2.7.1.2. Measurement error

The work of biomass equation development involves difficult tasks since it is main data collection method involves destruction on the tree. Once the tree is felled it will be divided into different sections and each section will be weighed for its fresh biomass. In this task there is lot of opportunity to lose tree materials for example by breakage of the tree branch during feeling and saw kerf in tree feeling and stem dissection which will underestimate the biomass of the tree

(Chavé *et al.,* 2014; Gibbs *et al.*, 2007). In addition to this there is also a chance of mixing branches from other trees which will overestimate the biomass of the tree. Another source of measurement error arises from tree shape (out-of-round bole shape) and instrument errors associated with plant material measurement (Canavan & Hann, 2004).

#### 2.7.1.3 Model misspecifications

These arise from the methods of model identification and calibration and are influenced primarily by the size and scope of sample data. In general terms, larger samples facilitate the identification and quantification of biomass allometries. Yet it is important to recognize that biomass samples are often hierarchically structured (Brown, 2002; Chavé *et al.,* 2014). Components of interest in above-ground biomass estimation are generally leaves, branches, and bole wood and bark; measurements of these components are taken on the same trees and these trees are often nested within plots that are in turn nested in stands.

These forms of data clustering must be accounted for to properly understand variation in the allometric relationships across a species' range. Also, biomass model parameters are often estimated on the log-transformed scale. These transformations are made to stabilize variation or so that the assumptions of parametric tests are satisfied. However, nonlinear transformation of variables fundamentally alters the meaning of model parameters complicating inference regarding the original allometric parameters of interest. Finally, most biomass models are developed in a parametric framework and errors will arise from the goodness-of-fit of the parametric approximations (Hailemariam *et.al*, 2015).

Other model specification error arises from omitted variables: In most forest inventory works height measurement is difficult especially in dense forest, so most allometric models excludes height from the model even though height is the best biomass predictor next to density and diameter ate breast height. Omitting of this variables will decrease the quality of the biomass models and increases the error in estimation (Brown, 2002).

### 2.7.2. Variation in biomass allometry

The use of allometric biomass equations is inevitable because the weighing of trees and their components for direct biomass determination is destructive and prohibitively expensive. However, these biomass equations are not applicable for all types of vegetation. Because tree allometry varies depending on elevation of the site, age class, diameter range and species of sampled trees (Brown, 2002; Chavé *et al*., 2014). It is important that biomass equations allows for calibration against easily measurable tree variables like DBH and height. Also the biomass models give an opportunity for the estimation of biomass specification of each biomass model has to be considered in the application of the model. For example altitude has a relationship with moisture stress and this will indirectly affect the density of the wood and the biomass (Bouffier *et al*., 2003). So even if the model is developed for the same species the elevation should be also in the same range.

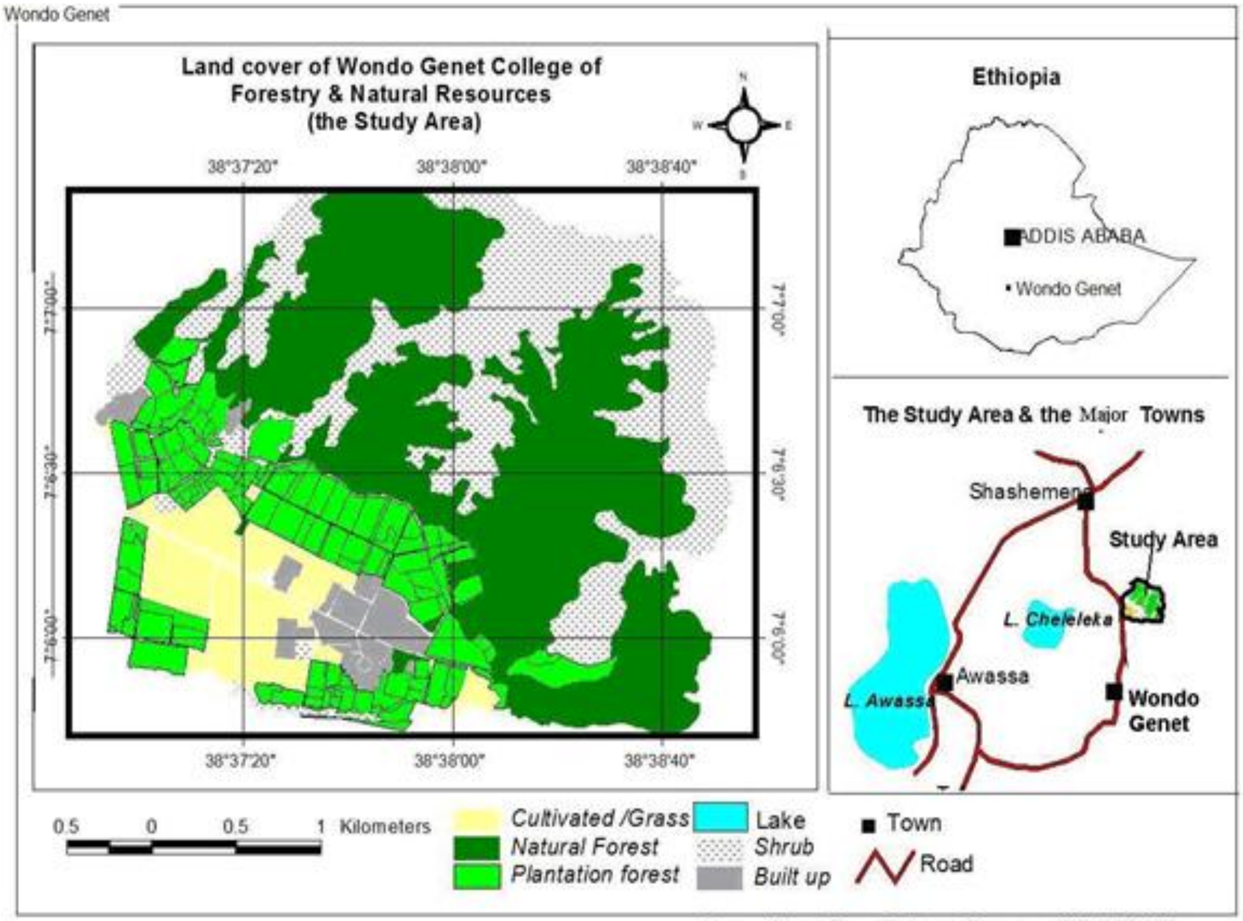
## 3. MATERIAL AND METHOD

### 3.1. Site description

The study was conducted at Wondo Genet college of Forestry and Natural Resources plantation forest of *Cuppressus lustanica* species. Geographically, it is located between $7^0$ 6' N latitude and $38^0$ 7' E longitude. It is 263 km south of Addis Ababa and 13 km south east of Shashemene. The topography is dominated by an escarpment, which forms the edge of the Hawassa basin. The elevation of the college compound ranges between 1800 to 2100 m above sea level. The rainfall has a bimodal pattern. The wet season cover two rainy seasons, a short rainfall period runs from March to April and long rainfall period cover from June to September. From December to February, there is a distinct dry period.

The mean annual precipitation is 1200 mm and the mean monthly maximum and minimum temperatures are 25 $^0$C and 19 $^0$C, respectively. The dominant soil type is sandy loam with high permeability (Lakemariam et al., 2013). Before the introduction of *Cuppressus lustanica* plantations in the area, the land was used to serve for cultivated crops and prior to that, it was fully natural forest land. Crops such as wheat, maize teff and coffee were among the annual and perennial crops cultivated in the area.

