IMPROVING BIOMASS ESTIMATION IN ETHIOPIAN MOIST AFROMONTANE FOREST THROUGH VOLUME MODEL

ABU MULATU[1*], MESELE NEGASH[3], MOTUMA TOLERA[2]

[1]*Ethiopian Forestry Development, Dire Dawa Center, P. O. Box 1708, Dire Dawa, Ethiopia.*
[2]*Ethiopian Forestry Development, Addis Ababa, P.O. Box 24536, Addis Ababa, Ethiopia.*
[3]*Hawassa University Wondo Genet College of Forestry and Natural Resources, P.O. Box 128, Shashemene, Ethiopia.*
[*]*Corresponding author email: abumulatu08@gmail.com*

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ABSTRACT

Forest biomass is estimated using a volume model, wood basic density (wbd), and biomass expansion factor (BEF). However, in Ethiopia, there is a shortage of volume models, hence the volume estimation was carried out using a generic model. As a result, estimation may be subject to bias when applied in areas outside its original geographic range of development. Consequently, there is a need for further research and data collection to enhance the accuracy and reliability of these equations. This study aims to develop species-specific volume models, biomass expansion factors, wood basic densities, and form factors for selected tree species in the moist evergreen Afromontane Forest of Ethiopia. A total of 59 trees were harvested for volume model, BEF, and wbd development. Nonlinear regression was employed to develop the models, and the developed models were compared with previously established models using goodness-of-fit measures. For the volume model, diameter at breast height explained 89 % - 99 % of the volume variation. Comparison with previously developed models indicates that the currently developed model yields the least error. The mean BEF for the study species was 1.58, while the mean wood basic density for all tree species was 0.58 g/cm3. The study demonstrated that species-specific volume models reduce errors in the estimation of forest volume and biomass.

Keywords: Biomass, Volume, Model, Forest

INTRODUCTION

Forest ecosystem provides a variety of goods and services, and among the services it provides, carbon sequestration is the main one. It's responsible for sequestering 45 % of terrestrial carbon and contributing to 50 % of net ecosystem production (McGarvey *et al.*, 2015). Unfortunately, unsustainable use of this resource leads to the degradation and loss of forest resources worldwide. Deforestation and forest degradation contribute 12-20 % of greenhouse gas emissions (Saatchi *et al*., 2011; van der Werf *et al*., 2009). In response to this problem, the United Nations Framework Convention on Climate Change (UNFCCC) proposes reducing emissions from degradation and deforestation; and integrating conservation and sustainable forest management to enhance forest carbon stocks (REDD+) as a solution for developing countries (Vanderhaegen *et al*., 2015). For the effective implementation of REDD+, it is vital to accurately measure and quantify the reduction in greenhouse gas emissions resulting from forest conservation and restoration activities. Additionally, this process encompasses the measurement of forest biomass and the quantification of carbon that is sequestered from the atmosphere and stored within the ecosystem as a result of these initiatives (Henry *et al*., 2011a). Moreover, Participating countries under REDD+ are obligated to provide precise quantification of their forest carbon stocks and changes via robust measurement, reporting and verification (MRV) systems.

Quantifying forest biomass can be done by converting available forest inventory data into biomass using a volume model, Wood Basic Density (WBD), and Biomass Expansion Factor (BEF) (IPCC, 2003; Somogyi *et al*., 2007). The volume model is used to compute the volume of a tree based on easily measurable characteristics like Diameter at Breast Height (DBH), tree height (ht), and crown width (CW). These equations are widely used for calculating biomass and carbon assessment by combining with WBD and BEF. Furthermore, this information is critical for making informed decisions regarding the sustainable harvesting of trees, and the management of forests (Dadzie, 2013; Mugasha *et al*., 2016). BEF is a ratio used in forestry to estimate the amount of biomass in a tree or stand of trees. It is calculated by dividing the total aboveground biomass by the stem biomass of a single tree (Levy, 2004). It takes into account the weight of branches, leaves, and foliage, which are not accounted for in conventional volume or diameter measurements. Additionally, by combining with wood basic density and the volume model, it can be used to quantify the amount of biomass and carbon that stored in a forest ecosystem. WBD is one of the most important tree variables in determining wood biomass when considering a broad range of vegetation types (Baker *et al*., 2004). It is calculated by dividing the dry mass of the wood by its green volume (Williamson & Wiemann, 2010). Form Factor of a tree is the ratio of its volume to the volume of a specified geometric solid of similar basal diameter and height. The calculation of tree volume using the form factor is essential for various applications in forestry, including timber estimation, biomass calculations, and ecological assessments. However, it varies among species and can be influenced by the age of the tree, its growth conditions, and even the specific site where it is located (Tenzin *et al*., 2016; Tiryana *et al*., 2021).

The establishment and application of volume allometric equations in Ethiopia are still in their preliminary stages, and there is a need for further research and data collection to enhance the precision and reliability of these equations. According to Henry *et al*., (2011b) from the estimated natural tree species only 2 % of tree species have allometric equations. Due to this volume estimation was conducted by the generic model. As a result, the estimation may be subject to bias when applied in areas outside its original geographic range of development (Ngomanda *et al*., 2014). Furthermore, form factors for the dominant tree species from the main forest types have not been determined in the country, although form factors among species were consistent (0.5) (Colgan *et al*., 2014). Due to this approach, it leads to uncertainty in tree volume quantification. In contrast, species-specific models and form factor are more advantageous because they account for variations in growth conditions and species, making them a more reliable choice. Hence, developing species-specific models and form factor helps to reduce uncertainty in the estimation of forest volume and biomass assessment (Sileshi, 2014). Therefore, the present study aims to develop a species-specific volume model, biomass expansion factor, wood basic density, and form factor for the selected five tree species existed in the Moist Evergreen Afromontane Forest of Ethiopia.

