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Research Article

Species-Specific Allometric Equations, Biomass Expansion Factor, and Wood Density of Native Tree Species in the Dry Afromontane Forest of Ethiopia

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A forest is a storehouse of carbon released from different sources when the activities of sustainable forest management, planting, and rehabilitation exist. However, few allometric equations are present to determine its contribution to carbon reduction. The target of the study was to develop species-specific allometric equations and establish a database for biomass expansion factor and wood density for five tree species grown in the dry Afromontane forest of Ethiopia. A direct or destructive sampling method was used on 62 trees from different diameter classes. The diameter at breast height and the total height of selected trees ranged from 7 to 48 cm and 6.7 to 23.4 m, respectively. Trees were felled and divided into various biomass sections. Stem and big branch discs were sampled to determine the wood density and volume of the trees. Sample wood and foliage were oven-dried for three days and two days at 105°C and 70°C, respectively, to get their dry weight. Total above-ground biomass was regressed using diameter at breast height, total height, wood density, and average crown diameter as independent variables. R software version 4.0.1 was used to fit the biomass equations. The best biomass models were determined to have lower AIC and RSE and highest adj. R^2. The biomass expansion factor and wood density of five tree species ranged from 1.19 to 1.40 and 0.53 to 0.74 g/cm^{-3}, respectively. Species-specific allometric equations were better than both mixed species and pan tropical models for the assessment of above-ground biomass in the Chilimo dry Afromontane forest of Ethiopia.

1. Introduction

Forests are considered the storehouse of carbon released from fossil fuels, industry, and land use change emissions if and only if the activities of sustainable forest management, planting, and rehabilitation exist [1]. Forests on all the continents accumulate 283 gigatonnes of carbon in their biomass alone. As a result, 229 to 263 petagrams of carbon are stored by tropical forests in various pools [2, 3]. According to FRA [4], there are five carbon pools in forest ecosystems: above- and below-ground biomass, dead wood, litter, and soil organic carbon.

The amount of carbon stored by the forest decreases from time to time due to deforestation and forest degradation. This led to an increase in the concentration of greenhouse gases in the atmosphere [5], which in turn caused climate change, one of the major challenges to human society and the environment in the world. This also brought critical challenges to Ethiopia [6].

To address the challenges of climate change, Ethiopia has developed and applied REDD$^+$ strategies for the last 10 years [6]. Accordingly, measurement, reporting, and verification (MRV) for greenhouse gas emissions, including greenhouse gases from deforestation and forest degradation, have been adopted. The estimation of the contribution of the forestry sector to REDD^{+} activities requires accurate biomass estimation methods [5].

Most of the time, both direct and indirect methods can be used to assess tree biomass [7]. The direct approach entails cutting down the tree and determining the precise masses of each of its components [8, 9]. Although it is quite accurate, it is expensive and time-consuming to cut down trees and separate them into different components [10]. In contrast, indirect methods are less expensive and take less time to estimate tree biomass since they use allometric models and biomass expansion factors that have already been developed [11]. In addition, when employing developed allometric equations, basic wood density, which is computed as the dry weight of wood divided by the green volume of wood, can be utilized to forecast biomass or estimates derived from volume and biomass expansion factors [12].

Allometric models for biomass estimation are scarce in the tropics compared to the species diversity of the area [10]. The majority of biomass models are created for tree species in South Africa and Latin America. Ethiopia in particular and sub-Saharan Africa in general have seen some studies seeking to build biomass equations [12–19].

Pan tropical allometric equations developed by many researchers may overestimate or underestimate the biomass since different tree species have very different tree architecture and wood density [7]. To reduce the estimation problem, both species-specific and mixed-species allometric equations for Ethiopia are required for forest biomass and carbon stock estimation. But the country lacks appropriate standard biomass tables and equations to calculate species-specific or mixed tree biomass. So, local allometric equations may solve this problem due to their ability to accurately estimate the amount of biomass in the forest and enable the country to benefit from the carbon market opportunity. It is also used by a country to report accurate and consistent data that meet international standards and to create a favorable policy on the environment [5].

Therefore, this study was aimed at developing species-specific allometric equations and establishing a database for biomass expansion factor and wood density for *Apodytes dimidiata*, *Cassipourea malosana*, *Celtis africana*, *Ilex mitis*, and *Myrica salicifolia* tree species in the Chilimo dry Afromontane forest of Ethiopia.