The natural vegetation of the site belongs to Afro-montane dry evergreen forest and grassland (Lakemariam *et al.*, 2013). The scattered remnants of the natural forest indicate that the dominant species were *Celtis africana* , *Cordia africana* , *Croton macrostachyus, Albizia gummifera, Prunus africana, Anningeria adolfifredricii, Milletia spp and Phonex spp.* There is also shrub vegetation distributed with a relatively high frequency throughout the area.



Source: Wondo Genet College of Forestry, GIS-Unit (2009)

Figure1. Study area map

### 3.2. Species description

In the study are different indigenous and exotic tree species are planted for production and performance test purposes. Among the established exotic species of the plantation, *Cupressus lusitanica* covers the largest area (53.8 hectare) in 32 stands (Yared, 2018). It is majorly managed for lumber production. The most frequently used spacing is 2.5 × 2.5 m (1600 trees/ha). For *Cupressus lustanica* plantation stands different silvicultural activities are applied timely based on the prescription on the management plan. Throughout the rotation age (from the date of the plantation to harvesting) the stands are pruned two to three times (low pruning and high pruning). Most stands are thinned at least twice and the final harvest is at the age of 25 year.

### 3.3. Sample size and sampling techniques

In the sampling size determination to make sure that the difference observed is only as a result of the difference in applied method all possible sources of error were considered in both the determination of samples (sampling error) and the measurements taken in the field (measurement error). In this study 30 *Cupressus lustanica* trees were sampled from three age groups (5 year, 12 year and 24 year). From each age group 10 trees were selected purposively. In the sampling of each individual tree, trees with the same DBH and height as the samples taken by Lakemariam *et al.,* 2013 were selected purposively to reduce the impact of sampled trees variation on the estimation accuracy of the model.

### 3.4. Inventory of trees

For each selected trees different tree variables (total tree height, diameter at breast height (1.3m from the ground), diameter at stump height (0.3m) and diameter at different height) were measured. The total height of the tree was measured by using the Vertex VL5 instrument. After measuring the total height of the tree the stem was partitioned into 3 to 8 equal sections. To estimate the volume of each section separately diameter was measured at the middle of each section using Gator eye caliper. The gator aye caliper measures the upper tree diameter at any height using the laser technology without climbing the tree.

### 3.5. Branch biomass estimation

#### 3.5.1. Branch biomass sampling

The branch biomass samples were harvested through semi-destructive method. First, the whole tree crown was stratified in to three strata namely lower, middle and top strata. These included twigs + leaves, branch and stems. The definition of these biomass components is indicated in table1. From each individual tree 10 % of the branch numbers (minimum of 3 branches) were destructively sampled. From each individual sample trees to take representative samples equal number of branches were harvested from all crown strata. From the totally selected 30 trees 144 branches were destructively sampled. The total branch weight of an individual tree was grouped into two as trimmed and untrimmed branch biomass. The remaining untrimmed branches were counted.

Secondly, the trimmed branches were further divided in to twigs + leaves and branch stem. Both the twigs + leaves and the branch stem were separately weighed to determine their fresh weights. Subsamples of twigs + leaves were randomly taken and measured for their fresh weight to determine dry to fresh weight ratio. The subsamples were later placed into plastic bag and labeled. The samples were oven dried at 70 ºC for 48 hours until it reaches to a constant weight.

For the branch two separate samples were taken randomly. One is for moisture content estimation and the other is for wood density estimation. Each samples of wood were weighted for their fresh weight to determine dry to fresh weight ratio.

The subsamples are placed in to plastic bag and labeled. The sample that is taken for density estimation was first used to estimate the volume by water displacement method and finally placed in to oven at 105 ºC for 72 hours until it reaches to a constant weight.

The samples that were taken for moisture content estimation were first weighed for their fresh weight to determine dry to fresh weight ratio. The subsamples are placed in an oven at 105 ºC for 72 hours until it reaches to a constant weight.

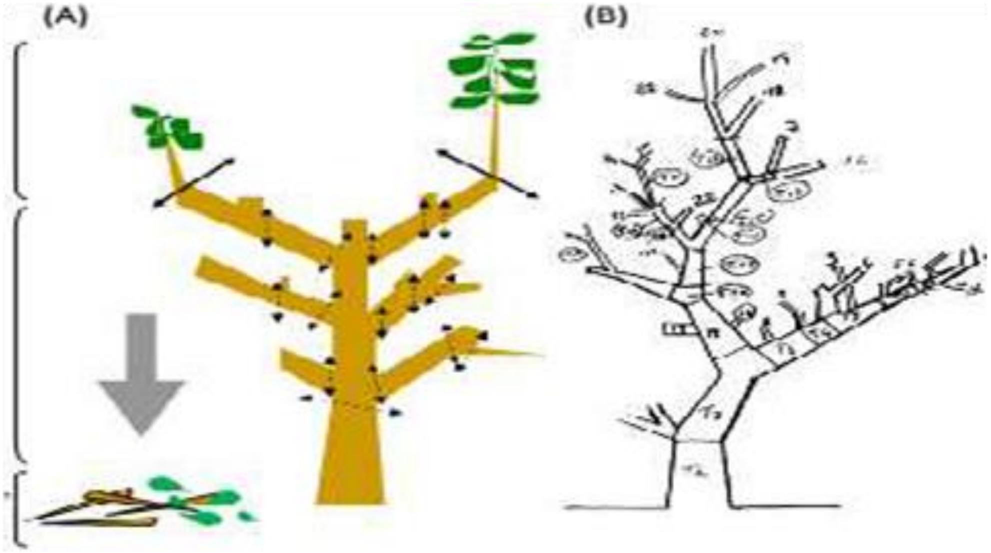


Figure2. Separation and measurement of trimmed and untrimmed biomass (3A) and numbering of the sections and branches measured on a trimmed tree (3B). (Picard N *et.al.*, 2012)

For purposes of measurement and analysis on this study the trees were divided into separate architectural components Lakemariam *et al.*, 2013

Table 1. Definition of separate tree architectural components.

| Component | Description |
|---|---|
| Stem | The main trunk of the tree from the bottom to the top. |
| Branch | Collection of side shoots arising from the main trunk and greater than 2 cm basal diameter. |
| Twigs + leaves | Collection of shoots arising from the branch or the main trunk and less than 2 cm basal diameter including leaves. |

### 3.5.2. Calculation of trimmed and untrimmed biomass

#### Calculating total aboveground dry biomass

The above ground tree biomass includes stem (bole), branch and leaves. For this study the above ground tree biomass was stratified in to three major components i.e. tree stem, branch and twigs + leaves (foliage)

$AGB = S_{biomass} + B_{biomass} + T_{biomass}$……………………………………..………………...equ. 1

#### Stem biomass estimation

$Stem_{biomass} = Volume_{stem} * Wood\ density$………………………………………………equ 2

The total volume of the stem is the sum of the volume of each section. Huber’s formula was used to calculate the volume of a section.

Huber formula $Vi = (\pi Di^2/4) \times Li$…………………………………..……………….. equ 3

Where: Vi volume of section i in meter cube

$\pi$ 3.14

Di mid diameter of the section i

Li length of the section i

$\text{Volume}_{\text{stem}} = \sum_{i=1}^{n} Vi$

Where Vi is the volume of section i and n is number of sections

The wood density of the stem was estimated via taking wood samples from the branch.

$\rho = \text{ oven dry mass } (g) \; / \; \text{volume } (cm3)$………………………….………………...equ 4

The volume of the wood sample was estimated by water displacement method (Figure2.). Oven dry mass is the mass that is obtained after drying the wood sample in the oven at 105 ºC for 72 hours until it reaches to a constant weight. Once the volume of each section was determined, the biomass was calculated by multiplying the volume of each section by the wood density. The sum of the biomass of each section gives the total stem dry biomass.

