Allometric equations for aboveground biomass estimation of *Olea europaea* L. subsp. *cuspidata* in Mana Angetu Forest

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**ABSTRACT**

**Introduction:** African wild olive, *Olea europaea* L. subsp. *cuspidata* (Wall. ex G. Don) Cif., L ‘Olivicolore is widely distributed in dry forest and forest margins, often with *Juniperus procera*, in east Africa and Ethiopia. It reaches southern Africa, also India and China, ranging from tall trees to stunted shrubs. Does best in good forest soil, but hardy and drought resistant once established, even in poor soils. It is used for firewood, charcoal, poles, posts, timber (furniture, carving, floors, and paneling), medicine (stem, bark, and leaves), bee forage, milk flavoring (smoking wood), toothbrushes (twigs), and walking sticks. Although the species has many economic and ecological functions, its environmental uses like carbon storage and climate change mitigation are less assessed. Therefore, the objective of the study was to develop species-specific allometric equations for *O. europaea* L. subsp. *cuspidata* using semi-destructive method and evaluate allometric models for estimating the aboveground biomass (AGB).

**Results and Discussions:** After all the necessary biomass calculations were done, seven AGB equations were developed. These regression equations relate AGB with diameter at breast height (DBH), height (H), and density (ρ) individually and in combination. Out of seven, four allometric equations were chosen based on goodness-of-fit statistics and three were rejected. The selected models were tested for accuracy based on observed data. The best models selected have higher $R^2$-adj and lower residual standard error and Akaike information criterion than rejected equations. The relations for all selected models are significant ($p < 0.000$), which showed strong correlation of AGB with selected dendrometric variables. Accordingly, the AGB was strongly correlated with DBH and was not significantly correlated with wood density and height individually in *O. europaea* L. subsp. *cuspidata* allometric equation development. In combination, AGB was strongly correlated with DBH and height; DBH and wood density; and the combination of DBH, height, and wood density. Species-specific equations are used for better carbon assessment than general equations.

**Introduction**

**Species description**

*Olea europaea* subsp. *cuspidata* (Oleaceae), commonly called African olive, brown olive, olive tree, small-fruited olive, and wild olive, is native to Africa (i.e., Egypt, Eritrea, Ethiopia, Somalia, Sudan, Kenya, Tanzania, Uganda, Burundi, Rwanda, Zaire, Angola, Malawi, Mozambique, Zambia, Zimbabwe, Botswana, Lesotho, Namibia, South Africa, and Swaziland), Madagascar, the Mascarenes (i.e., Mauritius and La Reunion), western Asia (i.e., Oman, Saudi Arabia, Yemen, Afghanistan, and Iran), the Indian subcontinent (i.e., northern India, Nepal, and Pakistan), and western China. It is found naturally in wild and also cultivated as a garden ornamental and grown commercially for its fruit and for the production of olive oil (http://www.biosecurity.qld.gov.au/).

*O. europaea* L. subsp. *cuspidata* (Wall. ex DC.) Ciffieri (synonym: *Olea africana* Mill.), the wild olive tree, is widely distributed in dry forests of Ethiopia. It usually reaches 15 m (seldom 25 m) in height and is found in dry forests and forest margins at 1250–3100 m (Friis 1992; Legesse 1993). *Olea* is a long-lived tree. It shows strong xeromorphic characteristics and can survive as an adult tree in dry microclimatic conditions. It is eagerly browsed and can withstand heavy browsing. Under favorable conditions, it may flower within 4–5 years (Legesse 1995). The fruits are fleshy and eaten by birds, leaving the seed with its hard endocarp (Tesfaye 2005).

Its oppositely arranged leaves are elongated in shape (6–10 cm long and 1–4 cm wide) and often with hooked tips. These leaves have glossy dark green upper surfaces and greenish or yellowish-brown lower surfaces. Its small creamy-white flowers have four petals that are joined into a very short tube at the base. Its purplish-black oval-shaped fruit (15–30 mm long and 6–20 mm wide) contains a single hard seed (10–15 mm long) surrounded by oily flesh. The much-branched stems are greenish-black to silvery-green in color and mostly held upright (i.e., erect). Older stems have a rough bark that is light or dark gray in color, while younger stems are smooth or slightly ribbed. It is distributed in Ethiopia from...
1250 to 3000 m above sea level in Afar, Tigray, Gondar, Shewa, Kefa, Gamogofa, Sidama, Bale, and Hararge, among others. It is an important species in evergreen montane scrub, often kept in fields and around churches when the forest is cut. The fruits are edible and sometimes 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 toothbrushes. The wood is hard, polishes well, and has many uses, including carving (Hedberg, Edwards, and Sileshi 2003). The species is disappearing for its uses unless well conservation and sustainable management are made.

