ALLOMETRIC MODEL FOR ESTIMATING VOLUME AND ABOVEGROUND BIOMASS OF *OLEA EUROPAEA* IN THE DRYAFROMONTANE FOREST, NORTH EAST ETHIOPIA

M.Sc. THESIS

BY: MEAZA ERKIHUN DAMTEW

HAWASSA UNIVERSITY, WONDO GENET COLLEGE OF FORESTRY AND NATURAL RESOURCES

NOVEMBER, 2020

WONDO GENET, ETHIOPIA

ALLOMETRIC MODEL FOR ESTIMATING VOLUME AND ABOVEGROUND BIOMASS OF *OLEA EUROPAEA* IN THE DRYAFROMONTANE FOREST, NORTH EAST ETHIOPIA

BY: MEAZA ERKIHUN DAMTEW

THESIS SUBMITTED TO THE

DEPARTMENT OF GENERAL FORESTRY,

WENDO GENET COLLEGE OF FORESTRY AND NATURAL RESOURCES,

SCHOOL OF GRADUATES STUDIES,

HAWASSA UNIVERSITY, WENDO GENET, ETHIOPIA

IN PARTIAL FULFILMENT OF THE

REQUIREMENTS FOR THE

DEGREE OF

MASTER OF SCIENCE IN FOREST RESOURCE ASSESSMENT AND MONITORING

NOVEMBER, 2020

WONDO GENET, ETHIOPIA

APPROVAL SHEET-1

This is to certify that the thesis entitled “Allometric Model for Estimating Volume and Aboveground Biomass of *Olea europaea* in the Dryafromontane Forest, Northeast Ethiopia”. is submitted in partial fulfillment of the requirement for the degree of Master of Sciences with specialization in Forest Resource Assessment and Monitoring of the graduate program under the department of General Forestry, Wondo genet College of Forestry and Natural Resources and is the study is an original research thesis has been carried out by Meaza Erkihun, Id. No MSc/FRAM/R013/11, under my supervision; and no part of the thesis have been submitted for any other degree or diploma.

The assistance and help received during the courses of this investigation have been rightly acknowledged. Therefore, I recommended it to be acceptable as fulfilling of the thesis requirements.

____________________	________________	________________
Major Advisor	Signature	Date
____________________	________________	________________
Co. Advisor	Signature	Date
____________________	________________	________________
Head of Department	Signature	Date
____________________	________________	________________
Graguate program	Signature	Date

APROVAL SHEET-II

We, the undersigned, members of the Board of Examiners of the final open defense by Meaza Erkihun have read and evaluated her thesis entitled "Allometric Model for Estimating Volume and Aboveground Biomass of *Olea europaea* in the Dryafromontane Forest, Northeast 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.

______________________	_____________	________
Name of the Chairperson	Signature	Date
______________________	_____________	________
Name of Internal Examiner	Signature	Date
______________________	_____________	________
Name of External Examiner	Signature	Date
______________________	_____________	________
Name of Major Advisor	Signature	Date
______________________	_____________	________
SGS approval	Signature	Date

ACKNOWLEGEMENTS

Primarily, I would like to thank the almighty God for helping me in all my duties. Had it not been for his assistance, it would have been impossible to overcome the challenges. My special thanks goes to express sincere thanks, appreciation and kindness to my advisors Dr. Motuma Tolera and Mr Amsalu Abich for their continued advice and support from the very beginning to the end of the thesis work by sharing their prior experience in the field, their help were invaluable to me and I gratefully acknowledge all kinds of their support.

I would like also thanks to the Amhara National Regional State of Environment, Forest and Wildlife Protection and Development Authority for giving educational chance for me and facilities for my study. I also want to thanks MRV project for allowing me to study and their financial support to my research project.

This work study by Korea International cooperation Agency (KOICA) under the title of strengthening the capacity to address climate change on forestry sector in Ethiopia (No.2018-004).

My thanks also go to all my friends; for their encouraging, motivating and assisting me during the field research work.

Lastly but not least, my especial thanks go to my parents, who have always been supported and assisted me overcome every difficulties and they have been providing me their kindness' and moral support through out my life.

TABLE OF CONTENTS Page

CANDIDET'S DECLARATION

I hereby declared that this thesis entitled "Allometric Model for Estimating Volume and Aboveground Biomass of *Olea europaea* in the Dryafromontane Forest, Northeast Ethiopia." is my own origional work. Any scholarly matter that is included in the thesis has been given recognition through citation.

This thesis is submitted in partial fulfillment of the requirements for MSc. degree in Forest Resource Assessment and Monitoring at Hawassa University Wondo Genet College of Forestry and Natural Resource. I solemnly declare that this thesis has not been submitted to any other institution anywhere for the award of any academic degree, diploma or certificate.

Meaza Erkihun Damtew	______________________	______________
Name of the Student	Signature	Date

DEDICATION

This thesis is dedicated to my beloved families for dedicating their time to support me through out my life.

ACRONYMS AND ABBREVIATIONS

AGB	Above ground biomass
ANRS	Amhara National Regional State
C	Carbon
CO_2	Carbon Dioxide
Cm	Centimeter
Dbh	Diameter at the breast height
FAO	Food and Agricultural Organization
Gt	Giga tone
H_m	Merchantable height
Ht	Total height
IPCC	Intergovernmental Panel on Climate Change
Kg	Kilogram
M	Meter
MRV	Measuring, Reporting and Verification
REDD+	Reduction of Emission from Deforestation and Forest Degradation and the role of conservation, sustainable management and enhancement of forest
SPSS	Statistical Package for Social Science
SSA	Sub-Saharan Africa

LIST OF TABLES Page

LIST OF FIGURE Page

ABSTRACT

Dry afromontane forests form the largest part of the existing natural vegetation in Ethiopia. Nevertheless, models for quantifying aboveground biomass (AGB) and volume of this forest are rare. The development of tree allometric models are crucial for accurate forest tree volume, biomass, and carbon assessment in forest ecosystem. The objective of this study was to develop species-specific models for predicting AGB and tree volume of the Olea europaea L.sub spp. Cuspidata in the Harego forest. A total of 15 sample trees were harvested and their biometric variables and biomass were measured. A set of models relating tree component volume and biomass to measured variables and wood density were developed using linear regression analysis. The form factor of the species was determined, the predicted values using form factor and fitted stem equation was comparable and provided accurate results. Log transformed data revealed that combined diameter at breast height (dbh) and merchantable height explained more than 95.6 % variability in the stem and total volume. Branch biomass was determined by dbh alone, explaining 87.7% of the variation in the branch volume. The average value of wood density decreased with increasing stem height and decreasing branch diameter sizes. wood density of the stem was higher than the branch. The large part of variation in tree component biomass was explained by both dbh and ht, whereas dbh alone explained 75.9% variability in the leaf biomass with high bias. The direct biomass measurement was 18.6% greater than the indirect measurement. The comparison with previously developed species-specific and general model revealed that these models produced large prediction errors and they cannot probably be applied outside their ranges. Thus, our new models are accurate and potentially to be applied for species-based tree component biomass predictions and will be helpful in planning sustainable forest management in the dry Afromontane forest.

Keywords: Destructive sampling, Form factor, Models, Wood density.

1. INTRODUCTION

1.1. Back ground

Forest is one of the world's largest renewable ecosystem providing different products for human demands. Besides, forest provides income generation, it serves as habitat for animals, watershed protection and climate change mitigation through sequestering atmospheric carbon dioxide (CO_2) and store as a biomass. As a result, global forests have stored about 296 Gt of carbon (C) in their biomass (FAO, 2015).

Allometric models quantifying biomass, volume, tree growth and C storage in terrestrial forest ecosystems and thus used with in forest management planning. The development of models has been based on relating easily measurable tree variables, such as diameter at breast height (dbh) and total tree height (ht), to biomass or volume. These variables are considered to be the most efficient for volume and biomass predictions (Brown, 1997; IPCC, 2003; Chave *et al*., 2014). Although the models form varies, they have been developed for tree species in different ecological regions of the world, which are some of species-specific (Xiang *et al*., 2016; Amsalu Abich *et al*., 2019) and site-specific models (Djomo *et al*., 2010; Rebeiro *et al*., 2011), whereas others are generic models (Chave *et al*., 2005 and 2014).

Recently, developing species and site-specific models are acknowledged and can improve biomass estimates (Kettering's *et al*., 2001) and again high level of accuracy in stand biomass predictions (Paul *et al*., 2016). However, few species-specific models have been developed in the dry and moist afromontane forests (Mehari Alebachew *et al*., 2016; Birhanu Kebede and Teshome Sormessa, 2018; Buruh Abebe *et al*., 2019).

1.2. Statement of the Problem

In Ethiopia, the growing stock of natural forest is not well understood due to lack of tree volume functions although few attempts are available for exotic tree species in plantation (Pohjonen and Pukkala, 1990; 1991; 1992; Tesfaye Teshome, 2005; Leakemariam Berhe and Goran Amoldsson, 2008). Globally, several models have been developed (Brown, 1997; Chave *et al*., 2005; Pilli *et al*., 2006; Sadeli Ilyas, 2013; Rutishauser *et al*., 2013; Abdullahi Jibrin and Aishetu Abdulkadir, 2015) in various regions to predict the contribution of forests to global C cycle. However, these generic models may provide unreliable estimates where they are applied outside their domain due to variation in biomass production (Chave *et al*., 2005; Premyslovska *et al*., 2007; Henry *et al*., 2011; Litton and Kauffman, 2008). In order to improve biomass estimates, assessment of the error due to the choice of model selection is needed through developing species-specific model based on empirical data.

Furthermore, wood basic density (wood density) is a key variable for converting forest/tree volume to biomass (Chave *et al*., 2005; Henry *et al*., 2010; Chave *et al*., 2014). However, it is subjected to different factors such as environments, floristic composition, vegetation zones and edaphic factors (Premyslovsk *et al*., 2007) causing variation in wood density results bias estimates. Moreover, variation in wood density within tree and between species was understood (Amsalu Abich and Asmamaw Alemu, 2020) and thus the influence of estimation errors for species-specific traits such as wood density on the biomass predictions needs further assessments. Moreover, biomass measurements can be done through direct weighing and indirect measurement. These issues can be reduced through measuring stem volume and then multiplying by wood density. But assessments of the error associated with indirect measurement is limited. Mehari et al.(2016) developed an allometric model for estimating aboveground biomass of *Olea europaea* at a given site using indirect biomass measurement. However, they did not assess the errors associated with indirect biomass measurement and wood density variation between tree components. This needs further assessments by considering these two biomass measurement methods and examining variation in wood density within tree species for improved biomass prediction. Thus, the development of new model and wood density determination for *Olea europaea* species in dry afromontane forest are essential to achieve the desired level of accuracy which is needed within sustainable forest management and assessments of C storage.

1.3. Objective of the Study

1.3.1. General objective

To develop models for estimating aboveground biomass and volume of *Olea europaea* species in the dry afromontane forest of North east Ethiopia.

1.3.2. Specific objectives

- To develop species-specific allometric model for estimating tree component volume and biomass of *Olea europaea* species.
- To assess wood density variation within the stem height and between tree components.
- To assess the applicability of species-specific and generic models developed elsewhere to dry afromontane forest of *Olea europaea* species.
- To compare the error that results when the biomass is indirectly estimated from stem volume and its wood density.

1.4 Research Questions

- What would be the suitable aboveground biomass and volume model for *Olea europaea* species?
- Are there variations in wood density along tree height and between tree components?
- Does generic model developed elsewhere is applicable to species based biomass predictions?
- What is the error resulting from indirect biomass measurement, estimating the stem volume and then multiplying by wood density?

1.5. Significance of the Study

Estimation of the wood density and development of biomass and volume model is important for assessing the productivity and sustainability of the forest (Liu *et al*., 2014). Therefore, this study provides insights about the tree volume, wood density and biomass of the selected species, for developing sustainable forest management in dry afromontane forest species of Ethiopia. This study can also provide accurate tools for monitoring the biomass, growing stock and carbon stock of *Olea europaea* in North eastern part of Ethiopia in Kombolcha and this can be a basis to support the REDD+ implementation in the Amhara region. In addition, this study can serve as reference for any biomass and volume model related researches for the area.