*Assumption: the sections cut are considered to be cylinder and density is considered to be the same in all the compartments of the tree stem.*

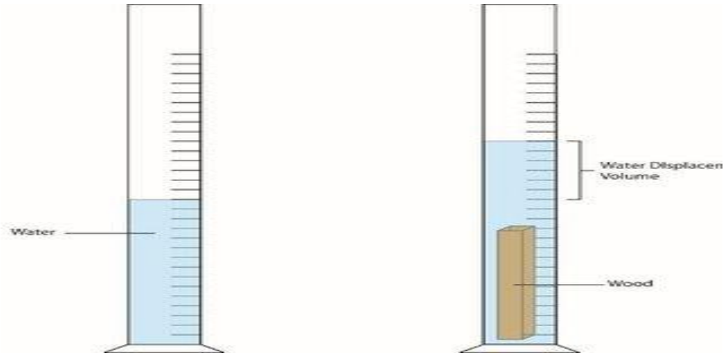


Figure3 .Estimation of sample fresh branch wood volume by water displacement (Picard N *et.al.*, 2012).

### Branch biomass estimation

The estimation of the branch biomass was done separately for both the trimmed and untrimmed part.

$B_{biomass} = B_{trimmed} + B_{untrimmed}$……………………………………………………….………...equ 5

#### Trimmed branch biomass

$B_{od} = B_{fresh} * MC_{branch}$…………………………………………………………………....equ 6

$MC_{branch} = \text{Branch weight}_{dry} / \text{Branch weight}_{fresh}$ ………………………..……..……… equ 7

Where MC is moisture content

B is branch

$B_{od}$ is branch oven dried

### Untrimmed branch biomass estimation

All the untrimmed branches were counted. The biomass of the untrimmed branches was estimated by multiplying the number of branches found by the average dry weight of the sampled branches

### Twig + leaves biomass estimation

$TL_{biomass} = TL_{trimmed} + TL_{untrimmed}$………………………………………………….………...equ 8

### Trimmed twig + leaves biomass

Trimmed TL = Fresh weight $_{TL}$ * MC $_{TL}$ ……………………………………..………....equ 9

MC $_{TF}$ = TL dry weight/ TL fresh weight …………………………………………….…....equ 10

Where MC moisture content
TL Twigs + leaves

### Untrimmed twigs + leaves biomass estimation

The biomass of the untrimmed twigs + leaves was estimated by multiplying the number of branches found by the average dry weight of the sampled twigs + leaves.

## 3.6. Developing biomass models

In this study 6 different biomass models were fitted (Table2). The best tree biomass predictor variables were selected based on the Pearson's correlation coefficient between the total biomass and different biometric parameters such as total height, DBH, DSH and $\rho$. Different biomass equations were developed using Statistical Package R software version R 3.6.1 (R Development core team 2019).

Table 2. Tested biomass equations for *Cupressus lustanica.*

| Model no. | Equation | Source |
|---|---|---|
| M1 | $Y = b_o D^2H + e$ | Leakemariam *et al.* (2013) |
| M2 | $Y = b_o (D^2H)^{b1} + e$ | Leakemariam *et al.* (2013) |
| M3 | $Y = b_0D^{b1}H^{b2}P^{b3} + e$ | Goodman *et al.* (2014) |
| M4 | $Y = b_o(D^2HP)^{b1} + e$ | Goodman *et al.* (2014) |
| M5 | $Y = b_o D^{b1} + e$ | Kusmana *et al.* (2018) |
| M6 | $Y = b_o D^{b1} H^{b2} + e$ | Kusmana *et al.* (2018) |

The first and the second models (M1 &M2) were selected based on the recommendation from previous study conducted on the same species and site by Leakemariam *et al.* (2013). These two models performed better than other fitted models in the study with the same number of sample trees. The 3rd and the 4th (M3 & M4) were selected because they were tested on other study conducted on tropical forest by harvesting 51 trees from wide diameter range (11 – 169 cm) by Goodman *et al.* (2014). According to this study these power functions having DBH, height and wood density performed better and they recommended to use these models on the development of biomass model for tropical species. M5 and M6 were selected based on the recommendation from study conducted on tropical species by Kusmana *et al.* (2018). In this study 30 trees were sampled and it is reported that the use of DBH and height has improved the efficiency of their model.

### 3.7. Model selection

For the selection of the best fitting model different statistical indicators were used. such as Coefficient of determination ($R^2$), Residual standard error of estimation (RSE), Akaike

Information Criterion (AIC), Bias (B), Prediction residuals sum of squares (PRESS) and Index of agreement (D) (Chave *et al*., 2005, Kozak, 2003; Leakemariam *et al*, 2013; Negash *et al*., 2013).

$R2 = 1 - \frac{SSE}{SST}$……………………………………………………………………...equ 11

$RSE = \sqrt{\mathrm{SSE}\ /\ (\mathrm{n} - 2)}$ …..........................................................................................equ 12

$RMSE = \sqrt{\sum(Yi - \hat{Y})/n}$ ...……………..……………………...……………………...equ 13

$\mathrm{PR}ESS = \sum_{i=1}^{n} \delta i\ \hat{}\ 2$…………………………………………………..…………………equ 14

$D = 1 - \frac{\sum_{i=1}^{N}(Yi - \hat{Y}i)\hat{}2}{\sum_{i=1}^{N}(/\ \widehat{Y}i - \bar{Y}\ /\ ) + (Yi - \bar{Y})\hat{}2}$……………………………………….……..………………..equ 15

$Bias = Yi - \hat{Y}$ .......................................................................................................equ 16

$AIC = -2(Log - likelihoodl) + 2P$ ……………………………………...…………equ 17

Where: n = number of observation

P = number of parameters fit + 1

SSE = Sum of square of error and

$\widehat{\mathrm{Y}}$ predicted value

$\mathrm{Y}_i$ Observed value

The best model should have the highest $R^2$ and D value and the lowest RSE, MAB, MB, SEE, PRESS and AIC value. The data and models obtained in this study will also be compared with the model for estimating total above ground biomass, developed by Lakemariam *et al*. (2013).

### 3.8. Comparison of alternative methods

For all the components and total above ground biomass models comparison the destructively developed models by Leakemariam *et al,* 2013 were used as a reference because the destructive method is assumed to be the most accurate method. For the total above ground biomass model in addition to the semi destructive method other generic biomass model that is developed for the same species in Mexico by Vigil, N. 2010 was also included in the comparison. This was done to compare the difference in estimation accuracy of the site and species specific semi destructively developed model with the destructively developed generic model. The comparison was made by taking the inventory data collected for 30 *Cupressus lustanica* trees for this study. Estimations were made by those three different models for all the 30 sampled trees. Pairwise t-test was used to check for the significance of the variation in biomass estimation between the three methods.

# 4. RESULTS

## 4.1. Individual *Cupressus lustanica* biomass

The DBH and height of the sampled trees (n = 30) ranges between 2.5 cm to 41 cm and 3m up to 26 m respectively. The wood density of *Cuppressus lustanica* in the study site was calculated to 0.41 g $cm^3$, ranging from 0.32 to 0.47 g $cm^3$. Stem biomass shared the highest proportion of the total biomass (77.28 %), followed by branch (14.3%) and twigs + leaves (8.42 %). The proportion of component biomass between trees sampled from different age group was different (Table 3). From the trees sampled from 5 years old stand the highest proportion of biomass was accounted by twigs + leaves followed by stem and branch. But for the trees from 12 and 24 years old the highest biomass proportion was covered by stem, and followed by branch and twigs + leaves biomass respectively.