2. Materials and Methods

2.1. Study Site Location. The Chilimo dry Afromontane forest belongs to the state-owned Oromia Forest and Wildlife Enterprise. With an elevation range of 2,470 to 2,900 meters above sea level, the forest may be found at latitudes 038° 08′ 679″ to 038° 10′ 283″ east and longitudes 09° 04′ 038″ to 09° 05′ 765″ north, respectively. The region's mean annual temperature varied between 15 and 20 degrees centigrade, and it averaged 1000 to 1264 mm of precipitation per year [20]. The climate of Chilimo forest might be described as warm temperate climate I (CWB) type following Köppen's classification system [21]. The forest has a total area of about 2500 hectares and is located 97 kilometers west of Addis Ababa, the capital of Ethiopia [22].

2.2. Vegetation Description of the Study Site. Chilimo forest is one of the few remnant forests located in the central highlands of Ethiopia and is composed of mixed broad-leaved tree species such as *Podocarpus falcatus*, *Olea europaea* subsp. *cuspidata*, *Scolopia theifolia*, *Rhus glutinosa*, *Olinia rochetiana*, *Allophylus abyssinicus*, and *Juniperus procera* [23, 24]. Soromessa and Kelbessa [22] reported that 213 different woody species, which belong to 83 families, and 18 plant species are registered as endemic to the Chilimo forest, of which one is endangered and three are considered vulnerable. Shumi [20] investigated 42 species, made up of 27 tree and 15 shrub species, in the forest. In addition, 33 different indigenous woody species (22 trees and 11 shrubs) were registered for Chilimo by Tesfaye et al. [19] in three forest sections.

2.3. Data Collection and Sampling. For the development of above-ground biomass equations, tree species such as *A. dimidiata*, *C. malosana*, *C. africana*, *I. mitis*, and *M. salicifolia* were chosen based on the importance value index (IVI). Then, based on previously collected tree data by Tesfaye et al. [25], diameter distributions at 10 cm were done on sample trees in each diameter class, and the number of harvestable trees from each diameter class was determined. Moreover, the basal area of each tree in each diameter class, the total basal area of all species in different classes, and the total number of trees harvested in each diameter class were calculated. The sampled tree diameter intervals ranged from 5 to 55 cm (Table 1). Trees with a broken crown, excessive branching, or less branching were not cut [26]. A total of 62 sampled trees were cut and portioned into different biomass sections. For *C. malosana* 14 trees were selected; 13 trees were selected for *A. dimidiata*, C. *africana*, *M. salicifolia*; and 9 trees forI. *mitis* were selected and cut (Table 1).

2.4. Biomass Data Collection. Before cutting down the chosen trees, environmental information like slope (%), altitude, and UTM coordinates (using a Garmin 72-channel GPS) were recorded. Additionally, DBH (cm) and average crown diameter (m) were measured. Then, using a chainsaw, test trees were cut down nearly to the ground. Diameter at a 2 m interval, total height (H), and commercial height (Hc) (height up to a top stem diameter of ≥7 cm) were measured using diameter tape and measuring tape. Then branches and foliage were removed. The felled trees were divided into four categories: stems (from the ground base to the top diameter of ≥7 cm), big branches (diameter ≥7 cm), small branches (diameter <7 cm up to 2 cm), and foliage (diameter <2 cm) [27]. The total fresh weights of all components were determined, and 200-gram subsamples were taken from small branches and foliage using a sensitive mass balance. Three and two discs, respectively, were taken from the stem and big branch for the purposes of determining the volume and density of the wood [26].

Table 1: Sample trees selected corresponding to tree size distribution.

DBH class	DBH interval (cm)	List of species and number of trees harvested					
		A. dimidiata	*C. malosana*	*C. africana*	*I. mitis*	*M. salicifolia*	Total number of trees cut down
1	[5–15)	4	3	1	2	2	12
2	[15–25)	2	6	5	2	5	20
3	[25–35)	7	5	2	0	5	19
4	[35–45)	0	0	5	3	1	9
5	[45–55)	0	0	0	2	0	2
	Total trees	13	14	13	9	13	62

The following formula was used to determine each component's total dry weight:

$$\begin{aligned}\text{Total dry weight of the small branches} &= \sum \text{total fresh weight of the small branches} \times \frac{\text{sample dry weight}}{\text{sample fresh weight}},\\ \text{Total dry weight of the foliage} &= \sum \text{total fresh weight of the foliage} \times \frac{\text{sample dry weight}}{\text{sample fresh weight}}.\end{aligned} \tag{1}$$