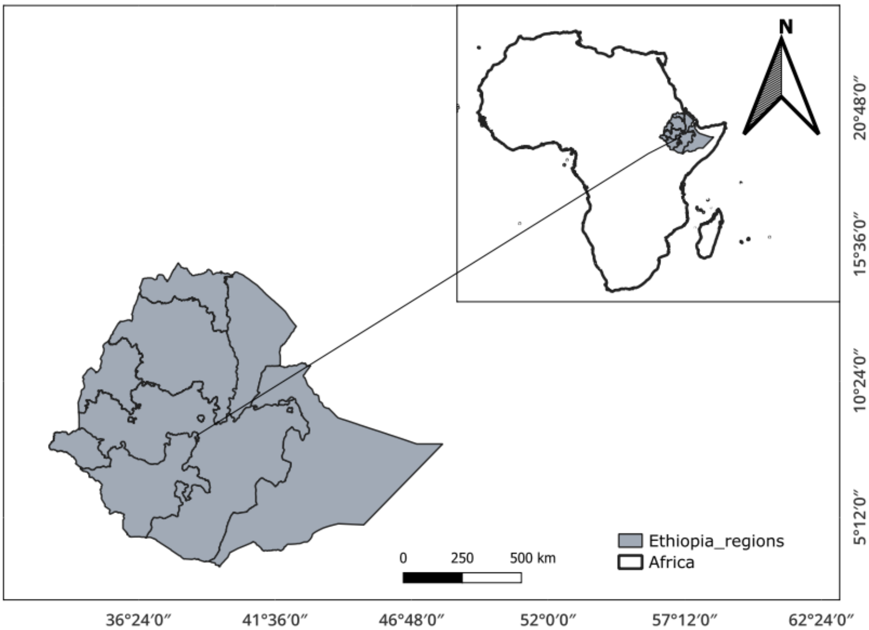
MATERIAL AND METHODS

Description of the study area.

The moist Afromontane Forest ecosystem is the most diverse in composition, structure, and habitat types. It's situated in a mountainous region, facilitating the existence of extensive ecological gradients along altitudinal variations (EBI, 2024). Consequently, substantial complexes of mountain forests exist, forming several distinct vegetation units. It constitutes a unique and ecologically significant biome found in Ethiopia, comprising various tree species such as *Celtis africana*, *Pouteria adolfi-friedericii*, *Acokanthera schimperi*, *Albizia gummifera, Millettia ferruginea, Croton macrostachyus, Syzgium guineense, Bersama abyssinica, Vepris dainellii, Schefflera volkensii, Prunus africana, Erthrina brucei*, and *Polyscias fulva*. It's categorized as high forests with closed continuous canopy cover, and the majority of the forests on the southwestern plateau that appear intact from above are coffee-managed forests significantly impacted by human activities (Senbeta *et al*., 2014).

Wondo Genet natural forest is categorized as a Moist Afromontane Forest. It is located in the southeast of Ethiopia and 270 km from the capital city of the country (Fig. 1). Geographically, the natural forest is located between 07˚4´ to 07˚8´ N and 038˚37´ to 038˚39´ E and it covers about 413 ha. The forest is owned by the Wondo Genet College of Forestry and Natural Resources. The elevation gradient at Wondo Genet catchments ranges between 1700 and 2600 (Girma *et al*., 2012). The area characterized by bimodal rainfall with a mean annual rainfall is 1200 mm. Additionally, the mean temperature in the study area is 19 °C (Dessie & Kinlund, 2008).

Fig. 1: Study area map



Data collection

Volume measurement

Prior to volume measurement, a forest inventory was conducted in the area. Based on this inventory result, five tree species were selected according to their dominance. A total of 59 individual trees comprising five tree species (*Albizia gummifera, Croton macrostachyus, Syzgium guineense, Vepris dainellii,* and *Bersama abyssinica*) were selected. The merchantable stem volume was determined by summing the log volumes with diameters greater than or equal to 10 cm, using the Huber's formula, which is effective for small logs (Syed Ahmad *et al*., 2020). On the other hand, the branch volume was estimated indirectly using the wood's basic density and branch weight. Finally, the total tree volume was obtained by adding the merchantable stem and branch volumes. For the determination of volume, the following formula is used (Akindele & LeMay, 2006).

$$\mathrm{Vi} = \pi \frac{\mathrm{L}}{4}(\mathrm{d}^2) \ldots\ldots\ldots 1$$

where: Vi = volume of a log i; d= middle diameter, L = length of log.

Wood basic density determination

To determine the wood basic density, sample discs were collected from selected tree species at three different heights: 1.3 meters above ground, 50 %, and 85 % of the total tree height (Tetemke *et al*., 2019). The weight of the sample disc was recorded in the field, and the dry weight being determined after the samples were dried in an oven at 103 °C until they reached a consistent weight (Williamson & Wiemann, 2010). To determine disc volume, the water displacement method was used. Finally, the wood basic density (g/cm^3) of the tree sample was determined by computing the ratio of the mean oven-dry mass of the disc sample (g) to its respective green volume (cm^3), according to the following formula.

$$\text{Wood basic density}(\boldsymbol{\rho}) = \frac{\text{oven−dry mass(g)}}{\text{green volume}(\text{cm}^3)} \ldots\ldots\ldots 2$$

Biomass expansion factor

BEF is used to ‘expand’ available tree stem biomass data to estimate the biomass of whole trees. Mathematically the BEF is calculated from the following formula:

$$\mathrm{AGB} = \mathrm{V} * \mathrm{WBD} * \mathrm{BEF} \ldots\ldots\ldots 3$$

where; BEF = biomass expansion factor, WBD = wood basic density, V = volume of the tree (merchantable or total volume of tree), AGB = above-ground biomass.