Table 3. Summary statistics of dry matter (kg/plant) of total aboveground and biomass components of sampled *Cuppressus lustanica* trees (n=30).

| Age group | Components | Mean | Minimum | Maximum | SD |
|---|---|---|---|---|---|
| 5 | Twigs + foliage | 5.93 | 1.25 | 12.83 | 3.64 |
| | Branches | 3.48 | 0.44 | 10.37 | 3.08 |
| | Stem | 5.66 | 0.36 | 18.24 | 5.09 |
| | Total aboveground | 15.07 | 2.05 | 41.44 | 11.62 |
| 12 | Twigs + foliage | 9.78 | 1.12 | 21.14 | 7.33 |
| | Branches | 10.2 | 0.33 | 33.74 | 11.14 |
| | Stem | 60.82 | 10.01 | 126.79 | 40.09 |
| | Total aboveground | 80.81 | 11.46 | 181.67 | 57.89 |
| 24 | Twigs + foliage | 25.47 | 6.85 | 46.76 | 14.96 |
| | Branches | 56.27 | 6.82 | 194.02 | 57.15 |
| | Stem | 311.52 | 96.24 | 540.51 | 151.86 |
| | Total aboveground | 393.26 | 109.91 | 752.21 | 214.44 |
| Average of all age groups | Twigs + foliage | 13.73 | 1.12 | 46.76 | 12.81 |
| | Branches | 23.32 | 0.33 | 194.02 | 40.31 |
| | Stem | 126 | 0.36 | 540.51 | 161.22 |
| | Total aboveground | 163.05 | 2.05 | 752.21 | 208.59 |

### 4.2. Biomass predictor variables for semi destructive method

The correlation between plant biomass (twigs + leaves, branch, stem and total above ground biomass) and different measureable tree parameters are shown in table4. The highest correlation was found between total above ground biomass and DBH and between stem biomass and total tree height which is 0.98. The second highest correlation was between stem biomass and DBH (0.97) followed by correlation between total above ground and total tree height (0.96). From all parameters DBH was significantly correlated with all tree biomass components and total above ground biomass. The lowest correlation value was recorded between twigs + leaves and wood density followed by correlation value between branches and wood density.

Table4. Summary of spearman's correlations between biomass components and *Cupressus lustanica* plant biometric parameters (n=30)

| Biomass component | DBH | Height | Density |
|---|---|---|---|
| Twigs + leaves | 0.91** | 0.75** | $0.10^{ns}$ |
| Branches | 0.93** | 0.81** | $0.15^{ns}$ |
| Stem | 0.97** | 0.98** | 0.48** |
| Total above ground | 0.98** | 0.96** | 0.40** |

ns not significant, $^{**}p < 0.01$

### 4.3. Biomass equations

The results of the 6 fitted biomass models are presented in table5. For the total above ground biomass and all the components except for branch biomass M6 was the best fitting model. M6 explained the variance in twigs + leaves, stem and total above ground biomass by 93%, 92% and

94% respectively. For the stem and total above ground biomass the coefficient $b_0$, $b_1$ and $b_2$ were significant ($P < 0.001$) on explaining the effect of DBH and height.

While for twigs + leaves the coefficient $b_2$ was not significant. For all biomass components and total above ground biomass except for the branch M6 has the lowest AIC, PRESS, RSE and bias values and the highest index of agreement (D). For branch biomass M1 was the best fitting model. M1 explained the variance in branch biomass by 90% and the coefficient $b_1$ was significant ($P < 0.001$) on explaining the effect of combined variable $D^2H$. In the branch biomass modeling the best fitting model (M1) has the highest $R^2$ (0.9) and index of agreement ($D = 0.95$) and the lowest AIC, PRESS and RSE values.

In all components and total above ground biomass modeling the coefficient $b_3$ was not significant, showing the less effect of wood density on the biomass estimation of the studied species. Generally the results show that DBH and total tree height were the best predictors of *Cupressus lustanica* biomass and M6 is the best equation to predict twigs + leaves, stem and total above ground biomass, while M1 is the best fitting model for branch biomass modeling.

Table 5. Equations and goodness-of-fit statistics values for the estimation of *Cupressus lustanica* biomass (kg dry matter/plant) by semi-destructive method.

| **Model** | | **Coefficients** | | | | **Goodness of fit statistics** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Number** | **Models** | **b0** | **b1** | **b2** | **b3** | **D** | **R2** | **AIC** | **RMSE** | **Bias** | **PRESS** | **RSE** | **RANK** |
| | **AGB** | | | | | | | | | | | | |
| M1 | y= bo D2H + e | 0.0137753*** | | | | 0.97 | 0.93 | 331.70 | 56.99 | 45.96 | 114103.70 | 57.96 | 6 |
| M2 | y= bo (D2H)b1 + e | 0.25538*** | 0.71648*** | | | 0.98 | 0.92 | 318.72 | 44.39 | 30.35 | 69800.81 | 45.95 | 3 |
| M3 | Y = b0Db1Hb2Pb3 + e | 0.06563*** | 0.97552*** | 1.60796*** | -0.10817ns | 0.98 | 0.94 | 316.40 | 39.96 | 30.28 | 77566.39 | 42.92 | 2 |
| M4 | Y= bo(D2HP)b1 + e | 0.51688*** | 0.72545ns | | | 0.98 | 0.92 | 322.04 | 46.92 | 35.42 | 83350.90 | 48.57 | 4 |
| M5 | Y = bo Db1 + e | 0.628*** | 1.8218*** | | | 0.97 | 0.88 | 330.85 | 54.34 | 34.92 | 103991.80 | 56.25 | 5 |
| M6 | Y = bo Db1 Hb2 + e | 0.07407*** | 1.01228*** | 1.5674*** | | 0.98 | 0.94 | 314.55 | 40.05 | 30.27 | 66023.72 | 42.22 | 1 |
| | **Twigs + leaves** | | | | | | | | | | | | |
| M1 | y= bo D2H + e | 0.001154*** | | | | 0.95 | 0.89 | 198.40 | 6.18 | 5.09 | 1203.48 | 6.284 | 6 |
| M2 | y= bo (D2H)b1 + e | 0.05685*** | 0.62044*** | | | 0.96 | 0.88 | 186.69 | 4.92 | 3.90 | 847.90 | 5.089 | 4 |
| M3 | Y = b0Db1Hb2Pb3 + e | 0.20456*** | 2.26093*** | -0.8976ns | 0.03394ns | 0.98 | 0.93 | 165.45 | 3.23 | 2.53 | 400.66 | 3.467 | 2 |
| M4 | Y= bo(D2HP)b1 + e | 0.11098ns | 0.62086ns | | | 0.95 | 0.85 | 193.15 | 5.47 | 4.35 | 1076.55 | 5.667 | 5 |
| M5 | Y = bo Db1 + e | 0.1007*** | 1.64363*** | | | 0.97 | 0.91 | 173.31 | 3.93 | 3.12 | 524.02 | 4.072 | 3 |
| M6 | Y = bo Db1 Hb2 + e | 0.19626*** | 2.24991*** | -0.88434*** | | 0.98 | 0.93 | 163.46 | 3.23 | 2.52 | 387.05 | 3.403 | 1 |
| | **Branch** | | | | | | | | | | | | |
| M1 | y= bo D2H + e | 0.0025368*** | | | | 0.95 | 0.90 | 243.29 | 13.06 | 9.93 | 5469.08 | 13.28 | 1 |
| M2 | y= bo (D2H)b1 + e | 0.006151*** | 0.914206*** | | | 0.95 | 0.86 | 244.80 | 12.95 | 9.88 | 5822.91 | 13.4 | 4 |
| M3 | Y = b0Db1Hb2Pb3 + e | 0.00226*** | 1.626098*** | 1.537963*** | 0.252084ns | 0.96 | 0.87 | 247.85 | 12.75 | 9.71 | 7487.89 | 13.69 | 2 |
| M4 | Y= bo(D2HP)b1 + e | 0.01275*** | 0.94461ns | | | 0.95 | 0.86 | 246.06 | 13.23 | 10.81 | 6215.91 | 13.69 | 5 |
| M5 | Y = bo Db1 + e | 0.0265*** | 2.23884*** | | | 0.95 | 0.83 | 248.04 | 13.67 | 10.29 | 6498.21 | 14.15 | 6 |
| M6 | Y = bo Db1 Hb2 + e | 0.001888*** | 1.551432*** | 1.588647*** | | 0.96 | 0.87 | 246.11 | 12.80 | 9.75 | 7039.21 | 13.49 | 3 |
| | **Stem** | | | | | | | | | | | | |
| M1 | y= bo D2H + e | 0.0100845*** | | | | 0.96 | 0.90 | 324.27 | 50.34 | 38.15 | 91113.07 | 51.2 | 6 |
| M2 | y= bo (D2H)b1 + e | 0.24441*** | 0.69047*** | | | 0.97 | 0.88 | 313.08 | 40.41 | 27.85 | 58780.14 | 41.82 | 3 |
| M3 | Y = b0Db1Hb2Pb3 + e | 0.03355*** | 0.69737*** | 1.98451*** | -0.22861ns | 0.98 | 0.92 | 307.18 | 34.26 | 24.46 | 63866.45 | 36.8 | 2 |
| M4 | Y= bo(D2HP)b1 + e | 0.49617*** | 0.69601ns | | | 0.97 | 0.88 | 314.43 | 41.33 | 28.83 | 64275.63 | 42.78 | 4 |
| M5 | Y = bo Db1 + e | 0.5621*** | 1.764*** | | | 0.95 | 0.82 | 324.23 | 48.66 | 34.66 | 83867.31 | 50.37 | 5 |
| M6 | Y = bo Db1 Hb2 + e | 0.04394*** | 0.77745*** | 1.89185*** | | 0.98 | 0.92 | 305.65 | 34.53 | 24.27 | 49186.71 | 36.4 | 1 |