2. LITRATURE REVIEW

2.1. Species description of *Olea europaea* species

The olive tree is an evergreen tree belonging to the family Oleaceae. *Olea europaea* originated from the wild olive tree, which is native to Africa, western Asia, the Indian subcontinent, and western china (Azene Bekele, 2007). It found in dry forests and forest margins at 1250–3100 m (Friis, 1986; Legesse Negashi, 1993); widely grown in the field and church and also distributed in dry forest often with *Juniperus procera* in east Africa and in different areas of Ethiopia (Abraham Yirgu *et al*., 2012; Birhanu Kebede and Teshome Sormessa, 2018). It usually reaches 15 m high to 25 m in height (Friss, 1986; Legesse Negashi, 1993). *Ole*a are long-lived tree. It shows strong xeromorphic characteristics and can survive as an adult tree in dry microclimatic conditions (Tesfaye Bekele, 2005).

Its leaves are elongated in shape and often with hooked tips. These leaves have glossy dark green upper surfaces and greenish or yellowish-brown lower surfaces. The much-branched stems are greenish-black to silvery-green in color and mostly held upright. Older stems have a rough bark i.e light or dark gray in color, while younger stems are smooth or slightly ribbed. It used to extract oil, leaves, twigs, and woods are used to fumigate pots for “Milk”, “Tella”, and “Tej” (local beverages), and twigs are also used as tooth brushes (Legesse Negashi, 1993; Tesfaye Bekele, 2005; Birhanu Kebede and Teshome Sormessa, 2018). The wood is hard, polishes well, and has many uses; including carving (Hedberg *et al*., 2003). It is important in this context to consider the wood density variation, biomass and volume model development of species.

2.2.Volume and form factor relationship

Volume is used to evaluate and monitor the commercial potential of a forest for timber, fuel wood production and harvest potential, understanding the ecological dynamic and productive capacity of forest stands. The estimation of volume of standing tree, proper form factor of desired species is essential. Without the factual data of form factor, the estimated volume of standing tree might be either over-estimated or under-estimated (Segura and Kanninen, 2005).

A form factor is the ratio of measured volume for a tree to a cylinder volume based on diameter at breast height (dbh) and h_m of the tree and measured through felling up of trees as well as using Wheeler Penta Prism for standing tree (Mugasha *et al*., 2013). Variations in the relationship between dbh and h_m, and consequently in f, are related to numerous environmental factors such as soil nutrients, climate, disturbance regime, successional status and topographic position, but also to tree species and several genetic factors (Mugasha *et al*., 2013).

2.3. Wood density determination

Wood density is the mass per unit volume of wood substance enclosed with in the boundary of surface of a wood. It is presented in units of oven dry weight in grams per cubic centimeter of green volume (Premyslovsk *et al*., 2007). Wood density is an essential variable for converting the forest volume to biomass and estimating global carbon stock (Fearnside, 1997; Baker *et al*., 2004; Chave *et al*., 2005; Premyslovska *et al*., 2007; Chave *et al*., 2014) and also be useful for the study of forest structure and response to environmental factors (e.g., Chudnoff, 1984).

Wood density differs according to species, soil, tree growth parameter condition, and topography (Fearnside, 1997) and influenced by environmental factors, floristic composition, vegetation zones and edaphic factors (Premyslovsk *et al*., 2007). Thus, geographical locality and species specific wood density determination is more appreciated to improve biomass and forest carbon stock prediction. According to Flores and Coomes (2011) wood density determination improvement could come from species-level phylogenies.

Wood density is usually required parameters which are used to develop allometric model. Kettering et al.(2001) and Chave et al.(2005). The differences in models among forest type related to wood density for each trees species. Many studies reported that higher estimations of biomass models related to higher wood density whereas lower biomass estimations showed forest with lower wood density (Nelson *et al*., 1999; Kettering *et al*., 2001; Chave *et al*., 2004; Kenzo *et al*., 2009). So, information on wood density and biomass development has generally not been given attention in Ethiopia. Therefore, this study is focused on determination and assessed the variation in wood density within tree species.

2.4. Forest biomass

Biomass is defined as the total amount / weight of living organic matter in trees. It is expressed as oven-dry tons per unit area and is useful in assessing forest structure, condition and also as indicator of site productivity (Brown, 1997). Estimates of growing stock are an indicator of biomass and carbon stocks, and may be used to assess change in forest attribtes.

According to IPCC (2006) and Ermias Bekure (2012) definition, above ground biomass is defined as all biomass of living vegetation, both woody and herbaceous above the soil, including stems, stump, branches, bark, seeds and foliage. The total amount of aboveground oven-dry mass of a forest is expressed in tons per unit area and it is the most important visible and dominant Carbon pool in natural and plantations forest (Jochem *et al*., 2011). The AGB of living tree is the most dynamic forest carbon pool. This carbon pool can be accurately measured, whereas other pools are less dynamics and more costly to quantify.

2.5. Allometric Model

Allometric model generally relates on easily measured independent variables like dbh, height to other components like biomass and provides relatively accurate estimation (Feng *et al*., 2012). It is the most common and reliable method for estimating biomass, net primary production, and biogeochemical budgets in forest ecosystems (Gower *et al*., 1999). They have been developed to satisfy various purposes in forest managements and ecology. Currently the use of allometric is wide spread in forestry, and widely used equations for studying variation in size and shape.

In order to develop an allometric relationship; there must be a strong relationship and an ability to quantify this relationship between the parts of the subject measured and the other quantities of interest (FAO, 2012; Picard *et al*., 2012).

The use of allometric equation is crucial step in estimating above and below ground biomass (David *et al*., 1998). Estimation of biomass is largely results of a common equation applied over a large area (Flombaum and Sala, 2006 and Shem *et al*., 2012). Allometric models developed from either single species or mixed species, it can be applied for the entire forest biomass estimation. Vishal et al.(2011) developed allometric model by obtaining the mean dbh of tree species to calculate the biomass accumulation equation obtaining the mean dbh of tree species to calculate the biomass accumulation in different tree components.

The form of allometric model varies widely from one another in terms of model selection but the most common used is linear regression equation Y= a + bx , where Y is the biomass and X is the dbh (Dudly, 1992). And also generalized linear model with gamma distribution and log link function was used to avoid the problem of back transformation (Kettering *et al*., 2001). Allometric power function equation $Y= ax^b$, and their linear equivalents, $\ln(Y) = \ln(a) + b\ln(X)$, where Y is the dependent variables and X is the independent variable and a is the intercept coefficient, b is the scaling exponent where used to predict biomass from independent variables (Shem *et al*., 2012). Those methods or analysis mechanisms are widely used at the development of the model.

Generally, there are money commonly used functions like polynomial, power models and their combinations. Several authors have shown that the inclusion of height in the power function generally gives only a slight improvement. Therefore the model developed is useful tool for assessing the potential of carbon sequestration in forests. And they represent key information for scaling biomass estimation for entire landscape (Shem *et al*., 2012).

2.6. Species specific allometric models

In Africa the absence of species specific or mixed species allometric models has led to broad use of pan tropical model to estimate tree biomass (Djomo *et al*., 2010). This lack of information has raised many discussions on the accuracy of these data, since models were derived from biomass collected outside of Africa (Djomo *et al*., 2010). Because of these their applications to particular species on specific sites should be limited (Brown *et al*., 1989; Houghton *et al*., 2000; Chave *et al*., 2001 and 2005).

Allometric models have been developed to measure carbon for a particular forest. Biomass of forest was estimated through species/site specific and general or mixed allometric models and the development of new, species specific allometric models is necessary to achieve higher level of accuracy (Basuki *et al*., 2009).

Moreover, the use of general allometric model can lead to bias in estimating of biomass for a particular species due to wood density variation among species and within species (Kuyah *et al*., 2012). Therefore, species specific allometric model is more preferable than general models due to difference in architecture and density among and within species (Kettering *et al*., 2001 and Henry *et al*., 2011).

2.7. Importance of development of volume and biomass

Development of biomass and volume model in the forest ecosystem is important for evaluating the productivity and sustainability of the forest. It gives information of the potential amount of carbon that can be emitted in the form of CO_2 (Liu *et al*., 2014). And also important for timber extraction, tracking changes in the carbon stocks of forest and global carbon cycle (Vashum and Jayakumar, 2012).

Nevertheless it is always advisable to use Species/site specific allometric models, different authors attempted to develop general allometric models that can be applied everywhere irrespective of site in order to apply them in areas where no site specific models are available. But unluckily existing general allometric models developed so far did not include data from Africa (Djomo *et al*., 2010).

2.8. Methods for developing biomass model

There are two main principal methods of field biomass estimation. The first one is the destructive method, and the second approach non-destructive method (Vashum and Jayakumar, 2012).

2.8.1. Destructive / harvest method

Destructive method involves felling/removing of the tree is mostly adopted for plantation forest. When using the destructive method the harvesting of trees in the identified area is the first necessary step. Subsequently, measurements of the different components of the trees. It is the most accurate method to calculate and develop regression models from destructively sampled trees (Aboal *et al*., 2005). Despite the fact that this method is highly accurate compared to any other AGB estimation method. It is very impractical due to a number of impeding factors. Among the limitations that this method has, applying it for a large area of forest or; degraded forests containing threatened species and diverse tree species is not reasonable. Despite the accurate estimations this method was unreasonable in the Amhara region of Ethiopia where the forest is already highly degraded with critically endangered species. Furthermore, the area is endowed with high diversity of tree species and additionally the study area was too much large (Gudeta Eshetu *et al*., 2014; Alemayehu Wassie, 2007).

In addition it requires large time, labor intensive, and resource commitment (destructive and expensive). Correspondingly, this method it is not practical for a large scale analysis (Somogyi *et al*., 2007; Vashum and Jayakumar, 2012).

2.8.2. Nondestructive method

The non-destructive method attempts to estimate the biomass of a tree without felling. Despite the fact that it is a destructive method tree should be felled and weighted for the validation of estimated biomass (Condit, 2008; Vashum and Jayakumar, 2012).

Therefore several researchers developed generalized and/or site specific multi-species or single species models for different forest types. These models are developed through creating relationships between different parameters of trees like dbh of the stem, diameter at stump height, total height of the tree, wood density etc. whereas the applicability of the model for single or mixed tree species and for specific or large-scale area depends on the employed data used to construct it (Somogyi *et al*., 2007). The destructive (felling of sample trees) in order to develop for site/species specific or general models for forest types.

Nonetheless several multispecies and single-species allometric models were not equally developed and disseminated across regions in the world. For instance species-specific allometric models exist for only 1% of tree species in Sub-Saharan Africa (SSA) (Henry *et al*., 2011). In addition to this the other limitation of allometric models is their uncertainty of in accurately estimating biomass (Kettering *et al*., 2001; Henry *et al*., 2011; Gudeta Sileshi *et al*., 2014; Mulugeta Mokria *et al*., 2018).

3. MATERIAL AND METHODS

3.1. Description of the Study Area

3.1.1. Geographical location

The study was conducted in Kombolcha town administrative in Galesa kebelle, Amhara National Regional State (ANRS) in North East Ethiopia. It lies between 11º3'30" N to 11º5'30" N latitude and 39º39'0" E to 39º43'0" E longitude. The study area is characterized by a rugged topography of mountains, plateaus and narrow valleys. 20.9% of the total area is considered to be plain with the slope ranging from 0 to 15%. The remaining 17.8%, 26.7%, and 34.6% of this town area was described to have a gradient of 15-30%, 30-50% and more than 50%, respectively (Tesfaye Bekele, 2000).