Form factor

The form factor is ratio of the actual tree volume to the volume of a geometric solid (cylinder). For the determination of the Form factor, tree diameter measurement at breast height and total height were taken as cylindrical volume, and the felled tree cross-cut (>2 m) lengths log until it reached 10 cm (Fadaei *et al*., 2008) for the determination of the true volume. Mathematically the form factor is determined by the following formula

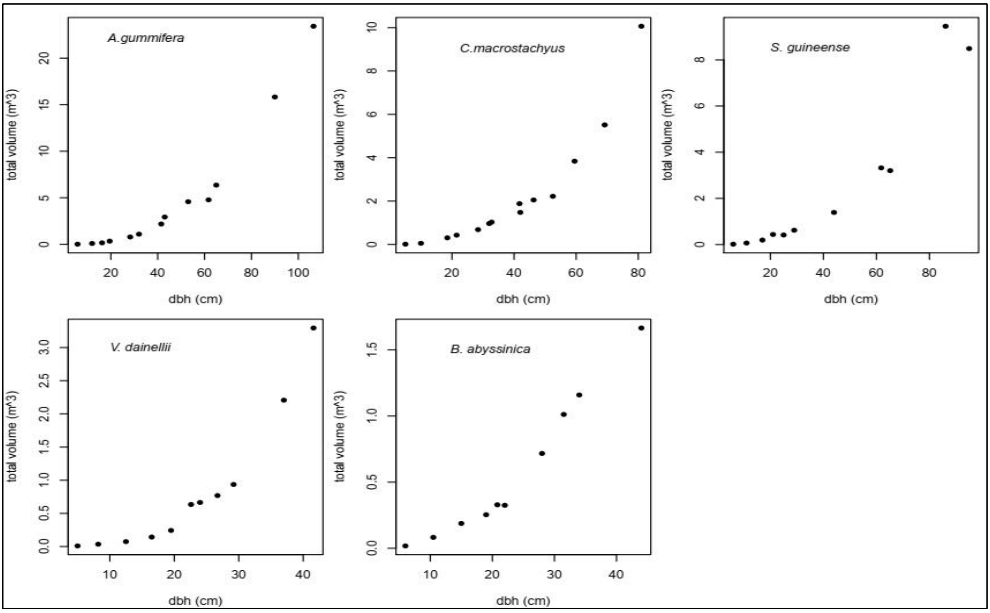
$$\textbf{Form factor} = \frac{\mathbf{V}}{\mathbf{Vat\ 1.3m}} \ldots\ldots\ldots 4$$

where: $\boldsymbol{V}$= tree true volume and $\boldsymbol{Vat\ 1.3m}$ = volume of the tree at diameter at breast height.

Data analysis

The data analysis was conducted using R-software version 4.0.1 (Team, 2021). Weighted regression was employed to tackle potential heteroscedasticity in nonlinear regression. The method for establishing the weighting factor was based on the approach outlined by Picard *et al*., (2012). The final weight was calculated using the formula 1/(DBH)^2c, with "c" denoting the weighting factor. Furthermore, scatter plots were generated to examine the relationships between the tree-dependent variables (AGB and volume) and the independent tree variable (DBH) (Fig. 2).

Fig. 2: Scatter plot between dependent (total volume) and independent (dbh) Variable



Volume model

For the establishment of models DBH was used as a single predictor and other tree variables such as crown diameter and tree height were combined with this variable. The volume equation adopted from the different published papers was used (Table 1) (Asrat *et al*., 2020a; Kachamba & Eid, 2016; Mauya *et al*., 2014; Mugasha *et al*., 2016a).

Table 1: Selected previously published volume model for comparison

Volume model	
Asrat *et al*., (2020a)	volume = 0.0001228 * (dbh)^2.55
Asrat et al., (2020a)	volume=0.0000605 * ((dbh^2)*(ht))^0.9789
Kachamba & Eid, (2016)	volume=0.000218 * ((dbh^2)*(ht))^0.896561
Mugasha *et al*., (2016)	volume=0.000076 * (dbh)^2.3488 * (ht)^0.3848
Mauya *et al*., (2014)	volume= 0.00016 * (dbh)^2.463
Mauya *et al*., (2014)	volume= 0.00011 * (dbh)^2.133 *(ht)^0.5758

$$\text{Vt, ms,b} = a * (\text{DBH})^{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{M1}$$
$$\text{Vt, ms, b} = a * (\text{DBH})^{b} * (ht)^{c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{M2}$$
$$\text{Vt, ms, b} = a * (\text{DBH} * ht)^{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{M3}$$
$$\text{Vb} = a * (\text{DBH}^{2} * cw)^{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{M4}$$
$$\text{Vb} = a * (\text{DBH})^{b} * (cw)^{c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{M5}$$

where Vt, ms, b, are total tree, merchantable stem, and branch volume in (m^3) respectively, and DBH is a tree diameter at breast height (cm), ht is a tree height in (m), cw is a crown diameter in (m) and a, b, c, are model parameters.

Model validation and comparisons

The developed allometric models were evaluated to measure their strength and accuracy while selecting the best goodness of fit. Thus, models that recorded the lowest value of mean prediction error (MPE), root mean square error (RMSE), Akiaka information criterion (AIC), and the higher values adjusted-R2 were selected (Asrat *et al*., 2020b). Paired t-test was used to compare the discrepancy between the observed and predicted values. Furthermore, a one-way analysis of variance (ANOVA) was conducted to examine the variation in wood basic density across stem positions (tree height) and tree species.

$$\text{RMSE} = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n}(yi - \widehat{yi}\right)^{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$
$$\text{RMSE\%} = \frac{RMSE}{\bar{y}} * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$
$$\text{MPE} = \frac{1}{n}\sum_{i=1}^{n}(yi - \widehat{yi}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 10$$
$$\text{MPE\%} = \frac{\text{MPE}}{\bar{\text{y}}} * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 11$$

where: MPE is the mean prediction error, RMSE is the root mean square error, $\boldsymbol{yi}$ is the observed value, $\hat{\boldsymbol{y}}i$ is the predicted value, $\bar{\mathbf{y}}$ is the mean observed value, and n is the number of observations.