The biomass of stems and big branches was estimated by using wood density times volume. The volume of the stem and big branch section was derived using Smalian's formula as cited by De Gier [28]. Finally, the following is used to get the dry weight of the total above-ground biomass:

$$\begin{aligned}&= \sum \text{total dry weight of stem} + \sum \text{total dry weight of big branches} + \sum \text{total dry weight of small branches}\\ &\quad + \sum \text{total dry weight of foliages}.\end{aligned} \tag{2}$$

2.5. Biomass Expansion Factor Data Collection. Bimass expansion factor was calculated using the total biomass and stem biomass of particular tree species (biomass was calculated using the log section stem volume and the corresponding log section's wood density) (M = WD∗V) where M is estimated biomass, WD disc wood density, and V is tree log volume.

2.6. Data Collection and Sampling for Wood Density. Three discs from the stem were cut at the base, middle, and top with a thickness of 5 cm to measure the density of the wood. Two discs from the base and top of the big branch were taken. The Central Ethiopia Environment and Forest Research Center laboratory received fresh weights that had been measured in the field and transferred there. After that, they were oven-dried at 105°C and 70°C for three days and two days, respectively, for wood and foliage, until a steady weight was achieved. The water displacement method was used to estimate each disc's volume (Figure 1).

2.7. Biomass Equations. Allometric equations were developed for selected tree species and validated following appropriate procedures. First of all, descriptive and scatter plot analyses were carried out in order to determine the biomass and see its relationships with dendrometric variables. The Spearman method is used in order to identify the best predictor variables. Then the best dendrometric variables tested for each total biomass were fitted individually using Statistical R version 4.0.1. A comparison was made using AIC, residual standard error, adj. R squared, and p value. Finally, the results were compared with [12, 30–33].

3. Data Analysis and Model Validation

The statistical analysis was conducted with R statistical software (https://www.r-project.org/versions/R-4.0.1), SAS version 9.2, and Microsoft Office Excel 2007 and decided at a significant level of 0.05 based on field and laboratory data. Transformed regression techniques were applied to develop allometric models to predict total biomass using independent variables including diameter at breast height, total height, wood density, and average crown diameter.

The model selection and validation were calculated based on the statistical significance of model parameter estimates: AIC, adjusted coefficient of determination (adj. R^2), relative bias in percent, mean prediction error (MPE), and RMSE [31]. The Akaike information criterion (AIC) was estimated from the following equation:

$$\text{AIC} = 2p - 2\ln(L), \tag{3}$$

where L is the likelihood of the fitted model; p is the total number of parameters in the model; and ln is the natural

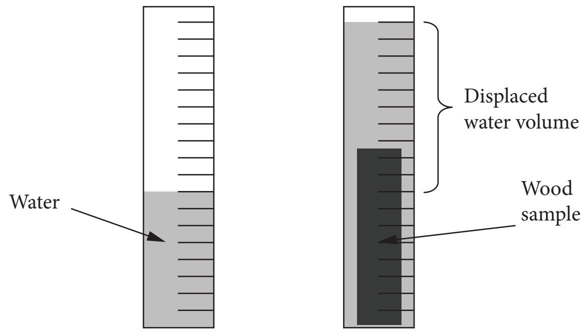

Figure 1: Sample volume measurement by water displacement [29].

logarithm. The developed allometric equation with the lowest AIC value is the best estimator.

The adjusted R squared was estimated as

$$\text{adj. } R^2 = 1 - \sum \frac{(\text{yi} - \text{yl})2}{(\text{yi} - \text{yj})2} \times \frac{n-1}{n-p}. \quad (4)$$

The adjusted R^2 value indicates the variation explained by the model from total variation. It is a value between 0 and 1, and the closer it is to 1, the better the quality of the fit is.

The mean prediction error was calculated by

$$\text{MPE} = \frac{\sum(\text{yi} - y1)}{n}. \quad (5)$$

The root mean square error was calculated using the following equation:

$$\text{RMSE} = \frac{\sqrt{(\text{yi} - y1)2}}{n}, \quad (6)$$

where y_i is the observed above-ground biomass in kg, y_l is the predicted above-ground biomass in kg, y_j is the mean observed biomass in kg, n is the number of observations, and p is the number of parameters.