**Allometric equations and forest**

Biomass estimation equations, also known as allometric equations or regression models, are used to estimate the biomass or volume of aboveground tree components based on diameter at breast height (DBH) and height data. These equations are derived based on measured values of tree weight related to its DBH and height from sample trees. Using biomass equations is a common and cost-effective method to estimate biomass of tree species present in a forest or plantation (Ravindranath and Ostwald 2008).

A number of circumstances call for sound estimates of tree biomass. Tree biomass is useful, for example, in assessing forest structure and condition (e.g., Westman and Rogers 1977); it is essential for estimates of forest productivity and carbon fluxes based on sequential changes in biomass (e.g., Chambers et al. 2001); it provides a means of assessing sequestration of carbon in wood, leaves, and roots (e.g., Cooper 1983; Specht and West 2003); and it can be used as an indicator of site productivity, both biological and economic.

Estimation of the accumulated biomass in the forest ecosystem is also important for assessing the productivity and sustainability of the forest. It also gives us an idea of the potential amount of carbon that can be emitted in the form of carbon dioxide when forests are being cleared or burned. Biomass estimation of the forest ecosystem enables us to estimate the amount of carbon dioxide that can be sequestered from the atmosphere by the forest. The accurate assessment of biomass estimates of a forest is important for many applications like timber extraction, tracking changes in the carbon stocks of forest, and global carbon cycle. Forest biomass can be estimated through field measurement and remote sensing and Geographic Information System (GIS) methods (Ravindranath and Ostwald 2008; Lu 2006).

Forests have major roles in mitigating climate change by sequestering carbon. They absorb CO₂ from atmosphere and store carbon through photosynthesis process in their leaves, stem, roots, and branches. Forest biomass is organic matter resulting from primary production through photosynthesis minus consumption through respiration and harvest. Biomass estimation provides information on the structure and fictional attributes of a forest. Relatively 50% of dry forest biomass comprised of carbon (UNFCCC 2010b).

The Kyoto Protocol, linked to UNFCCC, requests all member countries to assess and report national greenhouse gas emission regularly including carbon emission reflected at carbon stock changes in forests. They have been identified the need to establish an accurate inventory of forest carbon stocks. The Clean Development Mechanism is one of the mechanisms of the Kyoto Protocol by which carbon emission reduction and its estimation took on economic value. This in turn allows emission reduction projects such as afforestation/reforestation projects in developing countries that are particularly vulnerable to the adverse effects of climate change to earn Certified Emission Reduction credits. These credits can be traded and sold and used by industrialized countries to meet their emission reduction targets under the Kyoto Protocol (UNFCCC 2010a).

The development and use of allometric equations is the standard methodology for the estimation of tree, plot, and regional aboveground biomass (AGB) (Brown 1997). Allometric equations are important for quantifying biomass and carbon storage in terrestrial ecosystems. Several biomass-prediction equations have been developed from mixtures of tropical species (e.g., Dawkins 1961; Ogawa et al. 1965; Brown, Gillespie, and Lugo 1989; Overman, Witte, and Saldarriaga 1994; Brown 1997; Arau’jo et al., 1999; Chambers et al. 2001; Ketterings et al. 2001; Chave et al. 2005). So far, there is no allometric equation for *O. europaea* L. subsp. *cuspidata* in the study site and moist evergreen forest of Ethiopia.

Tropical forests, in particular, are major components of the terrestrial carbon cycle, accounting for 26% of global carbon storage in biomass and soils (Dixon et al. 1994; Geider et al. 2001; Grace 2004). Yet, accurate estimates of carbon sequestration in tropical forests are lacking for many areas, due in large part to a paucity of appropriate allometric models for predicting biomass in species-rich tropical ecosystems (Chave et al. 2005). Due to the high species diversity in tropical forests, much attention has been placed on developing generalized allometric models for tropical trees (Brown 1997; Zianis and Mencuccini 2004; Chave et al. 2005; Pilli, Anfodillo, and Carrer 2006). However, the use of generalized equations can lead to a bias in estimating biomass for a particular species (Clark et al. 2001; Cairns et al. 2003; Chave et al. 2004; Litton, Sandquist, and Cordell 2006; Pilli, Anfodillo, and Carrer 2006) although recent approaches incorporating data on wood density hold more promise (Chave et al. 2005).

Studies dealing with the estimation of biomass, site productivity, and the contribution of forests to the
global carbon balance require the use of allometric equations. There have been a great number of equations developed to estimate biomass components of trees and shrubs in various ecosystems in the world. This study reports that the choice of the allometric equations can influence the greenhouse gas emission balance assessment. The choice of the allometric model can overestimate the greenhouse gas by 40% in the Congo Basin (Henry et al. 2010). The site- and species-specific equation has great significance as the carbon balance assessment is influenced by the forest type, its structure, the ecological and climate zone classification, the type of land-use change, and the selected allometric equation to achieve the calculation. This study is critical for the establishment of environmental projects and the confidence between donors and project developers, particularly in the context of reducing emissions from deforestation and forest degradation as it is done locally considering the factors affecting the assessment.