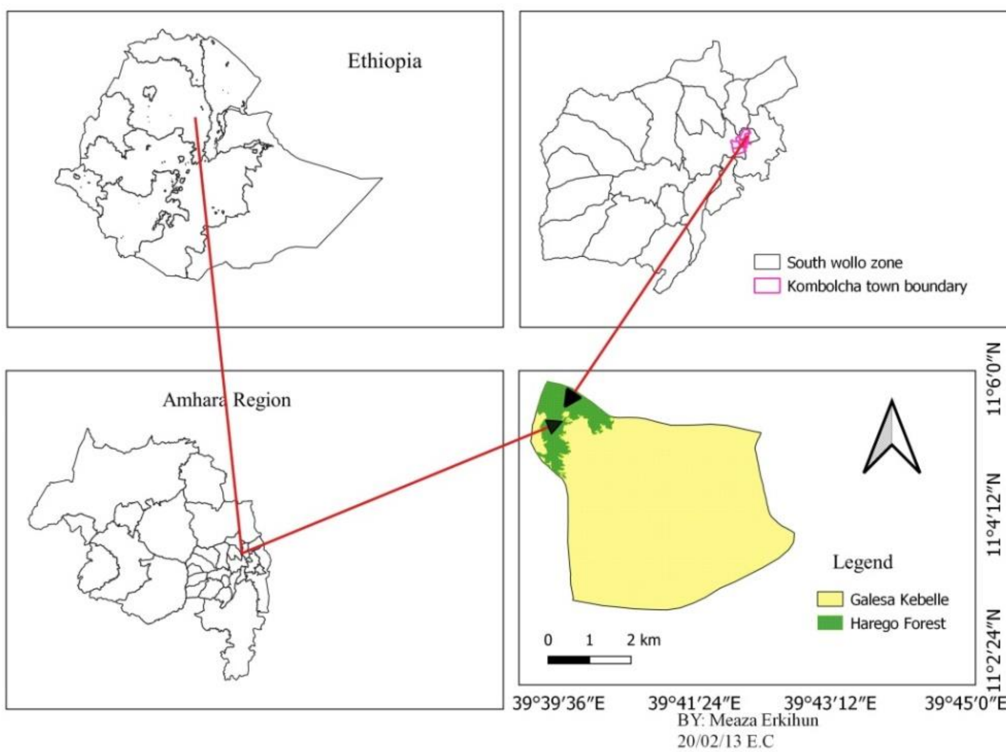


Figure 1 Location of the study area.

3.1.2. Climate

The rain fall distribution of Kombolcha town administrative is a bimodal pattern Belg and Kiremt. Belg is short rainy period lasting from March to April. The majority of the farmers depend on the summer (Kiremt) rains. Rainfall and temperature are highly influenced by altitude (Tesfaye, 2000). The annual average rain fall ranged from 725.1 to 1361.6 mm, the minimum and maximum temperatures were 13.12 and 32.1^{0}C and altitude of study site ranges from 800 meter above sea level (m.a.s.l) in the lowland bordering the Oromia zone to 1,750 m.a.s.l. (Eastern Amhara Metrology Agency, 2019).

3.1.3. Soil

The major soil types covering large parts of south wello zone, including Kombolcha town administrative, are Phaezoms, Cambisols, Lithosols, and Vertisols (Anon, 1988). Most Phaezoms, Cambisols, and Lithosols occur on steep slopes and are often shallow with many stones and rock outcrops. In some of the river plains, there are also fluvisols (alluvial deposits), which are generally good for agriculture (Kibrom Tekle, 1997).

3.1.4. Vegetation

Vegetation of the study area is characterized by shrub land, grassland, regenerating areas with pioneer species and degraded areas with little vegetation or devoid of vegetation cover and areas with remnants of dry afromontane forest with *Olea* and/or *Juniperus procera* as dominant species (Kibrom Tekle, 1997; Tesfaye Bekelle, 2000 and 2005). The vegetation of the study site (Harego forest) is dominated by *Olea europaea, Juniperus proceras, Eucalyptus* *globuleus, Eucalyptus camaldulenesis, Podocarpus falactas, Acacia* species and other exotic tree species (Tesfaye Bekele, 2000 and 2005).

3.2. Sample Collection and Preparation

3.2.1. Sample design

Dry afromontane forest ecosystem was selected for this study to determine volume and biomass models and wood density determination of eastern part of Amhara Region. To determined the composition and individual tree dimension parallel line transects will be laid in the forest. Along each transect, sample quadrats measuring 20 m*30 m (600 m^2) will be laid down. The distance between each quadrats and transect line will be determined in the field based on the size of the forest. The first transect will be aligned randomly at one side of the forest using a compass; then the others will be laid at fixed meter intervals from each other. All woody trees with dbh and total height greater than 5cm and 1.3 meter respectively will be recorded. dbh and total tree height will be measured by forest calliper and hypsometer, respectively. The sampled trees were, one dominant woody species was selected for model development.

3.2.2 Biomass measurement

Olea europaea species was purposively selected based on its abundance, which is frequently found in the protected area, for this study to develop model for tree component biomass and volume; to determine wood density of the species in the Harego forest, Kombolcha town administrative.

Biomass measurement can be conducted using direct and indirect measurement methods as described in the manual of Picard et al. (2012). Direct measurement consists of weighing the fresh biomass and then multiplying it by the ratio of dry to fresh biomass obtained from an aliquot. Indirect measurement consists of cubing the fresh volume and then multiplying it by the wood density. It is faster and easier to weigh stems of a large diameter size than direct weighing, but it may introduce an additional measurement errors due to irregularity of stem shape and also sampling method in wood density determination if the sample disc is taken at one stem position. Thus, we applied both measurement methods to quantify the errors associated with indirect method.

A total of 15 harvested trees aboveground biomass were used for developing allometric model to estimate tree volume and biomass. The tree diameter at breast height was measured and cut at heights of 30 cm above the ground level using Chainsaw, while the total height was measured after felled. Fallen trees were cross cut and partitioned into four components, such as stump, stem, branches and leaves. Tree merchantable height was defined at stem diameter of greater than 5 cm, which is consistent with other report (Vallet, 2006). The stem was divided into different sections considering the shape and size of tree diameter, and the dbh ranged from 5-10, 11-15, 16-20, 21-25, 26-30, 31-35, 36-40, > 40 whereas the branches were grouped as 5-10 cm, >10-15 cm and ≥16 cm diameter. These partitions of tree component into manageable logs, their lengths ranging from 1 to 2m, are used to facilitate weight and volume measurements. The length and diameter at three positions (lower, middle and upper) of each log was measured. Besides, the fresh weight of each component was measured immediately using sensitive balance scale (100 kg measuring capacity). Then, individual log volumes were calculated by multiplying the basal area of the different diameter sections of each log by its length using Newton's volume formula (West, 2009) to understand their influence on biomass estimates. Subsequently, the stem and branch volumes were determined for each tree by summing all individual log volumes.

3.2.2. Wood density determination

For wood density determination, whole (circular) discs including barks were taken at four positions and the discs thickness were 5 cm (Anneli Viherä-Aarnio1 and Pirkko Velling, 2017). The first and the second discs were taken at stump height and diameter at breast height (dbh), respectively and the other two discs were taken considering the shape and/or the diameter size. The volume of the discs was measured using water displacement method in which the volume of water displaced when an object is immersed in afluid and pushing it out of the way and taking it place. The volume of fluid displaced can then be measured by using graduated tube since the volume of water displaced equal to the initial mass (Fig. 2).

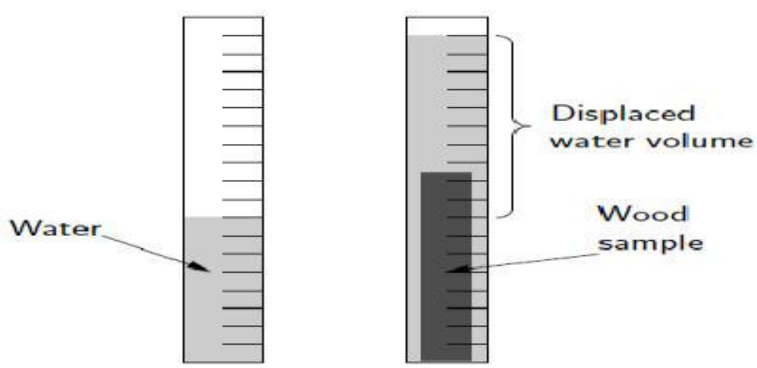


Figure 2 Measurement of the green volume of the sample discs (Picard *et al*., 2012).

Besides, 300-400 gram of leaves and twigs including < 1 cm diameter samples were taken for dry weight determination. Fresh weights of each compartment were recorded, measured in the field by using a digital balance and then samples were taken to the laboratory. These subsamples were oven dried at 105^0C for stem and 70^0C for twigs and leaf until constant weight were recorded at Dessie soil laboratory to reduce moisture content and to create high accuracy. These oven-dried samples were used to convert the total fresh weights of sample trees measured in the field into total oven-dry weight using equation 1 (Equ. 1).

3.2.3. Estimation of aboveground biomass

All collected data in section 3.2.1 and 3.2.2 were used for biomass equation development. The dry weight of the stumps, stems, and branches diameter size greater than 5 cm with the respective diameter were calculated by multiplying the fresh volume of each section by wood density. For branches, diameter less than 5cm, the dry weight was calculated through fresh weight multiplied by dry weight/fresh weight ratio of the corresponding samples (Equ.1). Finally, the total dry weight of a tree was obtained by summing the dry weight of the stump, stem, branches, twigs, and leaves.

$$TDW=\frac{SDW}{SFW}\times TFW \qquad \text{Equ.(1)}$$

Where, TDW, SDW, SFW and TFW are total dry weight (kg) of tree component, oven dry weight of the samples, fresh weight of the samples, and total fresh weight of a tree, respectively.

3.3. Data analysis

After the data were collected (the field and laboratory measurement) was completed, data analysis was accomplished by organizing and recording on the excel work sheet and finally analyzed using SPSS (Version 20). One-way ANOVA was used to examine the variation in wood density along stem height (between stem section) and between stem and branch. Paired sample t-test was employed to see the difference between direct biomass measurement and indirect biomass measurement.

3.3.1 Form factor

Form factor of a stem was determined as the ratio of actual stem volume to cylindrical volume (Equ.2), whereas the volume of a cylinder was calculated as the product of Π, diameter at breast height and merchantable tree height (Equ.3). The volume of an individual standing tree can be calculated as: assuming the form factor of the tree is known, the volume of a tree is the product of basal area and the height and form factor (Equ.4).

$$\text{Form factor}(f) = \frac{V_{act.}}{V_{cyl.}} \qquad \text{Equ. (2)}$$

$$V_{cyl.} = \frac{\pi dbh^2 h_m}{4} \qquad \text{Equ. (3)}$$

$$V_s = \frac{\pi dbh^2 h_m f}{4} \qquad \text{Equ. (4)}$$

Where Vs, V_{cyl}, dbh, h_m, and f represents stem volume (m^3), cylinder volume, diameter at breast height (cm), h_m merchantable height (m) and form factor, respectively.

3.3.2.Tree volume models

Linear regression analysis technique was employed (Segura and Kanninen, 2005; Malimbwi *et al*., 2016) for developing species-specific models to predict individual tree volume from independent variables, dbh and height. Before establishing equation, correlation and scatter plots were used to check if the relationship between independent and dependent variables were linear, but the relation was nonlinear and then the data was transformed to natural logarithm. In this case, the systematic bias resulted from log-transformation was corrected through multiplying the unit values (back transformed values) by correction factors (CF) (Baskerville, 1972; Smith, 1993), which was calculated from standard error of the estimate (SEE) of the equations (Equ. 5).

$$\mathrm{CF} = \exp\left(\frac{\mathrm{SEE}^2}{2}\right) \qquad \text{Equ. (5)}$$

Based on the allometric scaling relationship, volume is usually predicted from equations either with dbh only or with both dbh and h_m as independent variables. Thus, two volume equation were established and they are presented as follow.

$$\mathrm{V} = \exp(\alpha + \beta \ln(\mathrm{dbh})) \qquad \text{Equ. (6)}$$

$$\mathrm{V} = \exp(\alpha + \beta \ln(\mathrm{dbh}) + \beta_1 \ln(\mathrm{h_m})) \qquad \text{Equ. (7)}$$

Where V is stem and branch volume over bark (m^3), dbh is the diameter at breast height (cm), h_m is merchantable height (m), and α, β, and β_1 are parameter estimates.

3.3.3. Biomass model development

We have used the three commonly use predictor variables (i.e. dbh, ht, and ρ) to check their ability in explaining the variations in tree component biomass. Thus, four models were developed which are described as follows**:-**

$$\mathrm{AGB} = \exp(\alpha + \beta \ln(\mathrm{dbh})) \quad \text{M1}$$

$$\mathrm{AGB} = \exp\big(\alpha + \beta \ln(\mathrm{dbh}) + \beta_1 \ln(\mathrm{ht})\big) \quad \text{M2}$$

$$\mathrm{AGB} = \exp\big(\alpha + \beta \ln(\mathrm{dbh}) + \beta_2 \ln(\rho)\big) \quad \text{M3}$$

$$\mathrm{AGB} = \exp\big(\alpha + \beta \ln(\mathrm{dbh}) + \beta_1 \ln(\mathrm{ht}) + \beta_2 \ln(\rho)\big) \quad \text{M4}$$

Where α, c and β are constants, AGB, exp, ln, dbh, h, ρ and are aboveground biomass, exponential function, natural logarithm, diameter at breast height (cm) total tree height (m) and wood density (g cm^{-3}) regression parameters, respectively.