3.1. Allometric Biomass Models. Many species-specific and general allometric equations have been developed based on nonlinear regression model techniques [13, 27, 30, 31]. To avoid heteroscedasticity, a logarithmic transformation was applied [34, 35]. The correction factor (CF) formula was developed by Sprugel [36] and used to adjust for underestimation of biomass [31, 37]. Thus, the correction factor was computed using the residual standard error of the regression (RSE) for each allometric model.

$$\text{CF} = \exp^{(\text{RSE}_2/2)}. \quad (7)$$

Tested models:

(1) TAGB = exp $[a + b \ln(\text{DBH})]$ [38].
(2) TAGB = exp $[a + b \ln(\text{DBH}^2 * \text{H})]$ [38].
(3) TAGB = exp $[a + b \ln(\text{DBH}^2 * \text{WD})]$ [39].
(4) TAGB = exp $[a + b \ln(\text{DBH}^2 * \text{H} * \text{WD})]$ [31].
(5) TAGB = exp $[a + b \ln(\text{DBH}) + c \ln(\text{H})]$ [38].
(6) TAGB = exp $[a + b \ln(\text{DBH}) + c \ln(\text{CD})]$ [40].
(7) TAGB = exp $[a + b \ln(\text{DBH}) + c \ln(\text{H}) + d \ln$ (WD] [31].
(8) TAGB = exp $[a + b \ln(\text{DBH}) + c \ln(\text{H}) + d \ln$ (CD] [40].
(9) TAGB = exp $[a + b \ln(\text{DBH}) + c \ln(\text{H}) + d \ln$ (WD $+ e \ln$ (CD] [41].

Where TAGB (in kg) is the total above-ground biomass of trees as a response and DBH is the diameter at breast height (cm), H is height (m), WD is wood density (g·cm^{-3}), CD average crown diameter (m) as independent variables, exp is an exponential function, ln is natural logarithmic, $a$is intercept, and$b$, c, d, and e are model parameter estimates.

3.2. Biomass Expansion Factor Determination. The average ratio of all of the harvested trees' dry weights and stem weights was used to compute the BEF using the following equation:

$$\text{BEF} = \sum \frac{\text{tDwi}}{\text{tswi}}, \quad (8)$$

where BEF is the biomass expansion factor (unit less); tDWi (kg tree^{-1}) is the total dry weight of each individually sampled tree (stem, branches, and foliage); tSi (kg tree^{-1}) is the total dry weight of the stem alone and of each individually sampled tree; and n is the total number of sampled trees for each species [42].

3.3. Wood Density Determination. Wood density is calculated using the following formula [43]:

$$\text{WD} = \frac{M}{V}, \quad (9)$$

where WD is the wood density in grams per cubic centimeter, M is the oven-dry mass of wood in grams, and V is the green volume of wood in cubic centimeters.

3.4. Validation and Evaluation of Models. Model comparison was done by using our dataset to select a pan tropical model and tested by a paired t-test for comparison of actual total biomass with predicted total biomass by general models.

4. Results and Discussion

4.1. Results

4.1.1. Correlations between Above-Ground Biomass and Tree Variables. *A. dimidiata* tree species' total above-ground biomass had a stronger correlation with total tree height than DBH but a weaker correlation with the average crown diameter (CD) and was negatively correlated with WD of their total biomass (Table 2). Although the total biomass of *C. malosana* was weakly connected with the average (CD) and negatively correlated with WD, it was strongly correlated with DBH rather than H (Table 2). DBH, average (CD), and total tree height were highly linked with *C. africana's* total biomass and weakly correlated with WD (Table 2). In contrast to average (CD) and WD, the total biomass of *M. salicifolia* and *I. mitis* was substantially linked with total tree height after DBH (Table 2).

4.1.2. Species-Specific Allometric Equations for Studied Tree Species. The relationship between above-ground biomass and dendrometric predictor variables such as DBH, H, WD, and average CD was formulated for *A. dimidiata*, *C. malosana*, *C. africana*, *I. mitis*, and *M. salicifolia*. The prediction accuracy and validation potential of fitted allometric equations for total above-ground biomass are presented in Table 3 and supplemental material. The selected models had a high adjusted coefficient of determination (>89%), a p value less than 0.01, and a relatively low standard residual error (Table 3).