## 4.4. Comparison of alternative methods

### 4.4.1. Total above ground biomass models comparison

To estimate the difference in estimation accuracy of the three alternative methods (i.e. destructively developed site and species specific model (Leakemariam *et al*, 2013), semi destructively developed site and species specific model by this study (M6) and species specific generic model (Vigil, 2010)) biomass was estimated for 30 sampled by those alternative models. The result of the biomass estimation for the sampled trees shows that there is difference between the estimations of the three total above ground biomass models. To check if the difference was significant or not pairwise t-test was carried out by using the destructively developed model (Leakemariam *et al*, 2013) as a reference. The result of the test shows that difference between the destructive and the semi destructive method was insignificant (P=0.9059), while for the generic biomass model the difference was significant (P=0.0294) (Figure3.). The results of this significance test show that the estimation accuracy of the semi-destructively developed site and species specific model was better than the destructively developed generic model.

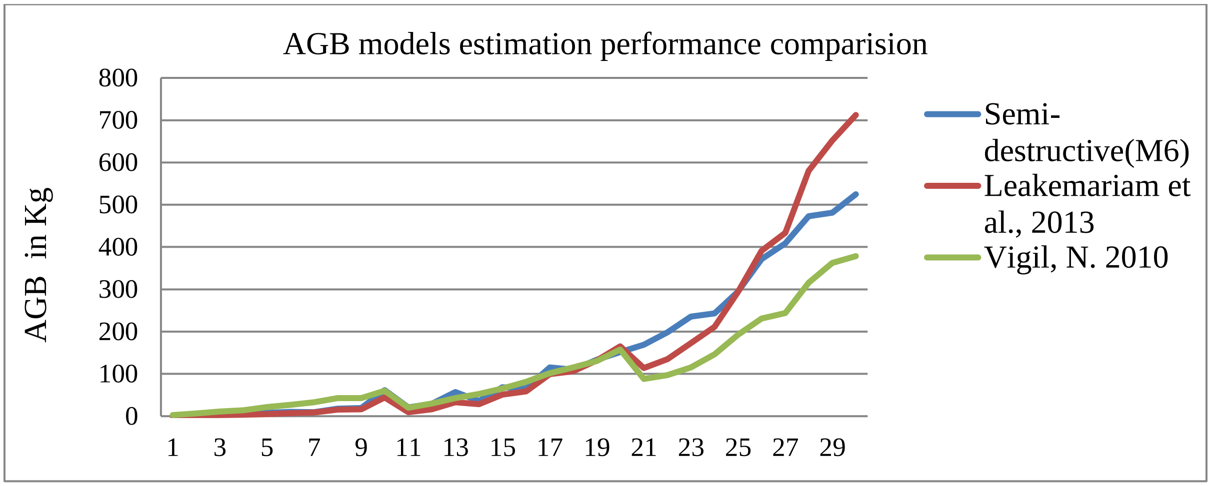


Figure 1. Comparison of alternative methods for above ground biomass models *of Cupressus lustanica*

### 4.4.2. Above ground component biomass models comparison

For the destructive method there were no component biomass models developed by Leakemariam *et al.,* 2013. So the component biomass models were developed by using destructively collected data by Leakemariam *et al.*, 2013. In the development of the component biomass models the same models and performance test statistics that were previously used by the author were used. The result of the model is shown below in Table 6.

As it is shown in table6 for twigs + leaves and branch biomass estimation M5 was the best fitting model. For both the twigs + leaves and branch biomass modeling in the selected model M5 DBH and the combined variable DH were able to describe the variation in biomass estimation by 97% and 96% respectively. For the stem biomass estimation M3 which uses DBH and total tree height was the best fitting model. In this model DBH and total tree height were able to describe the variation in stem biomass estimation by 98%. This infers that DBH and height were the best predictor variables for all component biomass estimation which is similar with the result reported by the author for above ground biomass modeling.

For the above ground component biomass models accuracy test pairwise t-test was applied by using the destructively developed models as a reference. Accordingly for the twigs + leaves and branch biomass the variation was significant (P=0.00035 for twigs + leaves and p=0.0480 for branch biomass), while it was insignificant for the stem biomass model (P=0.26247).

Table 6 . Equations and goodness-of-fit statistics values for the estimation of *Cupressus lustanica* biomass (kg dry matter/plant) by destructive method.