With the development of the REDD+ (reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries) mechanism and the emphasis put on the possible revenue that could be gained from forests and enhancement of forest carbon stocks in Ethiopia. This forest consists of different species of plants, including Warburgia ugandensis Sprague, Podocarpus falcatus (Thunb.) Mirb., and Polyscias fulva (Hiern.) Harms, that are commercially important in the country. The understorey bears natural coffee plants (Coffea arabica L.).

This study was used preferential sampling techniques which allow that all needed samples had the probability being involved in the study. Thirty individual trees per species having six DBH classes were used for semi-destructive measurements. These sample trees were selected based on the following criteria: an equal number of sample trees for each DBH class (classes established for each 10 cm interval); representative of the species as occurring in the general plot location; and avoiding hollow trees, trees with broken crowns, or truncated trees. Here, trees are stratified into six diameter classes of 2.5–10; 10.1–20; 20.1–30; 30.1–40; 40.1–50; and above 50 cm. Five trees per DBH class were selected randomly and assessed.

**Field measurements**

The methodology for field data gathering followed the *Manual for Building Tree Volume and Biomass Allometric Equations* prepared by Food and Agriculture Organization (FAO) (Picard, Saint-André, and Henry 2012). The following present the main steps involved in biomass measurement and allometric equation development.

The biomass of forests is particularly difficult to determine, given the architectural complexity of the trees they contain. Semi-destructive method was used due to human intervention is also particularly significant in these areas because of the rarity of forest resources and the magnitude of the demand for bioenergy. Grazing activities, coffee tree plantation under forest storey, and deforestation also limit regeneration, and small trees are often few in number. Biomass measurements are, therefore, semi-destructive and take full advantage of trimming to measure the biomass of the trimmed compartments. The height and DBH were measured for each tree under study by clinometer and caliper, respectively.

Generally, the trunk and the large branches were not trimmed; only the small branches were affected. The measurement of fresh biomass (in kilogram) was

**Objectives of the study**

The objective of the study was to develop species-specific allometric equations for *O. europaea* L. subsp. *cuspidata* using semi-destructive method and evaluate allometric models for estimating the AGB.

**Materials and methods**

### Study area description

The study was conducted in Mana Angetu Forest which is found in southwestern part of Bale Zone, southeastern Ethiopia. Dallo Mana has a distance of 125 km from Robe town, capital of Bale Zone, and 555 km from Addis Ababa. The mean annual temperature for Dallo Mana is 29.5°C, while mean annual rainfall is 701.5 mm. Agriculture is the backbone of the economy of the district (Basaznew, Ferew, and Mersha 2012).

The study area has a dry season from November to February with low rainfall, low temperature, and low humidity and eight months of wet season from March to October. The wet season is characterized by a high bimodal rainfall, high humidity, and higher night and lower day temperatures. Mana Angetu Forest is found in three districts of which 27,174.83 ha in Dallo Mana, 119,432.24 ha in Haranna Bulluq, and 48,586.13 in Madda Walabu District (Oromia Forest and Wildlife Enterprise, Mana Angetu District document). Mana Angetu Forest is a type of moist montane forest, and similar forest groups are also found in southwestern part of Ethiopia. This forest consists of different species of plants, including *Warburgia ugandensis* Sprague, *Podocarpus falcatus* (Thunb.) Mirb., and *Polyscias fulva* (Hiern.) Harms, that are commercially important in the country. The understorey bears natural coffee plants (*Coffea arabica* L.).
divided into two parts: measuring trimmed fresh biomass and measuring untrimmed fresh biomass (Figure 1).

**Measuring trimmed fresh biomass**

One branch was trimmed in compliance with saw. Measuring tape was used to determine the diameter at the base of the branch. Then, the leaves were separated from the trimmed branch. The fresh biomass of the leaves from the trimmed branch \(B_{\text{trimmed fresh leaf}}\) and the fresh biomass of the wood from the trimmed branch \(B_{\text{trimmed fresh wood}}\) were determined by weighing separately. Field-work electronic scales were used for weighing operations. Random samples of the leaves from the trimmed branch were taken. The samples of leaves which are called here “aliquots” \(B_{\text{fresh leaf}}\) in gram were measured. An aliquot of the wood was taken at random from the trimmed branch without debarking and its fresh mass \(B_{\text{aliquot fresh leafwood}}\) was measured in the field, immediately after cutting. These aliquots were placed in numbered plastic bags in which the weight of the empty bag was determined and brought to the laboratory of Addis Ababa University for fresh volume measurement of the wood aliquot and oven dry for dry mass estimation of the aliquots where the values were used to determine mean wood density \(\bar{\rho}\). The volume was measured using displacement method in which the volume of water displaced when the sample is immersed in water which is taken in graduated tube of suitable dimensions for the sample (Figure 2). The oven was set at temperature of 70ºC for leaves and 105ºC for wood dry biomass determinations until all the moisture contents of the aliquots are removed (Picard, Saint-André, and Henry 2012).