(1) Observed versus Predicted Total Biomass. The dotted line shows the adjusted line to the residuals, and the continuous line is the 1 : 1 line. The results of the paired t-test did not show a significant difference between observed and predicted total biomass for the developed models (Table 3 and Figure 2). The validation of observed and predicted values showed a linear relationship for all the targeted tree species. Based on the hypothesis, a one-to-one relationship between the observed and predicted above-ground biomass showed the better prediction accuracy of the model (Figure 2). The mean difference between the observed and predicted total biomass of the studied tree species ranged between 0.14 and −11.03 (Table4). Overestimation of above-ground biomass was seen in all studied tree species except *A. dimidiata.*

4.1.3. Fitted Allometric Equations for Mixed Tree Species. From fitted allometric equations for mixed tree species, the best model is the combination of (diameter at breast height, total tree height, wood density, and average crown diameter) exhibiting the highest adjusted R^2 value (Table 5). The lowest model explanation is seen when only using diameter at breast height; it explains variation by 84% of total above-ground biomass. However, the combination of diameter with other tree variables explained more than 85% of the variability of total above-ground biomass. The combination of wood density with diameter and height in different forms explains variability well (Table 5).

4.1.4. Biomass Expansion Factor and Wood Density of Studied Tree Species. The biomass expansion factor (BEF) of selected tree species ranged from 1.02 to 1.95, and the results demonstrate that the mean of BEF differed among species. The highest BEF was found for *C. malosana* and *A. dimidiata*, while the lowest was found for *C. africana* (Table 6).

The mean wood density (WD) values for chosen tree species are summarized, and the values ranged from 0.53 to 0.74 $g{\cdot}cm^{-3}$. The mean wood density of selected tree species ranged from 0.53 to 0.74 $g{\cdot}cm^{-3}$ and varied among the targeted species. The highest mean WD was recorded in *A. dimidiata*, while the lowest was recorded by *I. mitis* (Table 6).

4.1.5. Comparison of Species-Specific and Pan Tropical Models. There is no significant difference between the species-specific model and the observed above-ground biomass for *A. dimidiata* ($p > 0.05$). The total above-ground biomass of relative bias in *A. dimidiata* ranged from −0.17 to 2.44 kg, while the root mean square error ranged from 14 to 195.61 kg. While for all generalized models, $p < 0.05$ showed a significant difference between observed and predicted biomass. Positive mean prediction error values are significantly different from zero, implying an underestimation of the total above-ground biomass of selected tree species and vice versa (Table 4). While the root mean square error ranged from 4.34 to 285.7 kg, the species-specific allometric equations were more precise for *C. malosana* than generic ones. There was no discernible difference between the total biomass observed and predicted for *C. malosana* according to the species-specific allometric equations, Brown and Lugo [30]; and Chave et al. in [31, 32]. While the majority of studies overestimate biomass, Brown and Lugo [30] and Djomo et al. [33] both understate it (Table 4). For *C. africana*, the species-specific allometric equations were more precise than the generic ones. The observed and predicted total biomass by the species-specific allometric model and generalized model [30–32] had no significant difference for *I. mitis* at $p \leq 0.05$ (Table 4). The species-specific allometric equation was more accurate for *M. salicifolia* than the generalized model, with the lowest value of relative bias in percent ranging from 0.37 to 4.1 and the root mean square ranging from 39.78 to 438. There is no significant difference between the total above-ground biomass predicted by the species-specific allometric equation [33] and the observed biomass for *M. salicifolia* (Table 4). But there is a significant difference between observed and predicted biomass by other generalized models.

4.2. Discussion

4.2.1. Species-Specific Allometric Equations for Above-Ground Biomass. For the quantification of carbon storage, which is crucial for the carbon market credit, appropriate allometric equations are needed. The residual standard error is reduced when estimating total biomass

Table 2: Correlation between total above-ground biomass and tree variables.

Species	Biomass	Tree variable Correlation in %				p values			
		DBH	H	CD	WD	DBH	H	CD	WD
A. d	AGB	0.84	0.90	0.53	−0.15	0.00	0.00	0.63	0.06
C. m	AGB	0.94	0.80	0.53	−0.10	0.00	0.01	1.00	0.52
C. a	AGB	0.96	0.85	0.92	0.32	0.00	0.00	0.00	0.29
I. m	AGB	0.98	0.85	0.73	0.20	0.00	0.03	1.00	0.26
M. s	AGB	0.89	0.82	0.55	0.37	0.00	0.01	1.00	0.52

AGB: above-ground biomass; tree species: *Apodytes dimidiata* (A. d), *Cassipourea malosana* (C. m), *Celtis africana* (C. a), *Ilex mitis* (I. m), and *Myrica salicifolia* (M. s); DBH: diameter at breast height (cm); H: total tree height (m); CD: average crown diameter (m); WD: wood density (g·cm^{-3}).

Table 3: The best regression species-specific allometric equations for TAGB for studied tree species.