| **Model number** | **Models** | **Coefficients** | | | **Goodness of fit statistics** | | | | | **Rank** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **b0** | **b1** | **b2** | **R2** | **Bias** | **MAB** | **PRESS** | **RSE** | |
| | **Twigs +leaves** | | | | | | | | | |
| M1 | Y= exp(b0+b1*ln(D))+e | -2.2919 | 1.6618 | | 0.9 | 0.18868 | 3.40672 | 691.785 | 4.545 | 3 |
| M2 | Y= bo(D2H)b1 + e | 0.04962 | 0.63674 | | 0.86 | 0.55868 | 4.34072 | 1105.76 | 5.744 | 4 |
| M3 | Y=b0Db1Hb2+e | 0.22475 | 2.14392 | -0.7746 | 0.93 | -0.1215 | 2.87895 | 569.894 | 3.88 | 2 |
| M4 | Y= b0D2H+e | 1.17E-03 | | | 0.89 | 3.27544 | 5.37877 | 1435.14 | 6.877 | 5 |
| M5 | Y= boD+b1D2+b2DH+e | 0.58065 | 0.04001 | -0.0357 | 0.97 | -0.1726 | 2.79732 | 565.304 | 3.774 | 1 |
| | **Branch** | | | | | | | | | |
| M1 | Y= exp(b0+b1*ln(D))+e | -5.0023 | 2.5544 | | 0.81 | 0.13654 | 4.42983 | 1975.85 | 7.328 | 3 |
| M2 | Y= bo(D2H)b1 + e | 0.00147 | 1.02101 | | 0.88 | 0.68877 | 6.00897 | 3304.6 | 9.241 | 5 |
| M3 | Y=b0Db1Hb2+e | 0.02616 | 3.11664 | -1.0361 | 0.94 | -0.3202 | 3.83026 | 1621.76 | 6.491 | 2 |
| M4 | Y= b0D2H+e | 0.00183 | | | 0.92 | 0.51548 | 5.98145 | 2924.68 | 9.084 | 4 |
| M5 | Y= boD+b1D2+b2DH+e | -0.0598 | 0.09209 | -0.0561 | 0.96 | -0.0014 | 3.75824 | 1504.75 | 6.42 | 1 |
| | **Stem** | | | | | | | | | |
| M1 | Y= exp(b0+b1*ln(D))+e | -1.8492 | 2.2035 | | 0.93 | -4.2108 | 30.6105 | 67296 | 41.9 | 5 |
| M2 | Y= bo(D2H)b1 + e | 0.03879 | 0.89202 | | 0.97 | -2.3213 | 16.6397 | 27463.7 | 26.33 | 3 |
| M3 | Y=b0Db1Hb2+e | 0.00794 | 1.37133 | 1.82632 | 0.99 | 0.15367 | 13.1788 | 16326 | 19.46 | 1 |
| M4 | Y= b0D2H+e | 0.01265 | | | 0.98 | 4.59248 | 16.6452 | 30287.4 | 28.58 | 4 |
| M5 | Y= boD+b1D2+b2DH+e | -5.8212 | 0.15888 | 0.45267 | 0.99 | 2.09751 | 18.6793 | 24832.8 | 25.33 | 2 |

# 5. DISCUSSIONS

## 5.1. Cupressus lustanica biomass

The mean dry biomass *Cupressus lustanica* recorded in this study site was higher than that of reported by Yehualashet *et al*., 2019 for the same species in Egdu forest, Ethiopia. The difference is attributed to variation age, diameter and soil condition (Negash *et al.,* 2013). The wood density found in this study was comparable to default value published by IPCC, (2006) and for the same species (Yehualashet *et al*., 2019). The biomass proportion result of this study is similar with other studies (Hilmi, 2003; Ong *et al*., 2004; Leakemariam *et al*., 2013; Shengwang *et al*., 2019). As the age of the tree increases the proportion of the twigs + leaves to the total above ground biomass was decreasing. This result is similar with that reported by Leakemariam *et al*., *(*2013) for the same species and site. The main reason for the twigs + leaves biomass to cover the higher proportion of the 5 year sampled trees is likely due to pruning intensity, i.e. only low pruning is applied. While both low and high pruning were applied for 12 and 24 years old stands.

## 5.2 Biomass predictor variables for semi destructive method

In the semi destructive method stem and total aboveground biomass has shown strong correlation (0.96 - 0.98) with DBH and height. This shows the presence of strong direct relationship between the dependent and independent variables. Other authors have also reported similar findings different studies (Chave *et al.,* 2005; Leakemariam *et.al* 2013; Yehualashet *et al.,* 2019). In opposite to this several studies have also shown that tree height is poor predictor of aboveground biomass (Chave *et al.,* 2005; Negash *et, al.,* 2013; Segura *et al*., 2006).

Wood density was found to be less correlated with all biomass components and total above ground biomass. Compared to other components for the twigs + leaves there was no correlation and this likely because there was no woody part in this biomass component. This result is different from other study that reported using wood density has increased the efficiency of their model (Befikadu, 2014; Chave *et al.,* 2014).

### 5.3. Biomass equations

#### 5.3.1. Aboveground biomass equations

The best fitting above ground biomass model developed by the semi-destructive method (M6) with DBH and height explained 94 % variation in aboveground biomass of *Cupressus lustanica*. While the best model with DBH and height through destructive method by Leakemariam *et al.*, 2013 explained 97% of the aboveground biomass variation for the same species and age category. While it was greater than the value reported by Yehualashet *et.al*, 2019 ($R^2$=0.92) and Vigil (2010) ($R^2$=0.93) for the same species in Egdu forest, Ethiopia and in Mexico respectively. In addition to the $R^2$ M6 have also the highest index of agreement (D) and the lowest RMSE, AIC, and RSE values. This shows that the models biomass estimation accuracy.

In this study a model using DBH as a single predictor variable (M5) was able to describe the variation in biomass estimation by 88%. While M6 using DBH and Height described by 94%. This finding agreed with previous studies (Chave *et al*., 2014; Basuki *et al*., 2009; Ervan *et al.*, 2013; Krisnawati *et al.,* 2007) that showed the increment of equation performance as more variables are incorporated. But this result is different from some authors that confirmed the use of a single predictor variable mainly DBH has increased the efficiency of their model (Chave *et al.,* 2005; Segura *et al*., 2006).

### 5.3.2. Comparisons of aboveground component biomass equations

For the twigs + foliage and stem biomass M6 was the best fitting model. M6 combines DBH and total tree height and this combination was able to describe the difference in twigs + foliage and stem biomass estimation by 94% and 92% respectively. For the branch component the best fitting model M3 was able to describe the variation by 90%. The $R^2$ values of the biomass components in the semi destructive methods are less than the values of the destructive method (Leakemariam *et al.,* 2013). Generally, the result of the fitted models shows that DBH and height are the best predictor variables for all biomass components, while wood density shows less prediction capacity. The finding of this study is similar with other authors (Grote, R. 2002; Huy, B. *et al.,* 2016; Huy, B., 2012).

## 5.4. Comparison of biomass estimates

### 5.4.1. Comparison of aboveground biomass estimates among destructive, semi-destructive and generic methods.

Pairwise t-test results showed that the semi-destructively developed and generic models underestimated the total aboveground biomass of *Cupressus lustanica* by 18.7% and 39.4% in reference to destructive method. The pair wise t-test result shows that the difference was insignificant for the semi destructive model (P=0.906), while it was significant for the generic model (P=0.029). This implies semi-destructive method can accurately estimate the aboveground biomass of *Cupressus lustanica*. This in return reduces the costs of destructive harvest to develop the biomass model.

The reason for the semi-destructive models good estimation performance is likely to be the sample trees were selected from the same species and site as the reference model. A study conducted by (Montagu *et al.,* 2005) also emphasize that the site-specific biomass equations are more accurate in predicting the forest biomass estimates on the local level as they take the site effects into account. Furthermore, the stands having the same age and DBH as the destructively sampled trees were deliberately taken to reduce the error. Utilization of the latest measuring instruments is also believed to reduce the other possible source of error, while the higher significant variation of generic model in biomass estimate in reference to destructive method could be owing to the differences in climate, site and age where the models were developed. It can be inferred from the results that as expected, using the semi destructive, and site and species specific model for *Cupressus lustanica* above ground biomass estimation is better method than generic model. This is in agreement with those studies reported by (Cairns *et al*. 2003; Henry *et al*. 2011; Kairo *et al.,* 2009; Ketterings *et al.,* 2001).

### 5.4.2. Comparison of component biomass estimates among destructive and semi-destructive method

In the twigs + foliage and branch biomass estimation the semi destructively developed biomass models under and over estimated by 43.2% and 64.8% respectively. The result of pair wise t-test at 95% level of confidence shows that the differences were highly significant (P= 0.00035 and P = 0.0480 for twigs + leaves and branch respectively). One of the possible sources of this uncertainty is the difference in branch density (number of branches) which shows tendency of decrement with increment in branch size (Eslamdoust. *et al.,* 2016).