To compare the model performance, the model selected for comparison comprises one local model (Asrat *et al*., 2020a) and several regional models (Kachamba & Eid, 2016; Mauya *et al*., 2014; Mugasha *et al*., 2016a). These regional models are utilized for this area when local models are not available. Additionally, the selected best volume model is compared with local developed biomass model (Asrat *et al*., 2020b) and species-specific model (Mulatu *et al*., 2024) for the biomass estimation.

RESULTS AND DISCUSSION

Results

Investigating tree attribute relationships

A scatter plots showed that, DBH is highly correlated with total volume (Fig. 3). Consequently, DBH used as a single predictor and other tree variables such as crown diameter and tree height were combined with this variable. Additionally, nonlinear relationships between the dependent variable (volume) and independent variables (DBH, Diameter at stump height (DSH), total height, and crown diameter) established.

Volume model development

The results of the best volume allometric equation for the total volume model are presented in Table 2, and all tested volume allometric equations for total, branch, and merchantable stems are presented in the supplemental material (Appendix). For all tree species, DBH was found to be the most significant factor in explaining the variation in total volume, with the highest value of 99 % observed in *A. gummifera* and the lowest 89 % by *B. abyssinica*. When DBH and height were included in a model (M2), the total volume for *A. gummifera*, *V. dainellii*, and *B. abyssinica* was overestimated, while the total volume for *S. guineense* and *C. macrostachyus* was underestimated. When DBH and height were used as a single predictor in a model (M3), the total volume was overestimated for S. guineense, *B. abyssinica*, and *A. gummifera*, while it was underestimated for *V. dainellii* and *C. macrostachyus*. None of the tested models for estimating merchantable volume gave a significant parameter estimator for all tree species.

Table 2: Selected total volume allometric equation

Species	Model	Parameter		Adjusted R^2	RMSE		MPE		AIC
		a	b		m^3	%	m^3	%	
Albizia gummifera	1	0.0001697**	2.537***	0.99	0.48	10.03	-0.011	-0.24	3.06
Croton macrostachyus	1	0.0001823*	2.451***	0.91	0.77	35.47	0.08	3.66	-5.5
Syzygium guineense	1	0.0002999**	2.272***	0.92	0.89	35.33	0.01	0.39	-7.57
Vepris dainellii	1	0.00004802*	2.973***	0.98	0.14	16.12	0.019	2.2	-7.57
Bersama abyssinica	1	0.0003999*	2.231***	0.89	0.16	28.39	-0.023	-4.02	-28.34

Significance level: *<0.05; **<0.01; ***<0.001

Regarding branch volume, DBH as a single predictor was found to be significant by overestimating the branch volume for *B. abyssinica*, *A. gummifera*, and *S. guineense*. The finding indicates that, there is no significant difference between the observed and predicted total volume (Fig. 2). The null hypothesis (intercept = 0 and slope = 1) was accepted based on the p-value, which indicated no significant difference between the observed and predicted total volumes.

Total tree volume model comparison with previously published model.

Based on the comparison with several previously developed models, for A. gummifera and *B. abyssinica*, most of the tested models underestimate the total volume, except the model by Kachamba & Eid (2016), which overestimates the volume by 6.5 % and 33.82 %, respectively (Table 3). Conversely, all tested models underestimate the total volume for *V. dainellii*, while overestimating for *S. guineense*. Regarding *C. macrostachyus*, the tested models overestimate the total volume, except for Mauya *et al*., (2014) DBH and Mugasha *et al*., (2016) DBH and ht, which underestimate the total volume by 8.06 % and 4.12 %, respectively. For *S. guineense*, all the tested models overestimated the total volume, with the Kachamba & Eid (2016) model showing the highest overestimation at 49.84 %.

The result from the analysis indicates that the current volume model performs well in terms of estimation of the biomass (Table 4), especially when we compare it to Asrat *et al*., (2020). The current volume model underestimates the biomass for, *B. abyssinica* (10.26 %), *C. macrostachyus* (7.49 %), *V. dainellii* (11.33 %) whereas overestimates for *S. guineense* (1.87 %), and *A. gummifera* (1.19 %). On the other hand, a model developed by Mulatu *et al*. (2024) gives better accuracy in the estimation of biomass and consistently expects *S. guineense* in this case the volume model performed better than the biomass model.

Fig. 3: Observed versus predicted plot for selected best total volume model (M1)

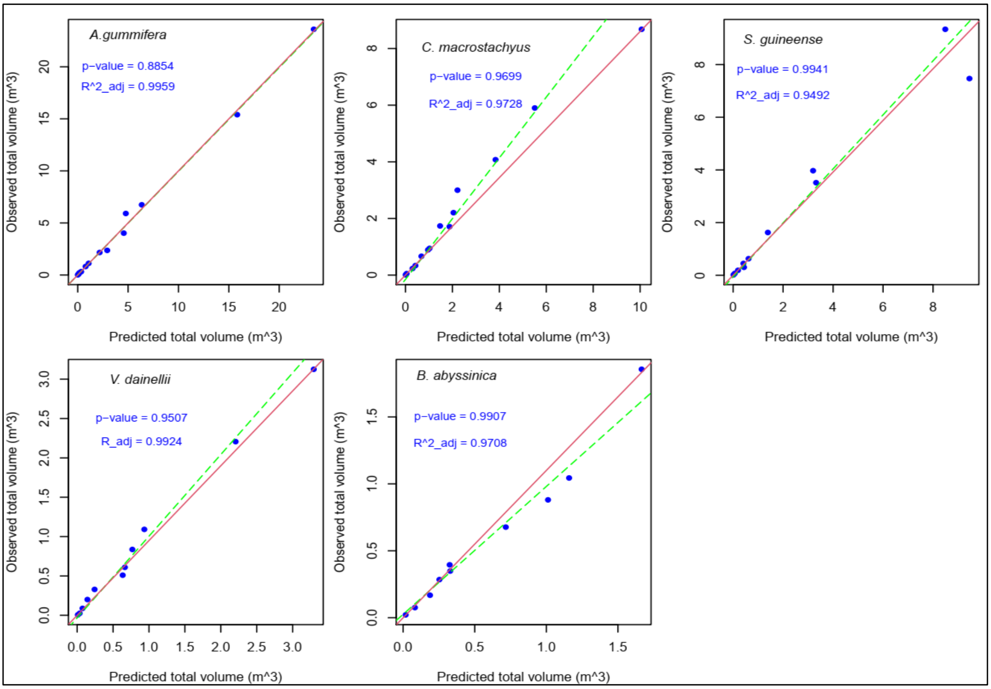


Table 3: Total volume allometric equation comparison with published allometric equation