Sp name	Equations	Adj. R^2	AIC	CF	RSE	p value
A. d	$\text{TAGB}_{\text{est}} = \exp\ (-3.03 + 1.20 * \ln\ (\text{dbh}) + 1.70 * \ln\ (\text{ht}))$	0.92	5.66	1.03	0.25	0.01
C. m	$\text{TAGB}_{\text{est}} = \exp\ (-2.02 + 1.52 * \ln\ (\text{dbh}) + 1.07 * \ln\ (\text{ht}))$	0.97	6.05	1.01	0.17	0.001
C. a	$\text{TAGB}_{\text{est}} = \exp\ (-1.39 + 0.80 * \ln\ (\text{dbh}^2 * \text{ht} * \text{wd}))$	0.96	−2.65	1.02	0.18	0.001
I. m	$\text{TAGB}_{\text{est}} = \exp\ (-2.73 + 0.98 * \ln\ (\text{dbh}^2 * \text{ht} * \text{wd}))$	0.99	−11.59	1.00	0.10	0.001
M. s	$\text{TAGB}_{\text{est}} = \exp\ (-3.06 + 1.93 * \ln\ (\text{dbh}) + 1.97 * \ln\ (\text{cd}))$	0.95	10.35	1.05	0.30	0.001

TAGB_{est}: total above-ground biomass estimation; Adj. R^2: coefficient of determination; AIC: Akaike information criterion; CF: correction factor; RSE: residual standard error.

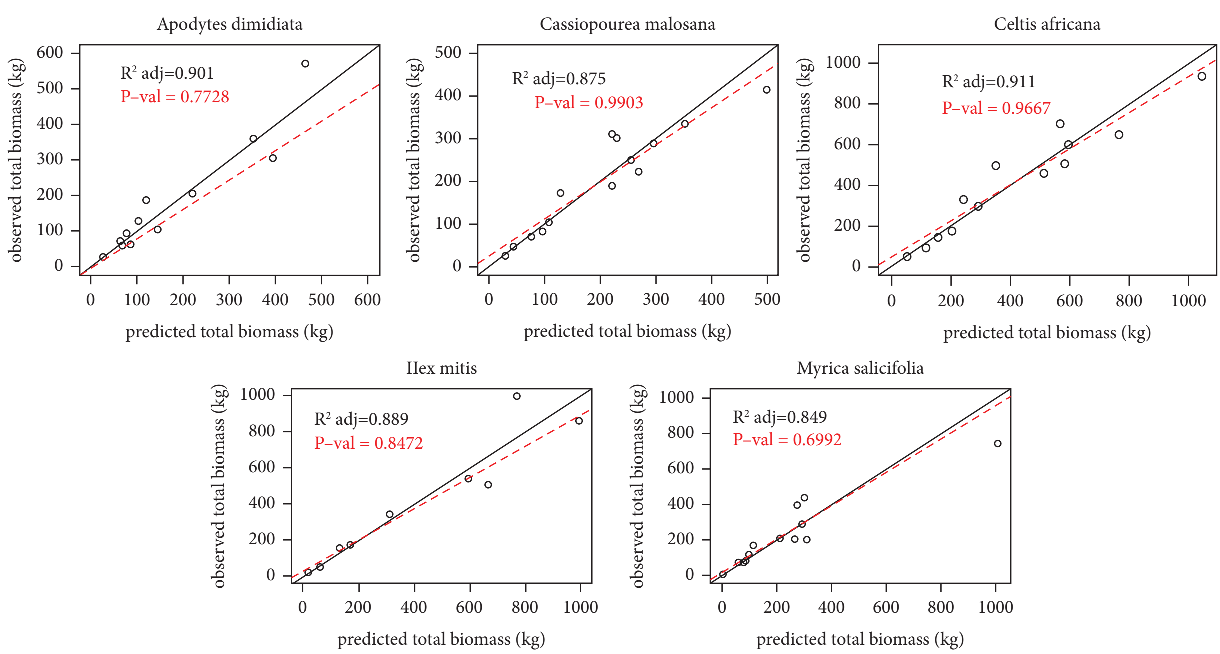

Figure 2: Observed versus predicted total biomass for studied tree species.

Table 4: Comparison of species-specific model with pan tropical model.