The other reason for the variation to be significant is likely to be the difference in the amount of branch removed by pruning for the destructively sampled and semi destructively sampled trees. In the case of the stem biomass the semi destructively developed model overestimated the biomass by 22.8%. Unlike the other above ground biomass components the semi destructively developed stem biomass model was able to estimate the stem biomass with insignificant variation in the 95% level of confidence (P= 0.26247). This is mainly because the whole stem part was sampled intensively. This result agrees with a study conducted on the component biomass modeling for coniferous and deciduous trees (Grote, R. 2002). This shows that the semi destructive method is another possible option for stem biomass estimation where the destructive method is not possible.

# 6. CONCLUSION

The total above ground biomass of 5 to 24 years old *Cupressus lustanica* grown in Wondo genet averaged 163.05 Kg per plant. From the total above ground biomass the stem accounts the highest proportion, followed by branch and twigs + leaves. The wood density of *Cupressus lustanica* was 0.41g/cm$^3$ which is closer to the value reported by IPCC, 2006. The result of this study also showed that DBH and height are better predictors of *Cupressus lustanica* biomass. The power equation Model M6 ($Y = b_0 D^{b1} H^{b2}$) for stem, twigs + leaves and aboveground biomasses while M1 ($Y = b_o D^2 H$) was the best for branch biomass. The pair wise t- test result showed that using the semi destructively developed site and species specific biomass model gives more accurate above ground biomass estimation than destructively developed generic model. Even though the destructive method is the most accurate method for tree biomass estimation but its destructive nature is a limiting factor for the applicability of this method. So, according to this study using the semi destructive method is another option of tree stem and aboveground biomass estimation in situations where the destructive method is not possible.

# 7. RECOMMENDATIONS

- Further study is needed to evaluate the applicability of the semi-destructive method for species with different tree architecture.
- To enhance the estimation accuracy of the semi destructive method further studies should be conducted on how to take more representative branch and twigs + leaves samples with less destruction.
- In addition to the semi destructive method further studies should be conducted on how to develop biomass equations with less or if possible with no destruction to the tree

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APPENDIX

Appendix 1. Data collection format for nondestructive measurement of stem volume and biomass data

| No | Height(m) | DBH(cm) | DSH(cm) | D1(cm) | D2(cm) | D3(cm) | D4(cm) | D5(cm) | D6(cm) | D7(cm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |
| 5 | | | | | | | | | | |
| 6 | | | | | | | | | | |
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| 21 | | | | | | | | | | |
| 22 | | | | | | | | | | |
| 23 | | | | | | | | | | |
| 24 | | | | | | | | | | |
| 25 | | | | | | | | | | |

Appendix 2. Data collection format for semi destructive measurement for twigs + leaves and branch biomass data collection

| No | DBH(cm) | Height(m) | Branch count | Replication | Fresh mass(g) | | | Dry mass(g) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Stratum1 | Stratum2 | Stratum3 | Stratum1 | Stratum2 | Stratum3 |
| 1 | | | | Sample1 | | | | | | |
| | | | | Sample2 | | | | | | |
| | | | | Sample3 | | | | | | |
| 2 | | | | Sample1 | | | | | | |
| | | | | Sample2 | | | | | | |
| | | | | Sample3 | | | | | | |
| 3 | | | | Sample1 | | | | | | |
| | | | | Sample2 | | | | | | |
| | | | | Sample3 | | | | | | |
| 4 | | | | Sample1 | | | | | | |
| | | | | Sample2 | | | | | | |
| | | | | Sample3 | | | | | | |
| 5 | | | | Sample1 | | | | | | |
| | | | | Sample2 | | | | | | |
| | | | | Sample3 | | | | | | |
| 6 | | | | Sample1 | | | | | | |
| | | | | Sample2 | | | | | | |
| | | | | Sample3 | | | | | | |
| 7 | | | | Sample1 | | | | | | |
| | | | | Sample2 | | | | | | |
| | | | | Sample3 | | | | | | |
| 8 | | | | Sample1 | | | | | | |
| | | | | Sample2 | | | | | | |
| | | | | Sample3 | | | | | | |

Appendix  3. Summary of Sampled *Cupressus lustanica* biomass by destructive method by Leakemariam *et.al (*2013)

| Age group | Sample Tree | DBH (cm) | Height (m) | Stem_Fw. (kg) | Stem_MC (%) | Stem_Dw. (kg) | Branch_Fw. (kg) | Branch_MC (%) | Branch_Dw (kg) | Twigs_FW (kg) | Twigs_MC (%) | Twigs-Dw (kg) | Total AGB_ Dw (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 years | 1 | 2.35 | 3.2 | 1.51 | 66.76 | 0.50192 | 0.65 | 55 | 0.2925 | 1.95 | 61.54 | 0.74997 | 1.544394 |
|  | 2 | 4.1 | 4.85 | 5.27 | 63.77 | 1.90932 | 2.1 | 54.68 | 0.95172 | 5.1 | 64.94 | 1.78806 | 4.649101 |
|  | 3 | 5.5 | 5.7 | 8.6 | 66.42 | 2.88788 | 2.42 | 54.55 | 1.09989 | 8.73 | 61.1 | 3.39597 | 7.38374 |
|  | 4 | 6.3 | 4.9 | 12.54 | 64.96 | 4.39402 | 3.48 | 52.4 | 1.65648 | 7.82 | 65.25 | 2.71745 | 8.767946 |
|  | 5 | 8.15 | 6.73 | 18.89 | 66.44 | 6.33948 | 6.6 | 54.21 | 3.02214 | 9.9 | 60.78 | 3.88278 | 13.244404 |
|  | 6 | 9.8 | 6.75 | 24.05 | 72.79 | 6.54401 | 10.48 | 52.91 | 4.935032 | 16.57 | 62.07 | 6.285001 | 17.764038 |
|  | 7 | 10.3 | 8.1 | 28.81 | 62.06 | 10.9305 | 11.64 | 53.5 | 5.4126 | 23.26 | 63.6 | 8.46664 | 24.809754 |
|  | 9 | 12.1 | 6.23 | 34.97 | 67.68 | 11.3023 | 11.69 | 53.12 | 5.480272 | 22.21 | 61.68 | 8.510872 | 25.293448 |
|  | 9 | 12.9 | 8.82 | 41.1 | 66.78 | 13.6534 | 11.93 | 50.33 | 5.925631 | 34.07 | 61.97 | 12.95682 | 32.535872 |
|  | 10 | 15.2 | 9.97 | 45.96 | 68.52 | 14.4682 | 14.87 | 53.53 | 6.910089 | 38.13 | 60.25 | 15.15668 | 36.534972 |
| 12 years | 1 | 7.6 | 11.85 | 23 | 56.02 | 10.1154 | 0.65 | 56.34 | 0.28379 | 2.72 | 59.69 | 1.096432 | 11.495622 |
|  | 2 | 9.8 | 16.7 | 69.13 | 63.11 | 25.5021 | 6.5 | 52.86 | 3.0641 | 8.75 | 64.02 | 3.14825 | 31.714407 |
|  | 3 | 11.7 | 15.41 | 78.7 | 61.46 | 30.331 | 1.67 | 53.89 | 0.770037 | 3.33 | 63.73 | 1.207791 | 32.308808 |
|  | 4 | 13.5 | 14.94 | 82.5 | 65.48 | 28.479 | 12.46 | 54.13 | 5.715402 | 23.54 | 61.48 | 9.067608 | 43.26201 |
|  | 5 | 15.2 | 14.95 | 140.51 | 62.54 | 52.635 | 14.3 | 53.02 | 6.71814 | 29.7 | 62.66 | 11.08998 | 70.443166 |
|  | 6 | 17.2 | 15.2 | 151.5 | 56.15 | 66.4328 | 10.4 | 55.89 | 4.58744 | 21.6 | 61.5 | 8.316 | 79.33619 |
|  | 7 | 19.2 | 17.8 | 184 | 61.89 | 70.1224 | 31.88 | 50.14 | 15.895368 | 53.12 | 59.07 | 21.74202 | 107.759784 |
|  | 8 | 21 | 19.2 | 211.1 | 62.29 | 79.6058 | 37.39 | 49.79 | 18.773519 | 43.61 | 60.15 | 17.37859 | 115.757914 |
|  | 9 | 22.6 | 16.73 | 265.29 | 56.71 | 114.844 | 43.2 | 48.93 | 22.06224 | 51.8 | 47.81 | 27.03442 | 163.940701 |
|  | 10 | 24.8 | 15.8 | 320 | 61.29 | 123.872 | 81.18 | 53.23 | 37.967886 | 56.82 | 64.55 | 20.14269 | 181.982576 |
| 24 years | 1 | 16.4 | 24.89 | 182.5 | 45.78 | 98.9515 | 6.22 | 43.65 | 3.50497 | 7.78 | 58.2 | 3.25204 | 105.70851 |
|  | 2 | 19 | 23.13 | 342.2 | 46.85 | 181.879 | 5 | 47.88 | 2.606 | 15 | 58.26 | 6.261 | 190.7463 |
|  | 3 | 21.5 | 24.3 | 352.5 | 50.01 | 176.215 | 17.79 | 48.16 | 9.222336 | 14.22 | 54.41 | 6.482898 | 191.919984 |
|  | 4 | 24 | 23.3 | 442.5 | 46.73 | 235.72 | 40.37 | 44.68 | 22.332684 | 33.63 | 41.09 | 19.81143 | 277.863867 |
|  | 5 | 28 | 23.8 | 500.5 | 53.68 | 231.832 | 87.6 | 43.47 | 49.52028 | 58.4 | 58.56 | 24.20096 | 305.55284 |
|  | 6 | 31 | 26.74 | 729.2 | 50.61 | 360.152 | 92.25 | 44.76 | 50.9589 | 71.75 | 59.95 | 28.73588 | 439.846655 |
|  | 7 | 33 | 27.3 | 717.5 | 47.38 | 377.549 | 47.34 | 45.32 | 25.885512 | 59.16 | 52.13 | 28.31989 | 431.753904 |
|  | 8 | 37 | 29.1 | 1115 | 50.33 | 553.821 | 116.5 | 46.44 | 62.3974 | 103.5 | 56.59 | 44.92935 | 661.14725 |
|  | 9 | 40 | 26.2 | 1007 | 55.01 | 453.049 | 151.25 | 46.12 | 81.4935 | 90.75 | 43.54 | 51.23745 | 585.78025 |
|  | 10 | 41 | 26.5 | 1101 | 51.69 | 531.893 | 392.29 | 42.86 | 224.154506 | 83.71 | 45.88 | 45.30385 | 801.351458 |