3.3.4. Model evaluation and comparison

3.3.4.1.Allometric model comparison with the previously published models

The developed allometric models were evaluated to measured their strength and accuracy while to select the best goodness-of-fit. Besides, A few biomass models have been developed for *Olea europaea* in the dry afromontane forest (Birhanu Kebede and Teshome Sormessa, 2018; Mehari Alebachew *et a1*., 2015; Buruh Abebe *et al*., 2019). These previously published species-specific models were applied to our data set to test the model reliability in biomass prediction outside their location.

The model evaluation and comparison were carried out using 95% confidence interval of the predictions, mean absolute prediction error measuring bias (MAPE, %), and mean absolute error measuring accuracy (MAE, kg), and mean prediction error (MPE, %) (Mugasha *et al*., 2013, Zeng *et al*., 2017) were used to compare the fitted model with previously published models. The statistical parameters used for evaluating and comparing are listed as follows:

$$\mathrm{MAE} = \left(\sum_{n=1}^{n} \frac{\left| X_{io} - X_{ip} \right|}{n} \right)$$

$$\mathrm{MAPE} = \frac{100}{\mathrm{n}} \left(\sum_{\mathrm{i}=1}^{\mathrm{n}} \frac{\left| \mathrm{X_{io}} - \mathrm{X_{ip}} \right|}{\mathrm{X_{io}}} \right)$$

$$\mathrm{MPE} = \left(\frac{\frac{\sum_{\mathrm{n}=1}^{\mathrm{n}} (\mathrm{X_{io}} - \mathrm{X_{ip}})}{\mathrm{n}}}{\bar{X}_{\mathrm{io}}} \right) * 100$$

Where, MAE, MAPE, MPE, ME,Xio, Xip, and n are coefficient of variation, mean absolute error, absolute mean prediction error, mean prediction error, observed biomass, predicted biomass, and number of sample trees, respectively.

4. RESULTS AND DISCUSSION

4.1. Results

4.1.1. Form factor

The biometric variables, form factor and measured tree component volume with their statistical parameters are presented in Table 1. The average values of stem, branch and total volumes of a tree were 0.178, 0.104 and 0.178 m^3, respectively. The stem form factor of the species was 0.615. The observed stem volume (Vs in m^3) and the predicted stem volume (Vsp) derived from form factor (Equ.4) was almost equivalent indicating the importance of form factor determination.

Table 1 Statistical summary of the dbh, h_m, f, the observed and the predicted values

Statistical parameters	Tree biometric variables		Tree driven variables				
	dbh (cm)	hm (m)	f	Vs (m^3)	Vb (m^3)	Vt (m^3)	Vsp (m^3)
Mean	21.7	7.80	0.615	0.178	0.104	0.275	0.178
Minimum	7.0	2.87	0.300	0.013	0.002	0.015	0.013
Maximum	34.0	10.64	1.190	0.343	0.270	0.612	0.343
Std.dev.	7.5	2.21	0.220	0.100	0.095	0.188	0.100
N	15	15	15	15	14	15	15

Where dbh, h_m, f, Vs, Vb, Vt, Vsp, were presented diameter at breast height, merchantable height, form factor, stem volume, branch volume, total volume and predicted stem volume.

4.1.2. Volume models

4.1.2.1 Correlation of dendrometric variables and volume of tree compartments.

The correlation of tree biometric variable and volume is given in Table 2. The stem volume of a tree was strongly correlated with dbh and merchantable height (h_m) of the species, but h_m did shows moderate and less correlation with total volume and branch. Moreover, scatter plot diagram also revealed that the data was close to the fitted regression line for the stem and total volume, thus the data were homogenous (Figure. 4). Based on this information, tree component volume models were developed (Table 3). Beside the observed and pridcted stem volume by different equations as shown in (Figure. 3).

Table 2 Spearman correlation coefficients and dendrometric variables

Species	Tree volume Component	Dendrometric variables	
		dbh (cm)	h_m(m)
Olea europaea	Stem	0.925***	0.863***
	Branch	0.925**	0.561*
	Total volume	0.961***	0.785**

Where, dbh is diameter at breast height, whereas h_m is merchantable height. *, **, *** indicates the level of correlation at $p < 0.05$, $p < 0.001$ and $p < 0.0001$, respectively.

Table 3 Parameter estimates and performance evaluation statistical indices for the volume model of tree components

Tree component	Model Code	Parameter estimate			statistical indices					
		α	β	β1	R^2	SEE	CF	MAE(kg)	MAPE(%)	MPE(%)
Stem	1	-8.094	2.033		0.934	0.2334	1.028	0.033	20.3	-3.3
	2	-7.763	1.208	1.076	0.968	0.1568	1.012	0.021	11.3	-0.8
Branch	1	-12.217	3.079		0.887	0.4625	1.113	-0.030	38.1	-0.3
Total volume	1	-8.826	2.390		0.948	0.2313	1.027	0.049	19.3	-1.9
	2	-8.625	1.890	0.653	0.952	0.2128	1.023	0.047	17.2	-0.6

Where, SEE, CF, MAE, MAPE, MPE, are Standard error of estimates, correction factors, mean absolute error, absolute mean prediction error and mean prediction error, respectively.

Table 3 shows the parameter estimates and the performance criteria of all the volume models. Natural log transformed data were pooled, 93.4 % of the variation in the stem volume was explained by dbh with MAPE of 20.3 % (Equ. 6). The addition of h_m as compound predictors improved the model performance (Equ. 7) compared with dbh alone equation 6, the MAE and MPE were also decreased by 0.012 m^3 and 2.5%, respectively. Thus, Equ. 7 was a good estimator of stem volume. High bias (MAPE=38.1%) was observed in branch volume Equ. 6 with adjusted R^2 of 88.7%. Combined dbh and h_m explained 95.2% variability in total volume and the Equ. 7 significantly ($p < 0.0001$) fitted. Although negligible difference, the performance of Equ. 7 was relatively revealed little evidence compared with Equ. 6 for the stem and total volume.

The best fit models are:-

$$Vs = [exp(-7.763 + 1.208\ ln(dbh) + 1.076 \ln(h_m))]x1.012 \qquad Equ. 7$$

$$Vb = \left[exp\left(-12.217 + 3.079\ ln(dbh)\right)\right]x1.113 \qquad Equ. 6$$

$$Vt = [exp(-8.625 + 1.89\ ln(dbh) + 0.653 \ln(h_m))]x1.023 \qquad Equ. 7$$

General volume equation calculated from form factor, basal area and h_m, was more accurate than stem equations. Equ. 7 gave higher value of MAPE (11.3%) and MAE of 0.02 m^3 than general volume equation.

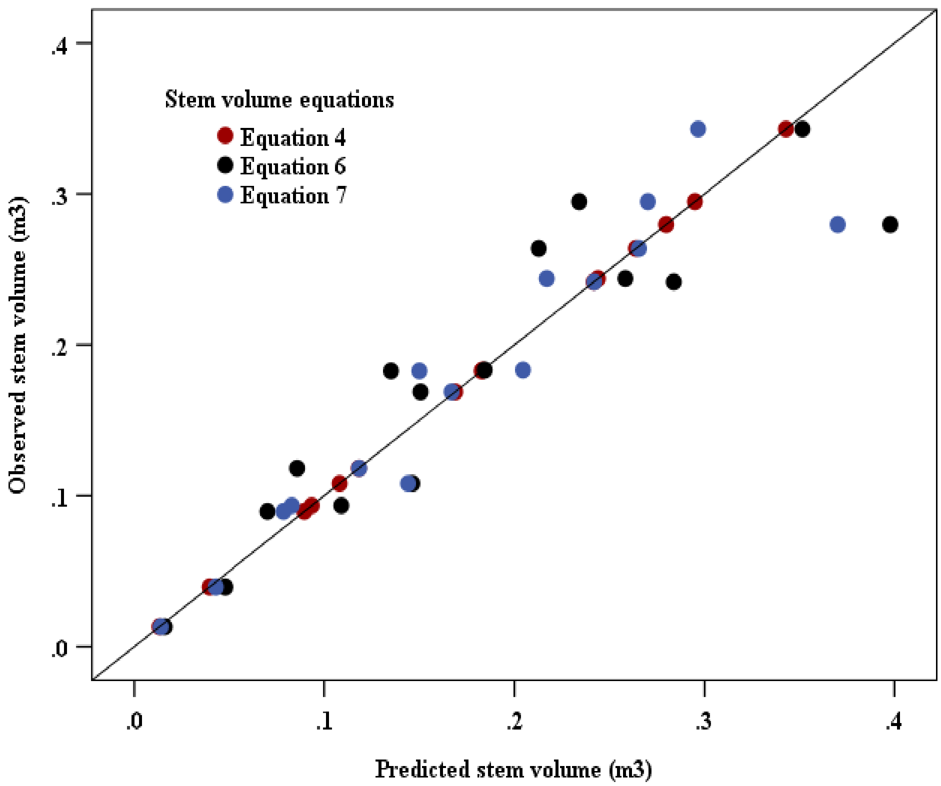
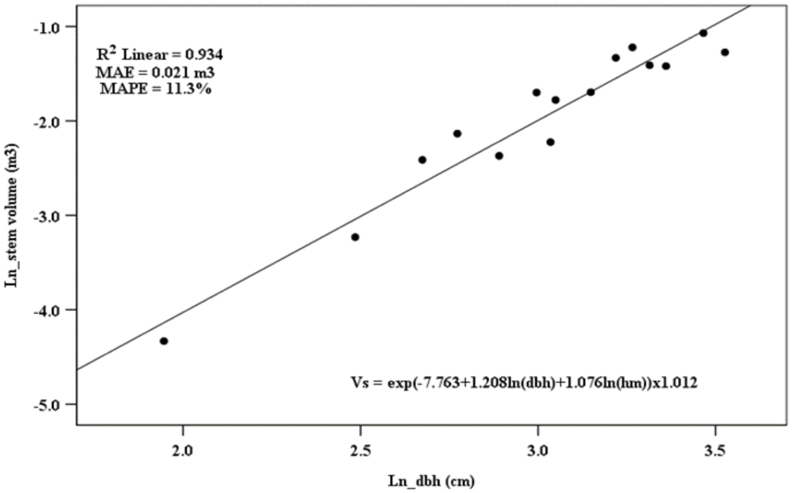
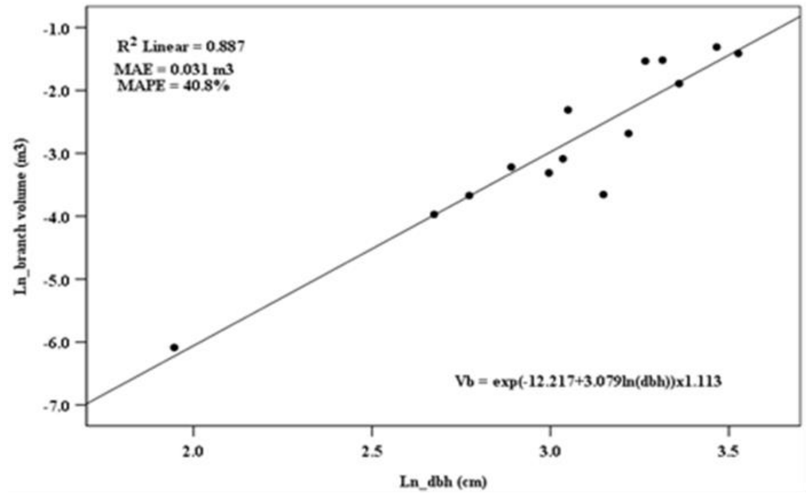


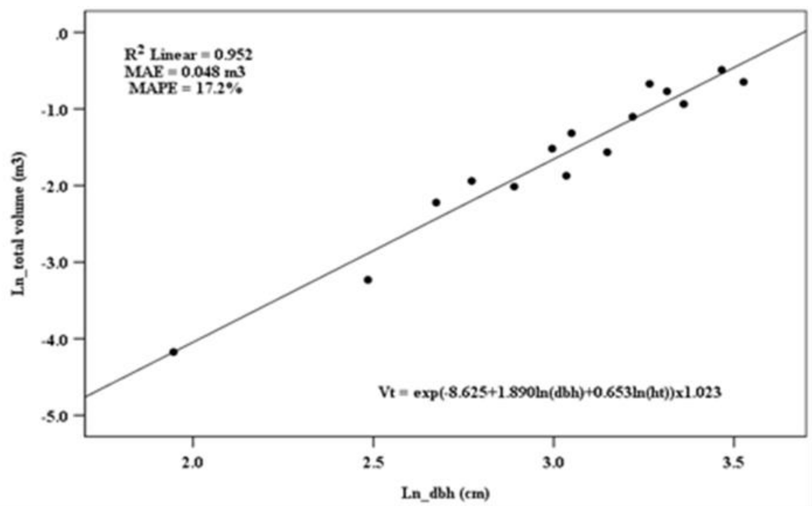
Figure 3 The observed and the predicted stem volume of the species



a) Stem volume



b) Branch volume



C) Total volume

Figure 4 The linear relationship of log Transformation of dbh (cm) and tree component volume (m3) of the species

4.1.3. Wood basic density determination

Wood basic density (wood density, ρ) of tree components was determined which is presented in Table (4). Although the difference was insignificant ($P > 0.05$), the average ρ of the stem was decreased with increasing sampling stem height. Based on paired sample t-test, the influence of wood density varies along stem height on biomass estimate was negligble. In branch classes, the ρ of class C3 was significantly different from class 1 and 2 ($P < 0.05$) and the value of average ρ was decreased as the diameter thickness (size) decreasing. With the exception of class C3, a significant ρ difference was not observed between branch class (C1 and C2) and stem sections (Fig. 5). Generally, the ρ of the stem was higher than branch. When compared to branch biomass estimated by its wood density, the predicted branch biomass by wood density of the stem significantly overestimated ($p < 0.003$).