Species	Model reference	Rel bias %	MPE	RMSE	t statistic	p value
A. d	This study	−0.17	3.88	14.00	0.30	0.39
Generalized	Brown and Lugo [30]	−2.46	54.80	197.60	4.16	0.01
Generalized	Chave et al. [31]	2.14	−47.60	171.44	−2.55	0.01
Generalized	Chave et al. [32]	2.22	−49.40	178.00	−2.26	0.02
Generalized	Djomo et al. [33]	−2.04	45.36	163.50	2.33	0.02
Generalized	Asrat et al. [12]	2.44	−54.30	195.61	−2.34	0.02
C. m	This study	−0.04	1.16	4.34	−0.01	0.50
Generalized	Brown and Lugo [30]	−0.81	22.71	85.00	1.60	0.07

Table 4: Continued.

Species	Model reference	Rel bias %	MPE	RMSE	t statistic	p value
Generalized	Chave et al. [31]	0.70	−19.62	73.42	−1.20	0.13
Generalized	Chave et al. [32]	0.71	−20.00	74.70	−1.08	0.15
Generalized	Djomo et al. [33]	−1.20	32.50	121.50	2.25	0.02
Generalized	Asrat et al. [12]	2.70	−76.35	285.70	−2.68	0.01
C. a	This study	1.43	−1.00	3.53	−0.04	0.48
Generalized	Brown and Lugo [30]	−20.10	46.10	166.20	1.82	0.05
Generalized	Chave et al. [31]	28.54	−160.20	577.60	−2.36	0.02
Generalized	Chave et al. [32]	33.10	−201.53	726.61	−2.35	0.02
Generalized	Djomo et al. [33]	−21.33	70.70	254.83	2.24	0.02
Generalized	Asrat et al. [12]	45.60	−265.5	957.40	−2.63	0.01
I. m	This study	0.26	−9.60	28.68	−0.20	0.42
Generalized	Brown and Lugo [30]	0.34	−12.21	36.64	−0.28	0.39
Generalized	Chave et al. [31]	−0.17	6.20	18.50	0.34	0.37
Generalized	Chave et al. [32]	0.40	−12.90	38.67	−0.73	0.24
Generalized	Djomo et al. [33]	−4.32	157.50	472.4	3.33	0.01
Generalized	Asrat et al. [12]	1.82	−66.30	198.81	−1.84	0.05
M. s	This study	0.37	−11.03	39.78	−0.40	0.35
Generalized	Brown and Lugo [30]	1.97	−58.44	210.70	−2.058	0.03
Generalized	Chave et al. [31]	2.35	−69.73	251.40	−3.09	0.01
Generalized	Chave et al. [32]	2.60	−76.90	277.32	−2.99	0.01
Generalized	Djomo et al. [33]	−1.20	34.75	125.30	1.56	0.07
Generalized	Asrat et al. [12]	4.10	−121.5	438.00	−2.90	0.01

Table 5: The best regression equations for total above-ground biomass for mixed tree species.

Allometric models	Adj. R^2	AIC	CF	RSE	p value	Rank
$TAGB_{est} = \exp\ (-1.30 + 2.13 * \ln\ (dbh)$	0.84	73.07	1.10	0.42	$2.2e-16$	8
$TAGB_{est} = \exp\ (-2.56 + 0.89 * \ln\ (dbh^2 * ht)$	0.89	49.50	1.06	0.35	$2.2e-16$	5
$TAGB_{est} = \exp\ (-0.80 + 1.06 * \ln\ (dbh^2 * wd)$	0.86	65.08	1.08	0.40	$2.2e-16$	7
$TAGB_{est} = \exp\ (-2.14 + 0.89 * \ln\ (dbh^2 * ht * wd)$	0.91	40.31	1.05	0.32	$2.2e-16$	3
$TAGB_{est} = \exp\ (-3.09 + 1.55 * \ln\ (dbh) + 1.36 * \ln\ (ht)$	0.90	47.97	1.06	0.34	$2.2e-16$	4
$TAGB_{est} = \exp\ (-1.02 + 2.14 * \ln\ (dbh) + 0.74 * \ln\ (wd)$	0.86	65.05	1.08	0.39	$2.2e-16$	6
$TAGB_{est} = \exp\ (2.74 + 1.61 * \ln\ (dbh) + 1.27 * \ln\ (ht) + 0.6 * \ln\ (wd)$	0.91	39.62	1.05	0.32	$2.2e-16$	2
$TAGB_{est} = \exp\ (2.82 + 1.41 * \ln\ (dbh) + 1.37 * \ln\ (ht) + 0.63 * \ln\ (wd) + 0.28 * \ln\ (cd)$	0.92	36.37	1.05	0.31	$2.2e-16$	1

Model performance information should be put on the top of Adj. R^2, AIC, CF, RSE, P value, and Rank.