Species	Previously developed models	predicted total volume in (m^3)	RMSE m^3	RMSE %	MPE m^3	MPE %
Albizia gummifera	Asrat *et al*., (2020b)(dbh)	3.69	1.95	40.53	1.11*	23.14
	Asrat *et al*., (2020b) (dbh^2ht)	3.83	2.02	42.00	0.98*	20.29
	Mauya *et al*., (2014) dbh	3.30	2.73	56.68	1.51*	31.41
	Mauya *et al*., (2014) ($a*dbh^b*ht^c$)	3.79	1.99	41.44	1.01*	21.04
	Kachamba & Eid, (2016)	5.12	1.31	27.21	-0.31	-6.50
	Mugasha *et al*., (2016) ($a*dbh^b*ht^c$)	3.51	2.28	47.49	1.30*	27.04
	Current model	**4.83**	**0.42**	**8.71**	**-0.02**	**-0.36**
Croton macrostachyus	Asrat *et al*., (2020b)(dbh)	2.19	0.39	18.12	-0.01	-0.48
	Asrat *et al*., (2020b) (dbh^2ht)	2.35	0.59	27.05	-0.18	-8.07
	Mauya *et al*., (2014) dbh	2.00	0.57	26.40	0.176	8.06
	Mauya *et al*., (2014) ($a*dbh^b*ht^c$)	2.35	0.53	24.46	-0.17	-7.71
	Kachamba & Eid, (2016)	3.35	1.48	68.18	-1.17***	-53.82
	Mugasha *et al*., (2016)Dbh and ht	2.09	0.51	23.49	0.09	4.12
	Current model	**2.17**	**0.45**	**20.82**	**0.01**	**0.22**
Syzygium	Asrat *et al*., (2020b)(dbh)	3.40	1.72	68.71	-0.89*	-35.45

guineense	Asrat *et al*., (2020b) (dbh^2ht)	2.73	0.84	33.36	-0.22	-8.59
	Mauya *et al*., (2014) dbh	3.04	1.16	46.05	-0.53	-21.23
	Mauya *et al*., (2014) ($a*dbh^b*ht^c$)	3.01	1.09	43.61	-0.51	-20.12
	Kachamba & Eid, (2016)	3.76	1.97	78.67	-1.25*	-49.84
	Mugasha *et al*., (2016) ($a*dbh^b*ht^c$)	2.92	1.04	41.61	-0.41	-16.22
	Current model	**2.51**	**0.69**	**27.87**	**0.002**	**0.07**
Bersama abyssinica	Asrat *et al*., (2020b)(dbh)	0.53	0.12	21.20	0.04	7.41
	Asrat *et al*., (2020b) (dbh^2ht)	0.47	0.14	24.62	0.11**	18.24
	Mauya *et al*., (2014) dbh	0.51	0.12	20.30	0.06*	10.80
	Mauya *et al*., (2014) ($a*dbh^b*ht^c$)	0.53	0.09	16.07	0.05	7.97
	Kachamba & Eid, (2016)	0.77	0.28	48.07	-0.19*	-33.82
	Mugasha *et al*., (2016) ($a*dbh^b*ht^c$)	0.46	0.15	26.28	0.11**	19.70
	Current model	**0.58**	**0.09**	**15.07**	**-0.00034**	**-0.06**
Vepris dainellii	Asrat *et al*., (2020b)(dbh)	0.52	0.63	70.79	0.37*	41.52
	Asrat *et al*., (2020b) (dbh^2ht)	0.48	0.70	78.58	0.41*	46.20
	Mauya *et al*., (2014) dbh	0.50	0.66	74.84	0.38*	43.59
	Mauya *et al*., (2014) ($a*dbh^b*ht^c$)	0.53	0.63	71.18	0.36*	40.37
	Kachamba & Eid, (2016)	0.78	0.37	41.62	0.11	12.28
	Mugasha *et al*., (2016) ($a*dbh^b*ht^c$)	0.46	0.71	80.30	0.43*	48.41
	Current model	**0.88**	**0.09**	**10.32**	**0.004**	**0.42**

Significance level: *p<0.05; **p<0.01; ***p<0.001

Table 4: A comparison of predicted AGB values for five tree species (*A. gummifera*, *B. abyssinica*, *C. macrostachyus*, *S. guineense*, and *V. dainellii*) based on current best volume model, local and species-specific biomass model:

species	Selected model for comparison	Predicted Agb in (kg)	RMSE		MPE	
			kg	%	kg	%
Albizia gummifera	Current model	2655.7	319.20	10.89	53.61	1.86
	Mulatu et al. 2024	2706.3	293.56	10.02	-0.99	-0.03
	Asrat et al., 2020	2646.5	590.47	20.15	63.5	2.17
Bersama abyssinica	Current model	350.9	1694.25	57.83	300.6	10.26
	Mulatu et al. 2024	390.02	56.97	16.09	-1.40	-0.40
	Asrat et al., 2020	379.6	70.84	20.00	8.38	2.37
	Current model	1086.8	296.78	25.26	87.96	7.49
	Mulatu et al. 2024	1187.3	208.76	17.77	-12.52	-1.07
Croton macrostachyus	Asrat et al., 2020	1586.5	618.44	52.64	-393.8	-33.52
Syzygium guineense	Current model	1579.6	134.86	8.70	-29.01	-1.87
	Mulatu et al. 2024	1618.2	150.95	9.74	-67.56	-4.36
	Asrat et al., 2020	2765.7*	2126.66	137.1	-1206.1	-77.8
Vepris dainellii	Current model	533.4	136.48	22.69	68.15	11.33
	Mulatu et al. 2024	552.4	162.30	26.98	49.10	8.16
	Asrat et al., 2020	588.01	211.00	35.08	13.49	2.24
	Significance level:	*<0.05; **<0.01; ***<0.001				