Table 4 The statistical parameters and tree component wood density of *Olea europaea* species in dry afromontane forest

Statistical parameters	The stem sections(g/cm3)					The branch classes(g/cm3)			
	S1	S2	S3	S4	S	C1	C2	C3	C
Mean	0.674	0.645	0.636	0.638	0.648	0.645	0.657	0.562	0.602
Minimum	0.580	0.306	0.383	0.518	0.306	0.632	0.607	0.347	0.347
Maximum	0.729	0.735	0.730	0.873	0.873	0.666	0.715	0.680	0.715
Std. dev.	0.043	0.105	0.090	0.083	0.082	0.019	0.035	0.083	0.080
N	15	15	15	14	15	3	8	14	14

Std. dev and n represent standard deviation and the number of sample trees. S is an average wood density of the stem, whereas C is average wood density of branch. The symbol of S1, 2, 3 and 4 denote stem section one, two etc…, whereas C1, C2 and C3 are branch classes 1, 2 and 3.

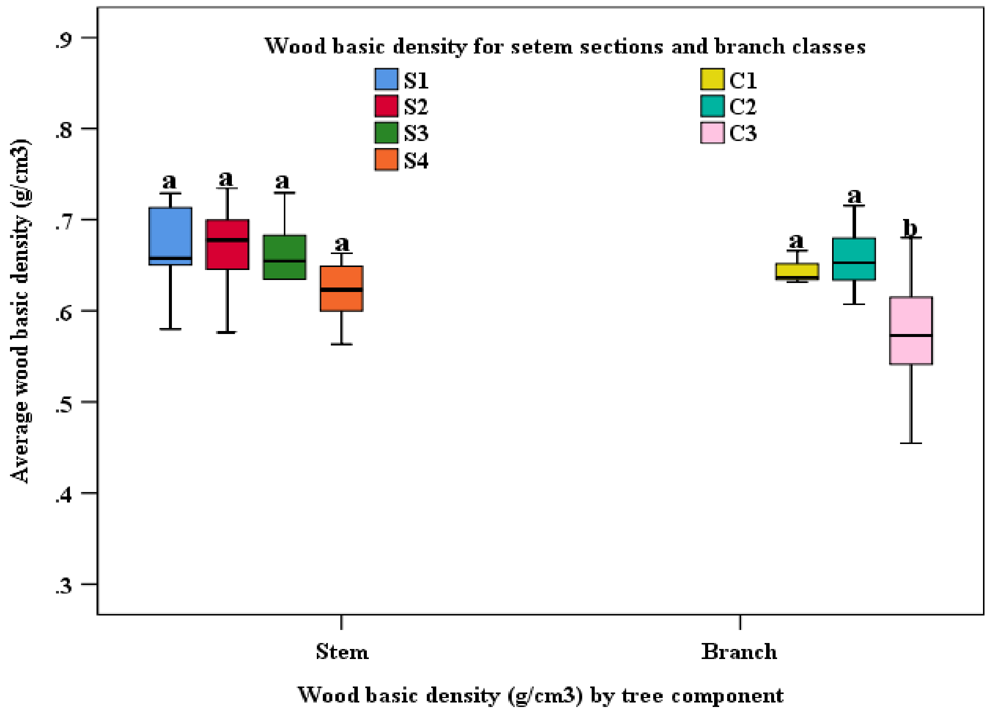


Figure 5 Comparison of the wood basic density for stem sections and branch thickness. The different letter indicates significant difference at $p < 0.05$

4.1.4. Allometricmodels for biomass

4.1.4.1. Biomass estimation

The aboveground biomass of (stem, branch, leave) and the total biomass of the study species were considered significant as it is dominant in the study area with dbh ranges. Each tree components accounted an average value of 148.8, 124.7, and 55.3 kg/trees for stem, branch and leaves, respectively and the predicted biomass of the tree component was comparable with the observed values (Table 5).

Table 5 Statistical summary of the dbh, ht,ρ, the observed and the predicted biomass of tree components (N=15)

Statistical parameters	Tree biometric variables			Tree driven variables							
	dbh (cm)	ht(m)	P	SBo (kg)	BrBo (kg)	LBo (kg)	AGBo (kg)	SBp (kg)	BrBp (kg)	LBp (kg)	TBp (kg)
Mean	21.7	10.68	0.65	148.78	124.72	55.28	328.78	178.54	136.56	59.41	335.92
Minimum	7	5.72	0.46	7.44	3.372	3.79	19.88	8.99	3.35	5.47	19.96
Maximum	34	14	0.72	273.27	340.20	107.35	720.83	361.79	395.58	131.09	745.71

Where SBo, BrBo, LBo, AGBo, SBp, BrBp, LBp, AGBp are observed and predicted biomass of the stem, branch, leave and AGB,respectively.

4.1.4.2. Correlation of dendrometric variables to biomass components.

Correlation between the independent and dependent variables was conducted to have a clue on best explanatory variables which might be selected to develop regression model. We found the AGB was strongly correlated with dbh, ht and wood density as indicated in Table 6. However, the branch and leaves biomass were moderately correlated to height, while branch biomass was relatively less correlated with wood density .

Table 6 Spearman correlation coefficients between tree component biomass and dendrometric variables for the studied species

Species	Biomass compartment	Dendrometric variables		
		dbh (cm)	ht(m)	P
Olea europaea	Stem	0.934***	0.887***	0.830***
	Branch	0.883***	0.736**	0.541*
	Leaves	0.913***	0.729**	0.785***
	Aboveground	0.944***	0.825***	0.805***

Where,dbh is diameter at breast height and ht is total tree height, whereas p is wood density.*, **, *** indicates the level of significant at p<0.05, p<0.01,and p<0.001, respectively.

4.1.4.3. Species-specific biomass model

In general, the performance of fitted model varied with tree component biomass. The parameter estimates and performance measure statistical indices are given in Table 7. Based on log transformed data dbh, ht and ρ explained greater than 96.1% variability in the stem biomass. Adding ht and/or wood density improved the model performance compared with dbh alone model of the stem. The accuracy of model containing three predictors (M3) was decreased from 33.8 (M1) to 22.5 kg (Table 7) with MAPE of 13.7% and thus this model was the best estimator of the stem biomass. Branch biomass was determined by both dbh and ht (adju.R^2= 0.888). The addition of ht decreased the value of MAE and MAPE by 6.6 kg and 14.1%, respectively as compared to dbh alone model (M1). Despite M1 relatively good prediction (MPE= -9.5%) ability, M2 was accurately predicted the branch biomass with MPE of negative 6.2%.

Diameter at breast height explained 75.9% of the variation in leave biomass with high bias (MAPE = 41.9%) and poor accuracy. The dbh and ht combination (M2), improved the model fitness, by 95.8% of the variation in AGB. The addition of ht and/wood density showed little evidence in the model performance as compared with dbh alone model, whereas both M2 and M3 had comparable performance. Thus, both M2 and M3 were the best estimator of AGB of the species. Moreover, the scatter plot diagram also revealed a best linear fit line and homogeneity of measured variables (Fig. 6) and thus the models were highly significant ($P < 0.0001$) and are accurately predicted the AGB of the species.

The best fit models are:-

$$\text{SB} = \left[\exp\left(1.72 + 0.727\ \ln(\text{dbh}) + 1.042\ \ln(\text{ht}) + 3.787\ \ln(\rho)\right)\right] \text{ x } 1.019$$

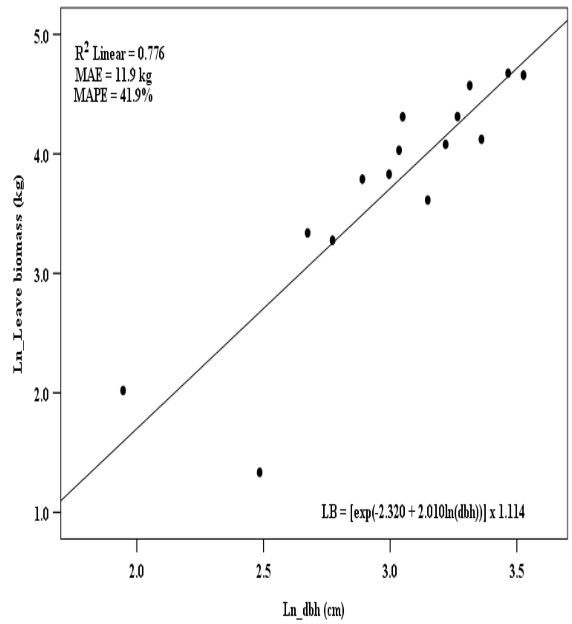
$$\text{BrB} = \left[\exp\left(-5.894 + 1.94\ \ln(\text{dbh}) + 1.858\ \ln(\text{ht})\right)\right] \text{ x } 1.108$$

$$\text{LB} = \left[\exp\left(-2.32 + 2.01\ \ln(\text{dbh})\right)\right] \text{ x } 1.114$$

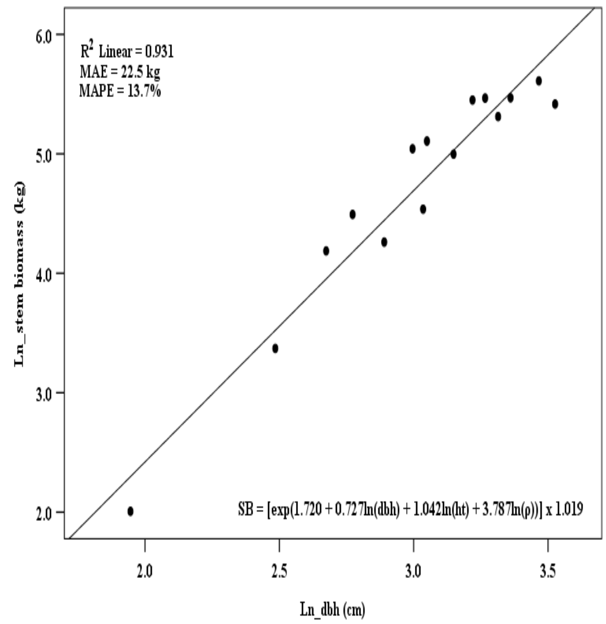
$$\text{AGB} = \left[\exp\left(-2.374 + 1.777\ \ln(\text{dbh}) + 1.064\ \ln(\text{ht})\right)\right] \text{ x } 1.022$$

Table 7 Model parameters and performance evaluation statistical indices for tree components