![Figure 1](image1.png)

*Figure 1*. Determination of total fresh biomass. (a) Separation and measurement of trimmed and untrimmed biomass; (b) numbering of the sections and branches measured on a trimmed tree. Source: Picard, Saint-André, and Henry (2012).

![Figure 2](image2.png)

*Figure 2*. Measuring sample volume by water displacement. Source: Picard, Saint-André, and Henry (2012).
**Measuring untrimmed fresh biomass**

The untrimmed biomass was measured indirectly as nondestructive. The different branches in the trimmed tree were numbered. The small untrimmed branches were processed differently from the large branches and the trunk. Basal diameter was measured for the small branches only. The biomass of these small untrimmed branches was estimated from the relationship between their basal diameter and their mass. The biomass of the trunk and the large branches was estimated from measurements of volumes \( V_i \) in \( \text{cm}^3 \) and mean wood density \( \bar{\rho} \) in \( \text{g cm}^{-3} \). The large branches and trunk were divided virtually into sections that are then materialized by marking the tree. The volume \( V_i \) of each section was obtained by measuring its diameter and its length. Sections about 1 m in length were taken in order to consider diameter variations along the length of the trunk and branches (Picard, Saint-André, and Henry 2012).

**Calculations**

The dry biomass of the tree was obtained by the sum of the trimmed dry biomass and the untrimmed dry biomass.

\[
B_{\text{dry}} = B_{\text{trimmed dry}} + B_{\text{untrimmed dry}} \quad (1)
\]

**Calculating trimmed biomass**

From the fresh biomass, \( B_{\text{aliquot fresh wood}} \) of a wood aliquot and its dry biomass, \( B_{\text{aliquot dry wood}} \), the moisture content of the wood was measured as given below (including bark).

\[
\chi_{\text{wood}} = \frac{B_{\text{aliquot dry wood}}}{B_{\text{aliquot fresh wood}}} \quad (2)
\]

Likewise, the moisture content of the leaves was calculated from the fresh biomass \( B_{\text{aliquot fresh leaf}} \) of the leaf aliquot and its dry biomass \( B_{\text{aliquot dry leaf}} \):

\[
\chi_{\text{leaf}} = \frac{B_{\text{aliquot dry leaf}}}{B_{\text{aliquot fresh leaf}}} \quad (3)
\]

Trimmed dry biomass then calculated:

\[
B_{\text{trimmed dry}} = B_{\text{trimmed fresh wood}} \times \chi_{\text{wood}} + B_{\text{trimmed fresh leaf}} \times \chi_{\text{leaf}} \quad (4)
\]

where \( B_{\text{trimmed fresh leaf}} \) is the fresh biomass of the leaves stripped from the trimmed branch and \( B_{\text{trimmed fresh wood}} \) is the fresh biomass of the wood in the trimmed branch.

**Calculating untrimmed biomass**

Two calculations were used to calculate the dry biomass of the untrimmed part (i.e., that still standing): one for the small branches and the other for the large branches and the trunk.

The untrimmed biomass is the sum of the two results.

\[
B_{\text{untrimmed dry}} = B_{\text{untrimmed dry branch}} + B_{\text{dry section}} \quad (5)
\]

Each section \( i \) of the trunk and the large branches may be considered to be a cylinder of volume (Smalian’s formula) (Picard, Saint-André, and Henry 2012).

\[
V_i = \frac{\pi}{8} L_i (D_{1i}^2 + D_{2i}^2) \quad (6)
\]

where \( V_i \) is the volume of the section \( i \), \( L_i \) is the length between \( D_{1i} \) and \( D_{2i} \) which is 1 m (100 cm), and \( D_{1i} \) and \( D_{2i} \) are the diameters of the two extremities of section \( i \). The dry biomass of the large branches and trunk were the product of mean wood density and total volume of the large branches and trunk (Picard, Saint-André, and Henry 2012).

\[
B_{\text{dry section}} = \bar{\rho} \times \sum_i V_i \quad (7)
\]

According to Picard, Saint-André, and Henry (2012), the sum corresponds to all the sections in the large branches and the trunk, and where mean wood density is calculated by

\[
\bar{\rho} = \frac{B_{\text{aliquot dry wood}}}{V_{\text{aliquot fresh wood}}} \quad (8)
\]

The dry biomass of the untrimmed small branches was calculated using a model between dry biomass and basal diameter. This model is established following the same procedure as for the development of an allometric model.

Linear-type equations were used:

\[
B_{\text{dry branch}} = a + bD \quad (9)
\]

where \( a \) and \( b \) were model parameters and \( D \) was branch basal diameter. Using a model of this type, the dry biomass of the untrimmed branches was:

\[
B_{\text{untrimmed dry branch}} = \sum_j (a + bD_j) \quad (10)
\]

where the sum is all the untrimmed small branches and \( D_j \) is the basal diameter of the branch \( j \).