Wood basic density

The highest mean wood basic density was recorded for Vepris dainellii (0.65 g/cm^3), whereas the lowest was by Croton macrostachyus (0.50 g/cm3), and the mean of all tree species was estimated to be 0.58 g/cm^3 (Table 5). The study showed that there is a significant difference in wood basic density among tree species at p<0.00. Regarding stem position (tree height), the study indicates that there is no wood basic density difference in stem position (tree height). Additionally, the paired t-test analysis between the branch and steam wood basic density indicates that there is no mean basic wood density difference between the branch and stem.

Form factor

The highest form factor, 0.66, was recorded by the *B. abyssinica*, while the lowest, 0.49, was recorded by the *C. macrostachyus* (Table 6). The Spearman correlation analysis indicated that all tree species exhibited a negative correlation between tree diameter and form factor. However, this correlation was only significant for *S. guineense* and *B. abyssinica* at p<0.05, with correlation coefficient values of -0.97 and -0.952, respectively. The correlation coefficient values for *A. gummifera*, *C. macrostachyus*, and *V. dainellii* were -0.615, -0.65, and -0.523, respectively, and were not significant. In terms of tree height, Pearson's correlation revealed a negative correlation between tree height and form factor for *S. guineense* and *B. abyssinica* at p<0.05, with correlation coefficient values of -0.884 and -0.952, respectively. However, for *A. gummifera*, *C. macrostachyus*, and *V. dainellii*, the correlation coefficient values were -0.644, -0.419, and -0.547, respectively, and were not significant.

Biomass expansion factor

The highest merchantable BEF was recorded for *V. dainellii* (3.57), whereas, the lowest was for *C. macrostachyus* (0.94). The mean BEF for the studied tree species was estimated at 1.59 (Table 7).

Table 5: Wood basic density of tree species

Species	N	wood density (g/cm^3)		
		Mean	Range	SD(±)
Albizia gummifera	13	0.55	0.49-0.66	0.054
Bersama abyssinica	10	0.61	0.56-0.68	0.037
Croton macrostachyus	14	0.50	0.41- 0.56	0.037
Vepris dainellii	11	0.65	0.60- 0.73	0.043
Syzygium guineense	11	0.63	0.54-0.79	0.079

Table 6: Form factor of the five trees species

Species	Form Factor		
	Mean	Range	SD (±)
Albizia gummifera	0.60	0.4- 0.77	0.11
Croton macrostachyus	0.49	0.35-0.78	0.12
Syzygium guineense	0.51	0.29-0.94	0.13
Vepris dainellii	0.64	0.49-0.82	0.15
Bersama abyssinica	0.66	0.44-0.93	0.04

Table 7: Biomass expansion factor for the selected tree species

species	BEF			
	N	Mean	Range	Sd (±)
Albizia gummifera	10	1.47	1.19-1.75	0.19
Croton macrostachyus	12	1.16	0.94-1.41	0.18
Syzygium guineense	9	1.55	1.19-1.92	0.26
Vepris dainellii	8	2.28	1.60-3.57	0.58
Bersama abyssinica	7	1.74	1.24-2.13	0.29

DISCUSSION

Volume model and compression with previously developed models

In Ethiopia, there is a limited availability of allometric equations for estimating the volume of trees growing in natural forests. The current study will play a significant role in addressing this gap. Additionally, it offers substantial benefits for biomass estimation through volume by applying BEF and WBD. Moreover, the study developed form factors for five selected tree species found in moist natural forests. This will contribute to more accurate volume and biomass assessments, which are critical for sustainable forest management and conservation efforts. Since, accurate volume estimation helps determine the stock of timber and non-timber products available in a forest, enabling forest managers to plan sustainable harvesting practices that do not exceed the forest's regenerative capacity. Biomass assessment, on the other hand, is essential for understanding the carbon storage potential of forests, a key factor in mitigating climate change. It also provides insights into the health and productivity of forest ecosystems.

Among the tested models, M1 which is DBH used as single predictor was found important in the estimation of total volume. The finding in line with (Asrat *et al*., 2020). The addition of tree height in dbh (M2) and using DBH and height (DBH2h) (M3), did not enhance model performance. The finding is in line with (Asrat *et al*., 2020a; Kachamba & Eid, 2016; Mauya *et al*., 2014). Regarding branch volume, the allometric equation with DBH as the single predictor performs well for estimating branch volume. However, the inclusion of crown diameter and tree height in the model did not improve its performance. The finding is inconsistent with the (Asrat *et al*., 2020a; Kachamba & Eid, 2016; Mauya *et al*., 2014). In all volume estimation cases, the inclusion of other tree variables than DBH doesn’t improve the model. The finding is inconsistent with (Henry *et al*., 2010), which stated that the inclusion of more than one tree variable improves the allometric equation.