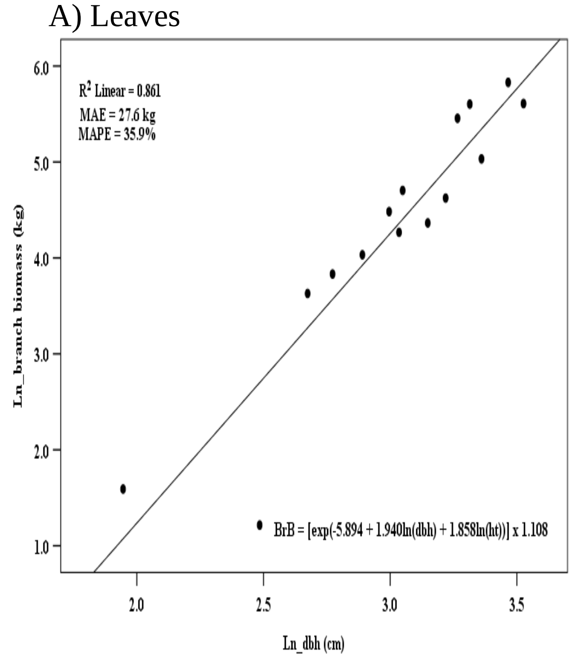
Tree component	Model Code	Parameter estimate				statstical indices					
		α	β	β1	β2	R^2	SEE	CF	MAE(kg)	MAPE(%)	MPE(%)
	1	-2.123	2.272			0.926	0.267	1.036	33.8	23.7	5.5
	2	-2.718	1.684	1.012		0.947	0.224	1.025	25.4	17.4	-4.4
	3	1.72	0.727	1.042	3.787	0.961	0.193	1.019	22.5	13.7	2.0
Stem	4	4.298		1.276	5.972	0.957	0.202	1.021	21.8	14.7	-0.7
	1	-4.802	3.019			0.851	0.522	1.146	34.2	52.5	-0.9
Branch	2	-5.894	1.94	1.858		0.888	0.453	1.108	27.6	38.5	-6.2
Leaves	1	-2.32	2.01			0.759	0.465	1.114	11.9	41.9	-7.5
	1	-1.749	2.395			0.935	0.26	1.034	57.4	21.1	-3.3
aboveground	2	-2.374	1.777	1.064		0.958	0.21	1.022	48.3	15.8	-2.2
biomass	3	-2.399	1.783	1.064	-0.022	0.954	0.219	1.024	48.8	16.0	-2.7



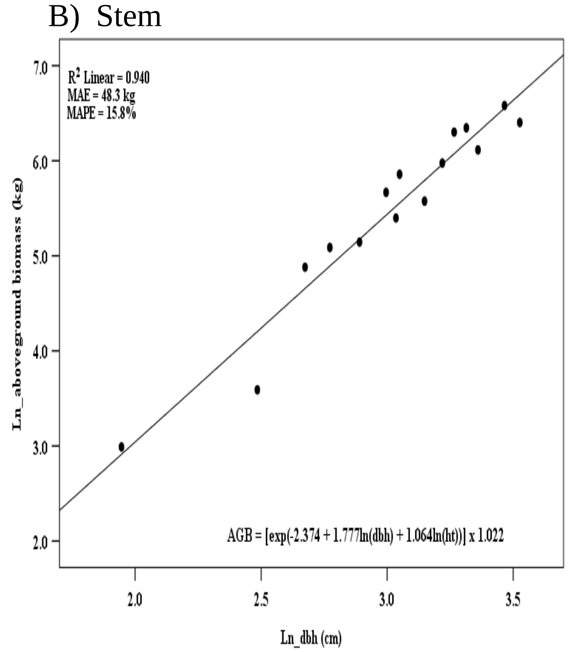
A) Leaves



B) Stem



C) Branch



D) Total above ground biomass

Figure 6 The linear relationship between log-transformed dbh and biomass of tre components. The solid line denots the fitted regression line

4.1.5. The errors due to indirect biomass measurement

When compared to the direct measurement, the indirect biomass measurement (the conversion of stem volume by wood density, SB_{in}) was significantly lower ($p < 0.0001$). Then, the weighed stem biomass (SB_{di}) and stem biomass computed by indirect measurement were pooled to regression. We found $SB_{di} = 7.686 + 1.66 SB_{in}$ (adju. $R^2 = 0.966$), but at 95% confidence interval of the intercept was -9.57 to 24.94 which is insignificant indicates the indirect measurement is still under estimated. As the result, the intercept was removed ($SB_{di} = 1.213\ SB_{in}$ with adjusted R^2 of 0.992) and thus the indirect biomass measurement was comparable, 1.3% less than the direct biomass measurement. We examined the influence of wood density variation along stem height and the volume formula used for calculating the stem volume and the effect was negligible.

4.1.6. Allometric model comparison with previously published models

Model comparison, previously published biomass models were applied to our data set, and the predicted values were under estimated. The selected models used for comparison are presented in Table 8. The MPE% values of previously developed model 5, 6 and 7 produced large prediction errors, ranging from 28.8 to 38.0% and the values were significantly different from zero ($p < 0.001$). Where as previous model of volume model were applied and the predicted volume were over estimated and the MPE was 14.9%.

Table 8 The selected generic allometric models used for comparison of biomass

Authors	Models AGB	Model Code	MPE(%)
Birhanu Kebede, and Teshome Sormessa, 2018	$AGB_{est} = 0.866 \times (dbh)^{1.432} \times (ht)^{0.608} \times (\rho)^{1.067}$	M 5	34.1***
Buruh Abebe *et al*., 2019	$AGB = 0.173 \times dbh^{2.250}$	M 6	38.0***
Chave et al. (2014)	$AGB = 0.0673 \times (dbh^2 \times ht \times \rho)^{0.976}$	M 7	28.8***

MPE, dbh , ht, ρ and AGB are mean prediction error (%), diameter at breast height (cm), total tree height (m), wood density (g cm^{-3}) and aboveground biomass (kg), respectively.

*** indicates the level of significanc at $p < 0.001$.

Table 9 The selected generic allometric models used for comparison of volumes

Authors	Models volume	Model Code	MPE(%)
Malbiew *et al*., 2016	$Vt = 0.00011 \times (dbh)^{2.133} \times (ht)^{0.5758}$	M 8	14.9***

MPE, dbh , ht and Vt are mean prediction error (%), diameter at breast height (cm) and total tree height (m), total volume (m3), respectively.

*** indicates the level of significanc at $p < 0.001$

4.2. Discussion

4.2.1. Volume models

Sustainable forest management requires a knowledge of forest growing stocks, which express in terms of volume per tree or hectare. Usually, volume is estimated as total volume per unit area, where by models predicting total tree volumes of individual trees are used. Substantial review on the volume and biomass models was made in Sub Saharan Africa (Henry *et al*., 2011); and most of them have been developed for tropical rainforest, but less biomass and volume models were available for dry tropical forests. Moreover, tree volume and biomass prediction tools for natural forests, including dry Afromontane forest, are not well established in Ethiopia. As a result, knowledge on the growing stocks and productivity of most natural forest tree species are poorly understood in the country. This implies the need of species and/or site context assessments in order to validate the existing prediction tools to gain accurate predictions.

Thus, species-specific volume models were developed for *Olea europaea* species. The stem volume of a tree can commonly be estimated from basal area, merchantable height and form factor, and thus form factor is an important variable in volume prediction. In this study, higher form factor (0.615) was observed than the previous reports, ranging from 0.482 to 0.559 for plantation species, (Tenzin *et al*., 2016), but it was within the ranges of African woodland species (Colgan *et al*., 2014). This indicates that there may be variation in form factor due to difference in tree species, management such as tree density and other edapho-climatic factors across the site. Although the difference between species was insignificant in dry woodlands

(Colgan *et al*., 2014), determining species specific form factor can provide accurate prediction as observed in the results (Fig. 3).

The overall regression accuracy of the allometric models for *O. europaea* was given by a very high value coefficient of determination. Log-transformed result showed that about 92.9% of the variation in stem volume was determined by dbh-alone, but the addition of h_m improved the equation performances compared with dbh-alone model. The volume model of stem that contain compound predictor had better prediction ability with MPE of negative 3.3%. Similarly, combined dbh and h_m accurately explained the total volume of tree species. It was consistent with the previous result (Akindel and Lemay, 2006), they found that both dbh and h_m are the best predictors of stem volume for species grouping models. However, branch volume model produced higher bias (MAPE = 38.1%) compared to stem and total volume models indicates the volume of branches having small diameter size might be less explained by dbh than large diameter sizes.

4.2.2. Wood density determination

Tree wood basic density (wood density, ρ) can be used for estimating forest biomass. Several studies publicized that biomass estimation can be improved when wood density (ρ) is included in the allometric models (Chave *et al*., 2005 and 2006). Thus, allometric models constructed from dbh, height and wood density together have reduced average deviation and improved the accuracy of biomass estimation (Basuki *et al*., 2009; Chave *et al*., 2005; Djomo *et al*., 2010). Although this importance, wood density variation in tropical tree species is high particularly in dry forests (Chave *et al*., 2004). This indicates the need of species-specific information supporting our work.

Wood density varied within stem sections and the mean value of stem ρ decreased as increasing the sampling height even though the difference was insignificant. This variation may be a source of bias estimate in biomass if the wood density determines at one stem position, which is commonly taken at dbh. Furthermore, the variation in ρ among tree component was observed, significant ρ difference was observed between stem section 1(S1) and branch diameter class 3 (C3) and this variation of ρ alone stem height and between stem and branch was investigated in the dry woodland species (Amsalu Abich and Asmamaw Alemu, 2020). In this study, wood density variation within stem section did not show significant effect on the stem biomass predictions. However, the predicted value of branch biomass was overestimated when the stem wood density was applied. This difference indicates that careful considerations should done when the wood density are planned for determination and application in the stem and tree components.

4.2.3. Species specific allometric model

According to Litton and Boone (2008), a species-specific model is more accurate for species-based predictions. The reason behind this accuracy is because architecture and density have great variation among species and within the same species. As a result, model development through single species-based components has significant accuracy to estimate the biomass of a particular tree (Ketterings *et al*., 2001 and Henry *et al*., 2011).

Correlation between the independent and dependent variables was conducted to have a clue on best explanatory variables which might be selected to develop regression model. As confirmed in many studies, we found the aboveground biomass was strongly correlated with dbh for the studied trees.

Height and wood density are the second important factor correlating with biomass showed a strong correlation in *Olea europaea*. Thus, a model for *Olea europaea* was developed, and tree component biomass was well determined by dbh and ht although significant difference was not observed between model forms.

When compared to model 1 (dbh alone), model 2 (both dbh and ht) was showed an improvement of model performance and this may give accurate biomass estimations, which is consistent with the previous reports (Mugasha *et al*., 2013, Zeng *et al*., 2017). Although the difference was insignificant, the addition of ht and wood density as compound predictors slightly improved the model's performance compared with dbh-alone model in the stem biomass. Besides, combined ht and wood density (M4) showed little evidence in the model performance compared to others. Similarly, the same trend was observed, dbh and ht were the best predictors in the above ground biomass. Our result was consistent with the findings of previous studies (Mehari Alebachew *et al*., 2016; Birhanu Kebede and Teshome Sormessa, 2018), they found that both dbh and ht are the best estimator of aboveground biomass of a species. Despite the model's performance was poor, dbh-alone explained 85.1 and 75.9% variability in the branch and leave biomass, respectively. For branch biomass, adding ht in the model provided more accurate prediction than dbh-alone model. However, Mehari Alebachew et al.(2016) found that both dbh and ht explained less than 79% of the variation in the branch biomass. Tree component biomass models such as branch and leaf biomass did not provide more accurate results than stem or aboveground biomass models. this indicates that the biomass of large tree components is more strongly correlated with dbh and ht than that of smaller and shorter-lived components, which is consistent with the findings of previous studies (Meheri Alebachew *et al*., 2016; Mesele Negash *et al*., 2013).

Thus, the fitted branch model 2 was a good estimator. In general, this model provides accurate biomass estimation at species level, which is consistent with previous reports in Ethiopia (Mesele Negash *et al*., 2013; Mehari Alebachew *et al*., 2016; Birhanu Kebede and Teshome Sormessa, 2018) and in elsewhere (Litton and Kauffman, 2008; Xiang *et al*., 2016).

4.2.3. The errors associated with biomass measurement methods

The indirect measurement, conversion of stem volume to biomass by its wood density was lower than the direct biomass measurement by 18.6% (MAPE), which is contradicted with other report (Mavouroulou *et al*., 2014). They found that the indirect biomass measurement is 19% greater than the direct measurement. The variation in wood density along stem height and the formula used to calculate the stem volume had very little evidence, but this measurement errors may highly associate with stem shape. This is because the stem shape is not smoothly changed towards the terminal of the tree and dominated by irregularity and this may contribute to diameter measurement error in the natural forest.