Based on the above equations, all the AGB of individual trees of the species were calculated. The below ground biomass is 20% of AGB as root-to-shoot ratio value of 1:5 (MacDicken 1997).
Data analysis and model selection

Allometric equations were developed using Statistical Package R software (version R 3.2.2) by single and multiple linear regression relations. Equation performance was carried out using various goodness-of-fit statistics, namely the coefficient of determination ($R^2$-adj), correlation, residual standard error (RSE), Akaike information criterion (AIC), and $p$ value. To fit the biomass models, different linear equations (Table 1) with additive error term were evaluated for each dry biomass weight compartment. The best one was selected based on the statistics calculated for each equation.

$R^2$ is the fraction of the total variation in yield that is explained by the model. It is a statistical measure of how close the data are to the fitted regression line. It is also known as the coefficient of determination or the coefficient of multiple determination for multiple regression. A value of $R^2 = 1$ means that all of the variation in the response variable is explained by variation in the explanatory variable, while a value of $R^2 = 0$ means none of the variation in the response variable is explained by variation in the explanatory variable. When independent variables are greater than one, $R^2$ adjusted is used just to adjust the coefficient of determination for the variables.

AIC is a measure of the relative quality of statistical models for a given set of data. Given a collection of models for the data, AIC estimates the quality of each model, relative to each of the other models. Hence, AIC provides a means for model selection. It is useful because it explicitly penalizes any superfluous parameters in the model, by adding 2 ($p + 1$) to the deviance. When comparing two models, the smaller the AIC, the better the fit is true.

$$AIC = -2\ln(L) + 2p$$

In this formula, $L$ is the likelihood of the fitted model and $p$ is the total number of parameters in the model. The best statistical model minimizes the value of AIC. As an alternative statistic, we also reported RSE, the standard error of the residuals, as the RSE of best model is minimized. Various statistics for evaluating goodness-of-fit statistics have been advocated in the literature (reviewed in Parresol 1999), but AIC and RSE reported together provide sufficient information on the quality of a statistical fit for a mixed-species regression model; similar to AIC, the larger RSE is, the poorer the regression model (Chave et al. 2005).

A $p$ value is an estimate of the probability that a particular result or a result more extreme than the result observed could have occurred by chance. In short, the $p$ value is a measure of the credibility of the null hypothesis (Crawley 2013). The $p$ value is a number between 0 and 1 and interpreted in the following way: A small $p$ value (typically ≤ 0.05) for this study indicates strong evidence of statistical significance of the work.

Results and discussions

Results

All the dependent, AGB, and independent, DBH (D in equations), density ($\rho$), and height (H), variables are obtained through calculations and measurements for *O. europaea* L. subsp. *cuspidata* in Mana Angetu moist evergreen forest (Appendix). The summary of the main variables is given in Table 2.

The dependent variable AGB underwent regression analysis with the dependent variables (DBH, density, and height) individually and in combination. Seven allometric equations were developed.

These regression equations related AGB with DBH, height (H), and wood density (D) individually and in combination. Out of seven, four allometric equations were chosen based on goodness-of-fit statistics and three were rejected. The regression equations between AGB and H, AGB and D as well as AGB with D and H were rejected due to their goodness-of-fit statistics has fitting problem.

The species-specific equations developed for *O. europaea* L. subsp. *cuspidata* are

$$AGBest = 0.866 \times (D)^{1.432} \times (H)^{0.608} \times (\rho)^{1.067}$$

(Model 1)

$$AGBest = 0.623 \times (D)^{1.352} \times (H)^{0.703}$$

(Model 2)

$$AGBest = 1.473 \times (D)^{1.725} \times (\rho)^{1.263}$$

(Model 3)

$$AGBest = 1.089 \times (D)^{1.684}$$

(Model 4)

The selected models were tested for accuracy based on measured data. According to the statistical rule, the best model should have higher $R^2$-adj and correlation and lower RSE and AIC than other developed equations. The coefficients for all selected models are statistically significant ($p < 0.000$), which showed strong correlation of AGB with dendrometric vari-

| Variables | Mean | SD  | Min | Max  |
|-----------|------|-----|-----|------|
| AGB       | 542.76 | 596.46 | 9.08 | 1971.39 |
| DBH       | 32.87 | 21.02 | 3.00 | 80.00 |
| Height    | 11.12 | 4.58 | 3.00 | 18   |
| Density   | 0.72  | 0.10 | 0.49 | 0.92 |
| $N$       | 30    | 30   | 30   | 30   |

The unit of AGB is kg, DBH is cm, height is m, and density is g/cm$^3$ and $N$ is the number of individual trees of the species used for the study.