Appendix 4. Summary of Sampled *Cupressus lustanica* trees biomass by semi-destructive method.

| Age group | Sample Tree | Height (m) | DBH (cm) | DSH (cm) | Branch_DW average (Kg) | Density (g/cm3) | Foilage_DW (Kg) | Branch_DW (Kg) | Stem_DW (Kg) | Total AGB (Kg) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 Years | 1 | 3.02 | 2.5 | 4.2 | 0.08 | 0.28 | 1.25 | 1.69 | 0.36 | 3.30 |
| | 2 | 3.86 | 4.1 | 6 | 0.13 | 0.30 | 1.90 | 2.64 | 1.38 | 5.92 |
| | 3 | 5.7 | 5.5 | 10 | 0.31 | 0.31 | 5.50 | 7.83 | 3.63 | 16.97 |
| | 4 | 5 | 6.3 | 8 | 0.38 | 0.33 | 6.42 | 7.15 | 4.78 | 18.35 |
| | 5 | 5 | 8.1 | 10 | 0.38 | 0.26 | 4.93 | 9.14 | 2.66 | 16.73 |
| | 6 | 5.5 | 9.2 | 10 | 0.53 | 0.26 | 9.42 | 18.86 | 5.40 | 33.68 |
| | 7 | 5 | 10.3 | 12.5 | 0.61 | 0.26 | 12.31 | 13.74 | 3.53 | 29.57 |
| | 8 | 6.7 | 12 | 14 | 0.68 | 0.26 | 13.43 | 21.73 | 7.58 | 42.75 |
| | 9 | 7 | 12 | 13.1 | 0.70 | 0.27 | 7.55 | 26.73 | 29.46 | 63.74 |
| | 10 | 13 | 14.5 | 16 | 0.80 | 0.31 | 6.53 | 12.46 | 8.57 | 27.56 |
| 12 Years | 11 | 9.7 | 7.75 | 9.75 | 0.14 | 0.42 | 1.12 | 1.99 | 21.48 | 24.59 |
| | 12 | 10.3 | 9.8 | 12 | 0.16 | 0.29 | 2.77 | 2.03 | 42.79 | 47.60 |
| | 13 | 14 | 12 | 15.2 | 0.55 | 0.32 | 3.65 | 2.71 | 71.89 | 78.25 |
| | 14 | 9.6 | 13.5 | 15.5 | 0.31 | 0.30 | 4.97 | 3.29 | 108.56 | 116.82 |
| | 15 | 13.5 | 15.2 | 16.25 | 0.46 | 0.35 | 7.80 | 0.64 | 20.18 | 28.62 |
| | 16 | 12.1 | 17.2 | 20 | 0.48 | 0.34 | 6.34 | 1.47 | 30.73 | 38.54 |
| | 17 | 16 | 19.5 | 24.5 | 0.88 | 0.37 | 15.69 | 6.64 | 106.37 | 128.70 |
| | 18 | 14.8 | 21 | 25.5 | 0.95 | 0.36 | 15.02 | 5.33 | 107.44 | 127.79 |
| | 19 | 16 | 22.5 | 27.5 | 1.33 | 0.31 | 19.33 | 33.62 | 137.97 | 190.91 |
| | 20 | 16.2 | 25 | 31.5 | 1.31 | 0.28 | 21.14 | 0.89 | 10.01 | 32.04 |
| 24 Year | 21 | 21.5 | 18 | 23.5 | 0.65 | 0.35 | 6.85 | 14.48 | 107.71 | 129.05 |
| | 22 | 23 | 19 | 32 | 0.63 | 0.45 | 7.06 | 18.24 | 108.96 | 134.25 |
| | 23 | 24 | 21 | 29 | 0.51 | 0.36 | 8.83 | 54.25 | 191.65 | 254.73 |
| | 24 | 22.5 | 24 | 27.5 | 1.60 | 0.36 | 20.50 | 36.04 | 183.71 | 240.25 |
| | 25 | 23 | 28 | 33 | 1.36 | 0.36 | 31.70 | 69.98 | 261.53 | 363.20 |
| | 26 | 25 | 31 | 35 | 1.50 | 0.31 | 29.08 | 75.45 | 315.07 | 419.59 |
| | 27 | 26 | 32 | 39 | 1.58 | 0.32 | 21.95 | 40.25 | 366.62 | 428.82 |
| | 28 | 26 | 37 | 45 | 2.05 | 0.38 | 37.30 | 95.83 | 303.20 | 436.32 |
| | 29 | 25 | 40 | 52.25 | 3.12 | 0.35 | 44.71 | 98.43 | 344.36 | 487.50 |
| | 30 | 26 | 41 | 55.5 | 3.88 | 0.27 | 46.76 | 107.01 | 353.95 | 507.73 |