4.2.4. Allometric model comparison with the previously published models

The predicted values by previously developed models were underestimated when we applied to our data set. These models also produced large prediction errors indicates the need of local species-specific models to gain more accurate estimates. This bias in biomass estimates might be associated with difference in climate variability and site condition, which affects plant growth. Moreover, the indirect biomass measurements and the use of stem wood density to estimate branch biomass provided large errors.

This variation in the biomass measurement method between scholars may be a source of bias in biomass estimate, since semi-destructive (Birhanu Kebede and Teshome Sormessa, 2018) and indirect measurements (Mehari Alebachew *et al.*, 2016) were applied for biomass measurement in the field.

5. CONCLUSION AND RECOMMENDATION

Developing species-specific volume and biomass models are important for understanding and monitoring the growing stocks and productivity of the tree species in the dry Afromontane forests. Allometric models relate to tree component volume and biomass to measured variables were developed based on 15 individual measurements of a dominant tree species. Tree component volume and biomass variables were observed within species. The stem form factor of a species was 0.615 and this value provides more accurate prediction than the fitted stem volume model, whereas volume models are provided accurate volume predictions for tree components. Combined dbh and h_m were a better volume estimator, explaining greater than 92.9% of variations in the stem and total volume, whereas the branch volume was determined by dbh alone.

Variation in the average values of wood density was observed along stem height, branch thickness and between tree components which is a source of bias in biomass estimates. The average values of wood density decreased as increasing the stem sampling height and decreasing branch diameter thickness. The effect of wood density variation within a tree was more pronounced in branch biomass estimation than stem biomass. This indicates the need of wood density determination for the stem and branch, which will be determined based on sample disc that would be taken at different branch diameter size and the stem height as evident our results.

Species-specific model provides a better biomass prediction for the species and tree components. The large part of the variation in the stem, branch and aboveground biomass was explained by both dbh and ht, whereas dbh alone explained 75.9% variability in the leaf biomass. Higher MAE and MAPE were observed in the branch and leaf biomass model than other tree component indicate diameter at breast height less potential in explaining small diameter size and thus the models are satisfactory in the tree component biomass predictions. Indirect biomass measurement was lower than the direct measurement indicates biomass measurement techniques, including conversion of stem volume to biomass by its wood density, may be a source of bias in biomass prediction. This measurement errors should be considered when indirect biomass measurement is planned in the field or will be incorporated in the model development process. In model comparison, all published species-specific models the generic model provided large prediction errors and these models cannot provide a better prediction when they are applied outside their range. Thus, developing a robust species-specific model for each species and tree components based on empirical data provides more accurate results than models developed elsewhere. Thus, our tree component models can be used to estimate carbon storage and assess ecological functions of tree species.

The following recommendations are forwarded to wisely use forest management/ conserve forest in a suitable manner

- the negative bias or underestimation of biomass due to indirect biomass measurements and the reliability of stem wood density in branch biomass estimation would be required further assessments in order to consider the effects in model development.
- The uncertainty in biomass and volume largely results due to lack of species-specific allometric equations thus, the allometric equations from this study can be reliably used by researchers and/or forest managers to calculate aboveground biomass, aboveground

carbon, belowground biomass and total biomass of the studied species within the specific forest type precisely in the future.

- The models from this study can be used as tool for measurement of the achievement of the estimation of AGB, volume and their associated uncertainty are also essential for international forest based climate change mitigation strategies such as REDD+ therefore, developing allometric equation through species-specific method for all the indigenous tree species that are found in Harego forest will give the accurate information on AGB and volume can be applicable whenever needed. Such accurate and precise information on reliable estimates of biomass and volume would be highly supportive on decisions by policy makers regarding sustainable management and use of forests as well as efforts for mitigating climate change for forests dominated by the study species.

REFERENCES

Abdullahi Jibrin and Aishetu Abdulkadir, 2015, Allometric models for biomass estimation in savanna woodland area, Niger state, Nigeria. *Int J Environ Chem Ecol Geol Geo phys Eng*, *9*, pp.270-278.

Aboal, J.R., Arévalo, J.R. and Fernandez, Á., 2005. Allometric relationships of different tree species and stand above ground biomass in the Gomera laurel forest (Canary Islands). *Flora-Morphology, Distribution, Functional Ecology of Plants*, *200*(3), pp.264-274.

Abraham Yirgu, Getachew, B. and Belay, T., 2012. Short communication report of an olive lacebug infestation on Olea europaea ssp. cuspidata (Wall. ex G. Don) PS Green in Desa'a natural forest. *Pest Management Journal of Ethiopia*, *75*, pp.70-75.

Akindele, S.O., & Lemay, V.M., 2006. Development of tree equations for common timber species in the tropical rain forest area of Nigeria. *Forest Ecology and Management*, *226*, 41-48. https://doi.org/10.1016/j.foreco.2006.01.022

Alemayehu Wassie, 2007 *Ethiopian church forests: opportunities and challenges for restoration*.

Amsalu Abich and Asmamaw Alemu, 2020. Inter and intra-species wood density variation of *Combretum-Terminalia*woodland in Northwest Ethiopia *Journal of Forestry Research*. 30(4), 1619–1632.

Amsalu Abich, Asmamaw,A., Gebremariam, Y., Mucheye, T., Kassie, M., and Gurebiyaw, K., 2019. Allometric models for predicting aboveground biomass of tree species in the *Combretum-Terminalia* woodlands of Amhara, Northwest Ethiopia.

Anon, 1988. National atlas of Ethiopia. Ethiopia Mapping Authority, Addis Ababa, 157pp.

Azene Bekele, 2007. Useful trees and shrubs of Ethiopia: Identification, propagation, and management in 17 Agro-ecological zones. *Nairobi: RELMA in ICRAF project*, *552*.

Baker, T.R., Phillips, O.L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., Erwin, T., Killeen, T.J., Laurance, S.G., Laurance, W.F. and Lewis, S.L., 2004. Variation in wood density determines spatial patterns in Amazonian forest biomass. *Global Change Biology*, *10*(5), pp.545-562.

Baskerville, G.L., 1972. Use of logarithmic regression in the estimation of plant biomass. *Canadian Journal of Forest Research*, *2*(1), pp.49-53.

Basuki, T.M., Van Laake, P.E., Skidmore, A.K. and Hussin, Y.A., 2009. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *Forest ecology and management*, *257*(8), pp.1684-1694.

Birhanu Kebede & Teshome Sormessa, 2018. Allometric equations for aboveground biomass estimation of Olea europaeaL.subsp. Cuspidata in ManaAngetu Forest. *Ecosystem Health and Sustainability*, *4*(1), pp.1-12.

Brown, S., 1997. *Estimating biomass and biomass change of tropical forests: a primer* (Vol. 134). Food & Agriculture Org.

Brown, S., Gillespie, A.J. and Lugo, A.E., 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. *Forest science*, *35*(4), pp.881-902.

Buruh Abebe, Birhane, E., Rannestad, M. and Eid, T., 2019. Allometric Models for Predicting Aboveground Biomass of Trees in the Dry Afromontane Forests of Northern Ethiopia. *Forests*, *10*(12), p.1114.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T. and Lescure, J.P., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, *145*(1), pp.87-99.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S. and Perez, R., 2004. Error propagation and scaling for tropical forest biomass estimates. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *359*(1443), pp.409-420

Chave, J., Muller-Landau, H.C., Baker, T.R., Easdale, T.A., Steege, H.T. and Webb, C.O., 2006. Regional and phylogenetic variation of wood density across 2456 neotropical tree species. *Ecological applications*, *16*(6), pp.2356-2367.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C. and Henry, M., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global change biology*, *20*(10), pp.3177-3190.

Chave, J., Riéra, B. and Dubois, M.A., 2001. Estimation of biomass in a neotropical forest of French Guiana: spatial and temporal variability. *Journal of Tropical Ecology*, pp.79-96.

Chudnoff, M., 1984. *Tropical timbers of the world* (No. 607). US Department of Agriculture, Forest Service.

Colgan, M.S., Swemmer, T. and Asner, G.P., 2014. Structural relationships between form factor, wood density, and biomass in African savanna woodlands. *Trees*, *28*(1), pp.91-102.https://doi.org/10.1007/s00468-013-0932-7

Condit, R., 2008. Methods for estimating aboveground biomass of forest and replacement vegetation in the tropics. *Center for Tropical Forest Science Research Manual*, *25*.

David, R., Palmiotto, P.A. and Strimbeck, G.R., 1998. Allometric equations for two South American conifers: test of a non-destructive method. *Forest Ecology and Management*, *106* (23), pp.55-71.

Djomo, A.N., Ibrahima, A., Saborowski, J. and Graven horst, G., 2010. Allometric equations for biomass estimations in Cameroon and pan moist tropical equations including biomass data from Africa. *Forest Ecology and Management*, *260*(10), pp.1873-1885.

Dudley, N.S. and Fownes, J.H., 1992. Preliminary biomass equations for eight species of fast-growing tropical trees. *Journal of tropical forest science*, pp.68-73.

Ermias Bekure, 2012. *Center for Environmental Sciences* (Doctoral dissertation, Addis Ababa University Addis Ababa, Ethiopia).

FAO, 2012. Climate change adaptation and mitigation: challenges and opportunities in the food sector. *Natural Resources Management and Environment Department, FAO, Rome*, p.150.

FAO, 2015. Global forest resources assessment. Desk reference. *Food and agriculture organization of the United Nations, Rome*.

Fearnside, P. M. 1997. Wood density for estimating forest biomass in Brazilian Amazonia. *Forest Ecology and Management*, 90, 59-87

Feng, Z., Guo, Q. and Kelly, M., 2012. Allometric equation choice impacts lidar-based forest biomass estimates: A case study from the Sierra National Forest, CA. *Agricultural and forest meteorology*, *165*, pp.64-72.

Flombaum, P. and Sala, O.E., 2007. A non-destructive and rapid method to estimate biomass and aboveground net primary production in arid environments.*Journal of Arid Environments*, 69 (2), pp.352-358.

Flores, O. and Coomes, D.A., 2011.Estimating the wood density of species for carbon stock assessments. *Methods in Ecology and Evolution*, *2*(2), pp.214-220

Friis, I.B., 1986. The forest vegetation of Ethiopia. *Symbolae Botanical Upsalienses*, *26*(2), pp.31-47.

Gower, S.T., Kucharik, C.J. and Norman, J.M., 1999.Direct and indirect estimation of leaf area index, fAPAR, and net primary production of terrestrial ecosystems. *Remote sensing of environment*, *70*(1), pp.29-51.

Gudeta Sileshi, 2014. A critical review of forest biomass estimation models, common mistakes and corrective measures. *Forest Ecology and Management*, *329*, pp.237-254.

Hedberg, I., Edwards, S. and Nemomissa, S., 2003. Flora of Ethiopia and Eritrea, Volume 4, Part 1: Apiaceae to Dipsacaceae. *Addis Ababa, Ethiopia and Uppsala, Sweden: The National Herbarium, Addis Ababa University*.

Henry, M., Besnard, A., Asante, W.A., Eshun, J., Adu-Bredu, S., Valentini, R., Bernoux, M. and Saint-André, L., 2010. Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa. *Forest Ecology and Management*, *260*(8), pp.1375-1388.

Henry, M., Picard, N., Trotta, C., Manlay, R., Valentini, R., Bernoux, M. and Saint-André, L., 2011. Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. *Silva Fennica*, *45*(3), pp.477-569.

Houghton, R.A., Skole, D.L., Nobre, C.A., Hackler, J.L., Lawrence, K.T. and Chomentowski, W.H., 2000. Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. *Nature*, *403*(6767), pp.301-304.

IPCC, 2003. Good practice guidance for land use, land-use change and forestry. *Good practice guidance for land use, land-use change and forestry*.

IPCC, 2006. Guidelines for National Greenhouse Gas Inventories: Chapter 4: Forest Land. *Institute for Global Environmental Strategies, Hayama, Japan*, pp.4-1.

Jochem, A., Hollaus, M., Rutzinger, M. and Höfle, B., 2011. Estimation of aboveground biomass in alpine forests: a semi-empirical approach considering canopy transparency derived from airborne LiDAR data. *Sensors*, *11*(1), pp.278-295.