Table 1. Dendrometric variables with correlation coefficients.

| Allometric equations | Coefficients | Intercept | $\beta_1$ | $\beta_2$ | $\beta_3$ |
|----------------------|--------------|-----------|-----------|-----------|-----------|
| AGB with D           | $\alpha$     | 0.086     | 1.684     | -         | -         |
| AGB with D + H       | $\alpha$     | -0.475    | 1.352     | 0.703     | -         |
| AGB with D + $\rho$  | $\alpha$     | 0.387     | 1.725     | 1.263     | -         |
| AGB with D + H + $\rho$ | $\alpha$ | -0.144    | 1.432     | 0.608     | 1.067     |

Table 2. The summary of the main variables of *Olea europaea* L. subsp. *cuspidata*. 

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ables. Accordingly, the AGB was strongly correlated with DBH but was not significantly correlated with wood density and height individually in *O. europaea* L. subsp. *cuspidata* allometric equation development. In combination, AGB was strongly correlated with DBH and height; DBH and wood density and the combination of DBH, height, and wood density.

When compared among selected allometric equations, the equation of AGB with DBH, H, and wood density is best fit with additive better $R^2$-adj and correlation and lowest RSE and AIC.

\[
\text{AGBest} = 0.866 \times (D)^{1.432} \times (H)^{0.608} \times (\rho)^{1.067} \\
\text{(Model 1)}
\]

And the next best regression equation is AGB with DBH and H, and this equation has 94.7 $R^2$-adj and 87.7 correlation which is strong correlation and statistically significant ($p < 0.000$) (Table 3).

\[
\text{AGBest} = 0.623 \times (D)^{1.352} \times (H)^{0.703} \\
\text{(Model 2)}
\]

The third model AGB with DBH and H is also best fit as it is statistically significant and has higher $R^2$-adj and correlation than DBH and D.

\[
\text{AGBest} = 1.473 \times (D)^{1.725} \times (\rho)^{1.263} \\
\text{(Model 3)}
\]

The fourth model is the best model among individually analyzed independent parameters, i.e., AGB with DBH has higher $R^2$-adj and correlation and lower RSE and AIC than AGB with H and AGB with density ($\rho$). As DBH increases, AGB also increases which showed AGB has direct correlation with DBH (Figure 3).

\[
\text{AGBest} = 1.089 \times (DBH)^{1.684} \\
\text{(Model 4)}
\]

In the equations AGBest = 1.089 × (DBH)$^{1.684}$, the independent variable (DBH) explained the dependent variable (AGB) by 93.6% with less AIC than with other independent dendrometric variables, height and density individually. Combining these independent variables provided better fit results and estimation values than the use of DBH alone, as several authors have advocated, DBH and height as well as the three independent variables DBH, height, and density best explained the dependent variable with the equations AGBest = 0.623 × (D)$^{1.352}$ × (H)$^{0.703}$ and AGBest = 0.866 × (DBH)$^{1.432}$ × (H)$^{0.608}$ × ($\rho$)$^{1.067}$, respectively, having the ability to explain the dependent variable (AGB) 94.7% and 95.4%, respectively.

AGB with $\rho$ and AGB with H and $\rho$ are not statistically significant. Therefore, they were rejected automatically. Although AGB with H is statistically significant, it has lowest $R^2$-adj (79%) and correlation and highest RSE and AIC when compared with selected models. Thus, it is rejected as the models containing $R^2$-adj greater than 93% were chosen.

**Table 3.** Dendrometric variables with goodness-of-fit statistics.

| Allometric equations | $R^2$-adj | Correlation % | AIC | RSE | $p$ Value |
|---------------------|-----------|---------------|-----|-----|-----------|
| Model 1             | 0.936     | 87.55         | 34.18 | 0.401 | <0.000    |
| Model 2             | 0.947     | 87.70         | 29.15 | 0.363 | <0.000    |
| Model 3             | 0.946     | 87.62         | 29.95 | 0.368 | <0.000    |
| Model 4             | 0.954     | 87.76         | 25.76 | 0.338 | <0.000    |

**Discussion**

The choice of allometric equations has a significant effect on the biomass calculations since the forest biomass estimates vary with age of the forest, site class, and stand density. The biomass and

![Figure 3. Relationship between AGB and DBH.](image-url)
distribution among components of woody plants are also affected by many factors including plant architecture and morphology, age, climatic and edaphic factors, and forest management practices (Basuki et al. 2009; Ketterings et al. 2001).

We develop highly significant \( (p < 0.000) \) species-specific allometric models which directly determine the biomass estimation. The accurate biomass estimations of trees are very crucial for various reasons from commercial use of wood to global carbon trade and also from sustainable forest management to climatic change mitigation.

According to Abola, Arevalo, and Fernandez (2005), allometric equations are being strongly different for different tree species within the same climatic zones. It has been reported previously and mainly attributed to differences in specific wood density (weight per volume) of the species, the floristic composition, and growth strategies of the species. Similarly, this study reveals that trees in the same DBH class of different species exhibit different AGB values.