The importance of DBH in volume assessment models can be attributed to its direct correlation with tree size and growth characteristics. As well, DBH is often the most significant variable in explaining variations in tree volume, as it captures the tree's cross-sectional area, which is a critical determinant of volume (Mugasha *et al*., 2016a; Štícha *et al*., 2019). Moreover, studies have shown that models incorporating DBH alone can gives comparable or superior accuracy to those that include additional variables such as height, primarily due to the increased uncertainty associated with height measurements (Di Cosmo & Gasparini, 2020; Mugasha *et al*., 2016a). The significance of DBH in the inclusion of volume allometric equations is attributed to its ease of measurement in field conditions and allowing for efficient data collection across large areas (Taffo *et al*., 2018). Furthermore, the incorporation of DBH in allometric equations is substantiated by its statistical significance in explaining biomass variability (Basuki *et al*., 2009).

The developed species-specific volume equation demonstrated the best performance compared to both site-specific and regionally-developed generic volume allometric equations. For all tree species, the currently developed model (M1) gives the lowest percentage error for all tree species. Moreover, the comparisons of the local biomass model indicate that species-specific factors play a significant role in model performance. This outcome underscores the significance of species-specific volume equations (Kaonga & Bayliss-Smith, 2010; Ketterings *et al*., 2001). The importance of species-specific allometric equations in estimating volume is significant, particularly in tropical forests, where biodiversity is high and tree species exhibit considerable variability in their growth patterns and structural characteristics (Gonzalez De Tanago *et al.*, 2018). However, in regional models these characteristics may be overlooked. Furthermore, the development of species-specific models can facilitate improved carbon stock assessment and inform conservation strategies. Moreover, the utilization of species-specific models is essential for accurate carbon accounting, which is vital for understanding and mitigating the effects of climate change (Tipu *et al*., 2021). The specificity of these models allows for enhanced estimations of carbon fluxes and reserves, which are crucial for effective forest management and conservation.

Wood basic density

The wood basic density from the selected tree species was determined and compared to the national average (0.612 g/cm^3) that is used for preparing the country's forest reference emission level (FRL) for the United Nations Framework Convention on Climate Change (UNFCCC) submission. Our findings revealed a lower wood basic density value than the national average wood basic density used for UNFCCC submission. However, our data were similar to the site-specific wood basic density developed by Asrat *et al*., (2020a), which was 0.582 g/cm^3.

The study showed that there is a significant difference in mean wood basic density between tree species $p<0.05$, which is in line with the findings of (Asrat *et al*., 2020a; Henry *et al*., 2010; Tesfaye *et al*., 2016; Ubuy *et al*., 2018). The nature of tree species and the environmental conditions in which they grow contribute to differences in wood basic density. Tree species growing in harsh environmental conditions like lower light, higher stress (wind, an abundance of wood-rotting fungi, or xylophages insects), and lower soil fertility tend to have higher wood density (Wiemann & Williamson, 1989), and tree species that undergo with damage tend to have higher wood density than other species (Curran *et al*., 2008). On the other hand, Nogueira *et al*., (2008)suggested that lower wood density associated with forest existed in the open land forest; hence, tree species that tend to fast growth have lower wood basic density than slow-growing tree species. Considering this, species-specific wood density is crucial to reduce bias in biomass estimation, as it is one of the most important tree attributes related to the carbon sequestration potential of the tree (Baker *et al*., 2004; Chave *et al*., 2009). In terms of stem position (tree height), there is no mean wood basic density difference between the tree stem position where the wood density samples are taken and the wood basic density value.

Biomass expansion factor and form factor

The study's outcome reveals that, the comparison with the default form factor used in the country (0.5), and tree species mean form factor indicates that for *A. gummifera*, *B. abyssinica*, and *V. dainellii* there is a significant difference at $p<0.05$. However, for tree species such as *C. macrostachyus* and *S. guineense*, there is no significant difference in the mean form factor and default form factor. Hence, tree, the nature of trees, including their form and branching patterns, is influenced by both genetic factors and environmental conditions (Adekunle *et al*., 2013; Tenzin *et al*., 2016). Furthermore, form factor is not static, but it's influenced by ecological interactions and environmental gradients, highlighting the need for species-specific and site-specific assessments (Duncanson *et al*., 2015). Due to this, the species-specific form factor helps to reduce error by accounting for the above-mentioned factors.

The result from the study indicates that, tree species like *V. dainellii* scored the highest BEF value. While the lowest was recorded by *C. macrostachyus*. The value of BEF varies with tree species based on the tree nature and growth condition of the tree like forest type, stand development, climate, and other growing conditions (IPCC, 2003). Additionally, tree size has an impact on the BEF value, trees tend to be large by nature and have lower BEF values than smaller ones (Brown, 1997). This is evident in our study tree species that are inherently large, such as *A. gummifera*, *S. guineense*, and *C. macrostachyus*, exhibit lower BEF as compared to relatively smaller tree species like *V. dainellii* and *B. abyssinica*. The value of the BEF found in this study is in the range of the recommended BEF value for Africa (Brown, 1997). Additionally, the mean BEF value similar to the BEF value of 1.5 recommended by IPCC, (2006) for tropical broad leaved forest. Also, the mean value of our total tree BEF was less than the value found in the (Segura & Kanninen, 2005)1.6 ± 0.2 on average.

CONCLUSION AND RECOMMENDATIONS

The study showed the importance of species-specific volume model, BEF, WBD, and form factor. Particularly, in the implementation of REDD+ initiatives and sustainable forest management by reducing the error in the selection model and providing accurate information for forest managers and policymakers. Applying dbh as a single predictor has an advantage over the other models by its simplicity to measures and accessibility for measurement. The study underscores the importance of using species-specific form factors for accurate quantification of tree volume, as default values may not capture the variability seen across different species. The implementation of the model necessitates consideration of its application to Moist montane forest, taking into account the specified environment.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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APPENDIX

Supplemental material

List of all tested volume models for all tree compartments and tree species.