Kenzo, T., Furutani, R., Hattori, D., Kendawang, J.J., Tanaka, S., Sakurai, K. and Ninomiya, I., 2009. Allometric equations for accurate estimation of above-ground biomass in logged-over tropical rainforests in Sarawak, Malaysia. *Journal of forest research*, *14*(6), p.365.

Kettering's, Q.M., Coe, R., van Noordwijk, M. and Palm, C.A., 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. *Forest Ecology and management*, *146*(1-3), pp.199-209

Kibrom Tekle, 1997. Land degradation problems and their implications for food shortage in South Wello, Ethiopia. *Environmental management*, *23*(4), pp.419-427.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R. and Neufeldt, H., 2012. Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. *Agriculture, ecosystems & environment*, *158*, pp.225-234.

Leakemariam Berhe and Goran Amoldsson, 2008. Tree taper models for Cupressuslusitanica plantations in Ethiopia. *Southern Forests: a Journal of Forest Science*, *70*(3), pp.193-203. https://doi.org/10.2989/SF.2008.70.3.2.663

Legesse Negashi, 1993. Investigations on the germination behavior of wild olive seeds and the nursery establishment of the germinants. *SINET: An Ethiopian Journal of Science (Ethiopia)*.

Litton, C.M. and Boone Kauffman, J., 2008. Allometric models for predicting aboveground biomass in two widespread woody plants in Hawaii. *Bio tropical*, *40*(3), pp.313-320

Liu, X., Ekoungoulou, R., Loumeto, J.J., Ifo, S.A., Bocko, Y.E. and Koula, F.E., 2014. Evaluation of carbon stocks in above-and below-ground biomass in Central Africa: case study of Lesio-louna tropical rainforest of Congo. *Bio geosciences Discussions*, *11*(7), pp.10703-10735

Malimbwi, R.E., Eid, T. and Chamshama, S.A.O., 2016. Allometric tree biomass and volume models in Tanzania

Mavouroulou, M, Q., Ngomanda, A., EngoneObiang, N.L., Lebamba, J., Gomat, H., Mankou, G.S., Loumeto, J., MidokoIponga, D., KossiDitsouga, F., ZingaKoumba, R. and BotsikaBobé, K.H., 2014. How to improve allometric equations to estimate forest biomass stocks? Some hints from a central African forest. *Canadian Journal of Forest Research*, *44*(7), pp.685-691.

Mehari Alebachew, Bravo-Oviedo, A., Bravo, F. and Ruiz-Peinado, R., 2016. Aboveground biomass equations for sustainable production of fuel wood in a native dry tropical afro-montane forest of Ethiopia. *Annals of Forest Science*, *73*(2), pp.411-423.

Mesele Negash, Starr, M., Kanninen, M. and Berhe, L., 2013. Allometric equations for estimating aboveground biomass of Coffeaarabica L. grown in the Rift Valley escarpment of Ethiopia. *Agroforestry systems*, *87*(4), pp.953-966. https://doi.org/10.1007/s10457-013-9611-3.

Mugasha, W.A., Eid, T., Bollandsås, O.M., Malimbwi, R.E., Chamshama, S.A.O., Zahabu, E. and Katani, J.Z., 2013. Allometric models for prediction of above-and belowground biomass of trees in the miombo woodlands of Tanzania. *Forest Ecology and Management*, *310*, pp.87-101.

Mulugeta Mokria, W., Gebrekirstos, A., Aynekulu, E., Belay, B., Gashaw, T. and Bräuning, A., 2018. Mixed-species allometric equations and estimation of aboveground biomass and carbon stocks in restoring degraded landscape in northern Ethiopia. *Environmental Research Letters*, *13*(2), p.024022.

Nelson, B.W., Mesquita, R., Pereira, J.L., De Souza, S.G.A., Batista, G.T. and Couto, L.B., 1999. Allometric regressions for improved estimate of secondary forest biomass in the central Amazon. *Forest ecology and management*, *117*(1-3), pp.149-167.

Paul, K.I., Roxburgh, S.H., Chave, J., England, J.R., Zerihun, A., Specht, A., Lewis, T., Bennett, L.T., Baker, T.G., Adams, M.A. and Huxtable, D., 2016. Testing the generality of above-ground biomass allometry across plant functional types at the continent scale. *Global change biology*, *22*(6), pp.2106-2124.

Picard, N., Saint-André, L., Henry, M. 2012. Manual for building tree volume and biomass allometric equations: From field measurement to prediction. Food and Agricultural Organization of the United Nations, Rome, and Centre de Coopération Internationale en Recherche Agronomique pour le Développement.

Pilli, R., Anfodillo, T. and Carrer, M., 2006. Towards a functional and simplified allometry for estimating forest biomass. *Forest Ecology and Management*, *237*(1-3), pp.583-593.

Pohjonen, V., & Pukkala, T. 1992. Juniperus procera Hocht. ex. Endl. in Ethiopian forestry. Forest Ecology and Management, 49(1–2), 75–85. https://doi.org/10.1016/0378-1127(92)90161-2

Pohjonen, V.M., 1991. Volume equations and volume tables of JuniperusproceraHocht. ex. Endl. *Forest ecology and management*, *44*(2-4), pp.185 200. https: //doi.org/ 10.1016/ 0378 -1127(91)90007-I

Pohjonen,V. and Pukkala, T., 1990. Eucalyptus globulus in Ethiopian forestry. *Forest EcologyandManagement*,*36*(1),pp.19-31.https://doi.org/10.1016/0378-1127(90)90061F

Přemyslovská, E., Slezingerová, J., Rybníček, M., Gryc, V., Vavrčík, H. and Praus, L., 2007, September. Basic density of wood in different forest type. In *Bioclimatology and natural hazards. International Scientific Conference, Pol'ananadDetvou. Slovakia. p* (pp. 17-20).

Ribeiro, M.C., Martensen, A.C., Metzger, J.P., Tabarelli, M., Scarano, F. and Fortin, M.J., 2011. The Brazilian Atlantic Forest: a shrinking biodiversity hotspot. In *Biodiversity hotspots* (pp. 405-434). Springer, Berlin, Heidelberg.

Rutishauser, E., Noor'an, F., Laumonier, Y., Halperin, J., Hergoualc'h, K. and Verchot, L., 2013. Generic allometric models including height best estimate forest biomass and carbon stocks in Indonesia. *Forest Ecology and Management*, *307*, pp.219-225.

Sadeli Ilyas, 2013. Allometric equation and carbon sequestration of Acacia mangiumWilld. In coal mining reclamation areas. *Civil and Environmental Research*, *3*(1), pp.8-16.

Segura, M.andKanninen, M., 2005. Allometric Models for Tree Volume and Total Aboveground Biomass in a Tropical Humid Forest in Costa Rica 1. *Biotropica: The Journal of Biology and Conservation*, *37*(1), pp.2-8.

Shem, k., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R. and Neufeldt, H., 2012. Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. *Agriculture, ecosystems & environment*, *158*, pp.225-234.

Smith, R.J., 1993. Logarithmic transformation bias in allometry. *American Journal of Physical Anthropology*, *90*(2), pp.215-228.

Somogyi, Z., Cienciala, E., Mäkipää, R., Muukkonen, P., Lehtonen, A. and Weiss, P., 2007. Indirect methods of large-scale forest biomass estimation. *European Journal of Forest Research*, *126*(2), pp.197-207

Tenzin, J., Wangchuk, T., &Hasernauer, H. (2016).Form factor functions for nine commercial tree species in Bhutan. An International Journal of Forest Research, 1-8. http://doi.Org/10.1093 /forestry/ cpw044

Tesfaye Bekele, 2000. *Plant population dynamics of Dodonaeaangustifolia and Olea europaea ssp. cuspidata in dry afromontane forests of Ethiopia* (Doctoral dissertation, Acta Universities Upsaliensis).

Tesfaye Bekele, 2005. Recruitment, survival and growth of Olea europaea subsp. cuspidata seedlings and juveniles in dry Afromontane forests of northern Ethiopia. *Tropical Ecology*, *46*(1), pp.113-126.

Tesfaye Teshome, 2005. A ratio method for predicting stem merchantable volume and associated taper equations for Cupressus lusitanica, Ethiopia. *Forest Ecology and Management*, 204(2-3), pp.171-179. https://doi.org/10.1016/j.foreco.2004.07.064

Vallet, P., Dhôte, J.F., Le Moguédec, G., Ravart, M. and Pignard, G., 2006. Development of total aboveground volume equations for seven important forest tree species in France. *Forest Ecology and Management*, *229*(1-3), pp.98-110.

Vashum, K.T. and Jayakumar, S., 2012. Methods to estimate above-ground biomass and carbon stock in natural forests-a review. *Journal of Ecosystem &Ecography*, *2*(4), pp.1-7.

Viherä-Aarnio A.,Velling P., 2017. Growth, wood density and bark thickness of silver birch originating from the Baltic countries and Finland in two Finnish provenance trials. Silva Fennica vol. 51 no. 4 article id 7731. 18 p. https://doi.org/10.14214/sf.7731

Vishal, S., Tewari, A., Kushwaha, S.P. and Dadhwal, V.K., 2011. Formulating allometric equations for estimating biomass and carbon stock in small diameter trees. *Forest Ecology and Management*, *261*(11), pp.1945-1949

West, P.W. and West, P.W., 2009. Tree and forest measurement (pp. 1-190). Berlin: Springer.

Xiang, W., Zhou, J., Ouyang, S., Zhang, S., Lei, P., Li, J., Deng, X., Fang, X. and Forrester, D.I., 2016. Species-specific and general allometric equations for estimating tree biomass components of subtropical forests in southern China. *European Journal of Forest Research*, *135*(5), pp.963-979.

Zeng, W., Zhang, L., Chen, X., Cheng, Z., Ma, K. and Li, Z., 2017. Construction of compatible and additive individual-tree biomass models for Pinustabulaeformis in China. *Canadian Journal of Forest Research*, *47*(4), pp.467-475.

ANNEX

Annex. 1 Parameter estimates and performance evaluation statistical indices for the volume model of tree components

Tree component	Model Code	Parameter estimate			statistical indices	
		A	β	β1	R^2	SEE
Stem	1	-8.094	2.033		0.934	0.2334
	2	-6.649		2.339	0.899	0.2779
	3	**-7.763**	**1.208**	**1.076**	**0.968**	**0.1568**
Branch	**1**	**-12.217**	**3.079**		**0.887**	**0.4625**
	2	-9.227		3.137	0.598	0.8529
	3	-12.573	-0.628	3.613	0.879	0.4667
Total volume	1	-8.826	2.390		0.948	0.2313
	2	**-8.625**	**1.890**	**0.653**	**0.952**	**0.2128**
	3	-6.899		2.635	0.832	0.21029

Annex. 2 Parameter estimates and performance evaluation statistical indices for the biomass model of tree components

Tree component	Model Code	Parameter estimate				Statical indexes	
		α	β	β1	β2	R^2	SEE
	1	-2.123	2.272			0.926	0.267
	2	-2.544		3.109		0.799	0.438
	3	8.454			8.714	0.916	0.294
	4	**-2.718**	**1.684**	**1.012**		**0.947**	**0.224**
	5	2.148	1.371		3.637	0.935	0.249
	6	**1.72**	**0.727**	**1.042**	**3.787**	**0.961**	**0.193**
Stem	**7**	**4.298**		**1.276**	**5.972**	**0.957**	**0.202**
	1	**-4.802**	**3.019**			**0.851**	**0.522**
	2	-5.693		4.273		0.79	0.619
	3	8.932			10.829	0.721	0.713
	4	**-5.894**	**1.94**	**1.858**		**0.888**	**0.453**
	5	3.251	1.419		3.251	0.791	0.498
Branch	**6**	**-5.155**	**0.394**	**-0.0781**	**2.729**	**0.933**	**0.283**
	1	**-2.32**	**2.01**			**0.759**	**0.465**
	2	-2.800		2.797		0.701	0.537
	3	6.767			7.074	0.615	0.587
Leaves	4	5.319		0.154	3.417	0.70	0.383
	1	-1.749	2.395			0.935	0.26
	2	-2.190		3.277		0.807	0.451
	3	9.259			8.850	0.847	0.401
	4	**-2.374**	**1.777**	**1.064**		**0.958**	**0.21**
Total	5	-1.990	2.446		-0.205	0.93	0.271
aboveground	6	3.931		1.639	5.352	0.918	0.294
biomass	**7**	**-2.399**	**1.783**	**1.064**	**-0.022**	**0.954**	**0.219**