Our models had incorporated crucial tree compartments, and the allometric equations are used to predict tree and stand biomass, based on easily measured tree variables such as DBH, height, and density. DBH as the only explanatory variable provides a satisfactory estimation of biomass since the total variation explained by the relationship is high and the associated bias was small. Our results also indicated that DBH is a strong indicator of AGB which agrees with the previous reports (Brown, Gillespie, and Lugo 1989; Ziani and Mencuccini 2004; Basuki et al. 2009), so DBH alone is a good predictor of biomass, especially in terms of multiple trade-offs between accuracy, cost, and practicability of the measurement. And also recommended that the use of model where tree biomass is determined from DBH only, which had a practical advantage because most of the inventories include DBH measurements. Moreover, DBH is easy to measure accurately in the field. Combination of DBH and H has better strength in some equations. Similar result is obtained in Taiwan (Li, Lin, and Yen 2016).

Wood density is also very important as it differs a lot among tree genus and species (Chave et al. 2006). In general, there is variability of basic wood density among species, individual of the same species, among geographical location, and with age (Abola, Arevalo, and Fernandez 2005; Nygard and Elfyng 2000). This study shows that wood density was affected by tree size. Smaller trees had a low mean value of density, while a high mean density was observed in larger trees.

**Allometric equation comparison**

The study developed species- and site-specific allometric equations due to the general allometric equations have bias in biomass estimation. Hence, the generalized allometric equations available for large landscape scales should be used with caution as the site greatly influences allometric relationships (Montagu et al. 2005). Kim et al. (2011), in their study, emphasize that the site-specific allometric equations are more accurate in predicting the forest biomass estimates on the local level as they take into account the site effects. According to the studies conducted by Vieilledent et al. (2012), when biomass allometric models are not available for a given forest site, a simple height diameter allometry is required to estimate the biomass and carbon stocks accurately from plot inventories.

Although the data used for their fits did not include any data from Africa, the pantropical allometric equations by Chave et al. (2005) are currently the most commonly used equations in Ethiopia. Given the regional differences in diameter–height allometry that have recently been evidenced (Banin et al. 2012), the lack of data originating from Africa in the building of Chave et al.’s equations may question their validity for Ethiopia. Therefore, better alternative to Chave et al.’s equations and other general equations, this study formulate site- and species-specific equations for *O. europaea* L. subsp. *cuspidata* from Mana Angetu forest, south east Ethiopia, moist evergreen forest. Studies also supported equations that have been developed from African tropical rain forests (Deans, Moran, and Grace 1996; Djomo et al. 2010; Henry et al. 2010; Ebury et al. 2011; Vieilledent et al. 2012; Fayolle et al. 2013). The limitation of these site-specific equations inherent to the cost of biomass measurement and they are generally based on a small sample size.

General allometric equations that ignored species specific equations could not provide reasonable estimates of the most biomass components. It also mostly indicated the overestimation in biomass by general allometric equations. However, more precise estimation of component biomass requires species-specific equations. This has been noted in many species under divergent biomes and site conditions (Crow and Schlaegel 1988; Gower, Kucharik, and Norman 1999).

The variation in biomass and carbon stock estimates of forests can be due to the allometric models selected to calculate the biomass and/or carbon stocks. For example, Mehari et al. (2014) indicated that the generalized allometric models by Brown, Gillespie, and Lugo (1989) showed the poorest results with 32–59% average deviation for AGB predictions of five tree species in Ethiopia. Similarly, the model by Chave et al. (2005) was indicated to be unsuitable for three species in Ethiopia including *Allophylus abyssinicus*, *Olinia rochetiana*, and *Rhus glutinosa* (Mehari et al. 2014). Hence, it is generally agreed that site- and species-specific allometric models are ideal to estimate both biomass and carbon stocks of forests.
Accordingly, species-specific allometric equations were developed with a high significance ($p < 0.000$) fit linear regression for *O. europaea* L. subsp. *cuspidata*. Therefore, the equations developed by this study will help in the better assessment of carbon inventory for *O. europaea* L. subsp. *cuspidata* that is found in Mana Angetu Forest which is a vast evergreen montane forest in southeastern Ethiopia and similar forest types in the country.

In Figure 4, the measured one is found based on semi-destructive procedural method for equation development. Specific equation is the one which is developed for *O. europaea* L. subsp. *cuspidata* in this study and the general equation is taken from Chave et al. (2005) for tropical moist evergreen forest.

As it is indicated in Figure 4, the AGB of the species using field data calculation, specific equation, and general equation showed differences. AGB using the general equation overestimated for the higher DBH classes and underestimated for the lower DBH classes. Similar result is obtained in Hawaii, USA (Litton and Kauffman 2008).