Compartment	model	Parameter a	Parameter b	Parameter c	Adjusted R^2	RMSE m^3	RMSE %	MPE m^3	MPE %	AIC
Albizia gummifera										
Total volume	1	0.00016**	2.537***		0.99	0.48	10.03	-0.01	-0.24	-3.06
	2	0.00024*	2.683***	-0.29	0.98	0.77	15.96	-0.03	-0.68	-3.19
	3	0.00006	0.99***		0.92	1.87	38.87	-0.01	-0.21	13.86
Merchantable	1	0.000007	3.064***		0.98	0.42	20.69	-0.07	-3.45	-19.98
	2	0.000012	3.291***	-0.45	0.95	0.64	31.63	-0.15	-7.44	-20.95
	3	0.0000064	1.109***		0.62	1.87	92.44	-0.36	-17.59	-3.90
Branch	1	0.00024**	2.328***		0.99	0.34	12.22	-0.04	-1.34	-6.94
	2	0.0002797	2.39***	-0.12	0.99	0.34	12.04	-0.06	-2.09	-5.14
	3	0.000096	0.9122***		0.91	1.05	37.66	-0.04	-1.53	2.60
	4	0.00019	0.8812***		0.97	0.61	21.84	0.12	4.30	-5.50
	5	0.00024*	2.228**	0.153	0.99	0.37	13.23	-0.001	-0.04	2.38
Croton macrostachyus										
Total volume	1	0.00018*	2.451***		0.91	0.77	35.47	0.08	3.66	-5.50
	2	0.00014	2.41***	0.136	0.88	0.84	38.69	0.09	4.24	-3.62
	3	0.0000034	1.224***		0.90	0.80	36.80	0.15	7.11	-1.66
Merchantable	1	0.000004	3.071***		0.94	0.21	31.18	-0.02	-3.02	-24.12
	2	0.000076	2.03***	-1.34	0.90	0.26	39.13	-0.03	-4.94	-25.27
	3	0.0000002	1.397***		0.93	0.22	33.30	-0.02	-2.52	-18.92
Branch	1	0.000257	2.276***		0.86	0.64	42.41	0.04	2.49	-7.24
	2	0.000056	1.934***	0.89	0.76	0.80	53.05	0.07	4.91	-9.58
	3	0.000049	0.9562***		0.81	0.75	49.22	0.06	4.01	-11.55
	4	0.000686	0.748***		0.83	0.70	46.01	0.05	3.26	-5.32
	5	0.000226	2.374***	-0.09	0.84	0.65	43.01	0.03	2.04	-2.39
Syzgium guineense										
Total	1	0.00029**	2.272***		0.92	0.89	35.33	0.01	0.39	-7.57
	2	0.000084	1.94***	0.866	0.88	0.99	39.34	0.06	2.23	-9.24
	3	0.00005	0.986***		0.79	1.42	56.48	-0.13	-5.13	-11.20
Merchantable	1	0.000005	3.077***		0.73	0.92	73.81	-0.13	-10.26	-15.70
	2	0.000006	3.119***	-0.11	0.68	0.94	75.35	-0.12	-9.73	-13.70
	3	0.000002	1.216***		0.61	1.10	87.81	-0.05	-3.86	-15.29
Branch	1	0.00043**	2.043***		0.97	0.22	17.60	-0.07	-5.35	-14.21

	2	0.000039	1.453***	1.568**	0.96	0.26	20.69	-0.03	-2.51	-22.64
	3	0.00012**	0.859***		0.97	0.25	19.51	-0.07	-5.29	-21.66
	4	0.0006709	0.709***		0.93	0.36	28.42	-0.04	-3.21	-36.57
	5	0.00021***	2.791***	-0.85**	0.99	0.14	10.98	0.00	0.29	-3.41
Vepris dainellii										
Total volume	1	0.000048*	2.973***		0.98	0.14	16.12	0.02	2.20	-7.57
	2	0.000124*	4.018***	-1.67**	0.99	0.08	9.58	-0.01	-1.06	-9.24
	3	0.000008	1.25***		0.94	0.23	25.79	0.04	4.92	-11.20
Merchantable	1	0.0000015	3.809***		0.94	0.17	31.89	0.02	2.81	-25.20
	2	0.000009	5.393***	-2.675	0.96	0.12	22.55	0.01	2.79	-27.94
	3	0.0000002	1.591***		0.80	0.30	56.61	0.06	11.62	-21.01
Branch	1	0.0002009	2.2933***		0.78	0.14	40.97	-0.02	-4.76	-31.62
	2	0.0001383	1.976**	0.54	0.65	0.17	48.18	-0.03	-7.72	-30.18
	3	0.0001091	0.8853***		0.86	0.11	32.40	-0.01	-2.12	-31.94
	4	0.0001506	0.887***		0.75	0.15	43.72	-0.02	-4.32	-29.88
	5	0.0002305	2.407***	-0.189	0.73	0.15	42.44	-0.01	-3.70	-26.70
Bersama abyssinica										
Total volume	1	0.0003999*	2.231***		0.89	0.16	28.39	-0.02	-4.02	-28.34
	2	0.0003303	2.1375***	0.19	0.86	0.17	29.83	-0.03	-5.94	-26.77
	3	0.0001737	0.889***		0.94	0.12	21.33	-0.02	-3.24	-23.92
Merchantable	1	0.0000376	2.669***		0.47	0.17	67.63	-0.03	-11.84	-27.06
	2	0.00007791	2.993**	-0.69	-0.47	0.26	105.65	-0.06	-23.01	-25.64
	3	0.000027	0.991***		0.72	0.12	49.36	-0.02	-8.82	-24.18
Branch	1	0.00026*	2.193***		0.91	0.08	24.93	-0.01	-3.53	-37.13
	2	0.0001155*	1.753***	0.87**	0.97	0.04	13.30	-0.01	-2.14	-46.42
	3	0.00012**	0.8744***		0.98	0.04	11.59	0.00	-1.20	-48.42
	4	0.0004168	0.7678***		0.74	0.14	41.69	0.05	14.24	-36.94
	5	0.0002563*	2.1163***	0.132	0.92	0.07	21.52	-0.01	-4.10	-21.02