The equations somewhat varied in their estimations, and the errors are higher in case of applying general allometric models. Likewise, general allometric model is developed for the variety of species that may grow in larger geographic area which is not considering the climate, the altitude, and soil type that affect the tree biomass. But the species-specific model is very specific as the name implies for a particular species in a particular geographic area in a particular situation due to this fact the study developed species-specific models which generate better accurate biomass estimation.

Conclusions and recommendations

**Conclusion**

By using semi-destructive methodology, the biomass and density of 30 tree individuals of *O. europaea* L. subsp. *cuspidata* was calculated. The DBH and height of the species were measured in the field in Mana Angetu Forest. After the data were compiled on excel, regression analysis was done by using R 3.2.2 software to formulate allometric equations. Seven allometric equations were developed between the dependent variable AGB of the species and its dendrometric independent variables (DBH, height, and density). However, only four equations are accepted based on the statistical significance. The equations are fit as species-specific equations for *O. europaea* L. subsp. *cuspidata* in moist evergreen forest of Ethiopia and fit as site-specific equation for *O. europaea* L. subsp. *cuspidata* found in Mana Angetu Forest which is located in southeastern Ethiopia, Bale Zone of Oromia National Regional State.

The application of generalized models for estimating AGB produced biased results for some of the species studied. Given the great diversity of species and variability within species that characterize tropical forests, the development of species-specific models is suggested to improve biomass estimation accuracy and reduce uncertainty. The equations developed in this study can be used for estimating forest carbon stocks, identifying carbon sink capacity, establishing carbon trade value, and informing management policies related to sustainability and fuel-wood harvesting for this species.

**Recommendations**

For climate change mitigation, forest sustainable conservation and proper assessment and report of national greenhouse sequestration and carbon stock are very important. For this use, allometric equation is a crucial step in estimating AGB. In choosing allometric equations, site- and species-specific equations are very preferable as the general equations are making bias in biomass estimation. As Ethiopia has many tree species, it is recommended to develop species-specific
allometric equations for all of them for better assessment of carbon stock to meet national and international reporting requirements for greenhouse gas inventories.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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Appendix

Aboveground biomass (kg), DBH (cm), height (m), and density (g/cm$^3$) of 30 individuals of *Olea europaea* L. subsp. *cuspidata* used for this study

| AGB      | BGB  | TB     | DBH | D     | H  |
|----------|------|--------|-----|-------|----|
| 121.85   | 24.37| 146.22 | 23  | 0.678 | 8  |
| 17.55    | 3.51 | 21.06  | 6   | 0.923 | 4  |
| 174.34   | 34.87| 209.21 | 31  | 0.728 | 7  |
| 184.49   | 36.90| 221.39 | 27  | 0.696 | 9  |
| 268.95   | 53.79| 322.75 | 26  | 0.652 | 14 |
| 1451.60  | 290.32| 1741.92| 48  | 0.743 | 17 |
| 161.17   | 32.23| 193.40 | 28  | 0.641 | 10 |
| 349.91   | 69.98| 419.90 | 32  | 0.792 | 16 |
| 163.11   | 32.62| 195.73 | 25  | 0.537 | 15 |
| 20.69    | 4.14 | 24.83  | 4   | 0.819 | 5  |
| 9.08     | 1.82 | 10.90  | 3   | 0.771 | 4  |
| 637.56   | 127.51| 765.07 | 50  | 0.685 | 17 |
| 470.13   | 94.03| 564.16 | 43  | 0.697 | 13 |
| 554.71   | 110.94| 665.65 | 41  | 0.794 | 18 |
| 10.22    | 2.04 | 12.26  | 5   | 0.668 | 3  |
| 14.08    | 2.82 | 16.89  | 4   | 0.715 | 4.5|
| 1860.92  | 372.18| 2233.10| 64  | 0.761 | 18 |
| 1971.39  | 394.28| 2365.67| 59  | 0.743 | 18 |
| 106.02   | 21.20| 127.22 | 18  | 0.655 | 10 |
| 605.97   | 121.19| 727.16 | 39  | 0.694 | 13 |
| 582.11   | 116.42| 698.53 | 35  | 0.899 | 11 |
| 1302.48  | 260.50| 1562.98| 50  | 0.639 | 15 |
| 200.12   | 40.02| 240.14 | 20  | 0.736 | 11 |
| 216.77   | 43.35| 260.12 | 18  | 0.677 | 10 |
| 656.84   | 131.37| 788.21 | 39  | 0.895 | 15 |
| 185.79   | 37.16| 222.94 | 19  | 0.761 | 8  |
| 79.96    | 15.99| 95.95  | 14  | 0.592 | 7  |
| 1615.88  | 323.18| 1939.05| 80  | 0.619 | 10 |
| 1484.40  | 296.88| 1781.28| 68  | 0.750 | 12 |
| 804.80   | 160.96| 965.76 | 67  | 0.495 | 11 |