Table 6: Mean and range of biomass expansion factor and wood density (mean ± SD) for studied tree species.

Species name	Mean per species		Range per species	
	BEF	WD	BEF	WD
A. d	1.24 ± 0.10	0.74 ± 0.17	1.01–1.85	0.52–1.09
C. m	1.40 ± 0.24	0.71 ± 0.13	1.02–1.95	0.51–0.90
C. a	1.19 ± 0.09	0.74 ± 0.14	1.05–1.41	0.59–1.00
I. m	1.37 ± 0.14	0.53 ± 0.10	1.12–1.54	0.42–0.74
M. s	1.27 ± 0.15	0.55 ± 0.07	1.07–1.56	0.42–0.64

SD: standard deviation.

using diameter at breast height and height. Our findings concur with those of Ali et al. [44]; Brown and Lugo [30, 45], Overman et al. [46]; and Tesfaye et al. [19] who found that combining diameter and height as independent variables led to more accurate results. But in contrast to our findings, the addition of height did not improve the models [47] or raise the coefficient of determination [48].

According to Ogawa's [49] findings, the prediction accuracy increased when the squared diameter and height were combined. They disagreed with the conclusions of the earlier studies [13, 33, 50] and discovered that dbh^2ht was a suitable predictor of total above-ground biomass. Most of the time, the wood density to total biomass spearman correlation was weak and statistically insignificant ($p > 0.05$). The residual standard error for *C. africana*, *I. mitis*, and *M. salicifolia* decreased when wood density was added to diameter and height for total biomass (supplemental material (available here)). This is consistent with the reports from Ali et al. [44], Chave et al. [32], and Goodman et al. [41] and is in contrast with those of other research studies conducted elsewhere

[47, 51, 52]. For the species *C. malosana*, wood density did not make the model more accurate. According to Baker et al. [51]; Njana et al. [52]; and Tetemke et al. [47], these results are consistent.

Crown diameter was crucial for biomass estimation, increasing the coefficient of determination for *M. salicifolia* from 0.89 to 0.94 (supplemental material (available here)). Our findings concur with those of Hofstad [48] and Conti et al. [53]. According to Tetemke et al. [47], diameter and crown width make for superior independent variable pairings when compared to the more common diameter and height. This is due to the diameter of the crown being the easiest field measurement variable [54], and species might have the same architecture and branching patterns, which disagrees with the report of Ali et al. [44], who discovered that diameter and height are more crucial for determining the above-ground biomass than crown factors.

Depending on the availability of data from forest inventory, any model with substantial model parameter estimates (supplemental material (available here)) may be used to estimate total above-ground biomass.

4.2.2. Biomass Expansion Factor. The biomass expansion factor (BEF) for the targeted tree species ranged from 1.19 to 1.40 (Table 6). The findings of Levy [55], who reported a BEF of 1.31 to 1.69 for 129 conifer species in Great Britain, were consistent with our findings. This resemblance may result from the estimation technique used. The results of *A. dimidiata* and those of Giri [56] were very similar. He mentioned that the species of Aillanthus excels had a biomass expansion factor of 1.23. Our results fell short of the IPCC's estimated biomass expansion factor for tropical forest stands, which is 3.4. The difference may be explained by the strong correlations between basal area, volume, tree height, and biomass expansion parameters [57]. Our results are higher than those of Momba and Bux [58] who discovered 0.8731 tropical dry trees in eastern Sinaloa, Mexico. This was caused by biomass expansion factors that depend on the size of the tree or are directly proportional to the total biomass of trees [59]. The results of Iranmanesh et al. [57], who reported a BEF for single stem vegetation of Brant's Oak species at 2.37, are very different from ours.

4.2.3. Wood Density. The mean wood density of the sampled tree species varied between 0.53 and 0.74 $g{\cdot}cm^{-3}$ (Table 6). This outcome was comparable to that reported by Olale et al. [60] who found mean wood density of 0.42 to 0.73 $g{\cdot}cm^{-3}$ for a few different tree species in Western Kenya. While Tesfaye et al. [25] researched the Chilimo forest for the prominent native tree species (0.44 to 0.67 $g{\cdot}cm^{-3}$), their findings differ greatly from ours. According to Gartner and Meinzer [61], this difference may be explained by the diameter range and species characteristics. In comparison to the chosen tree species, *Apodytes dimidiata*, *Cassipourea malosana,* and *Celtis africana* had higher wood densities (Table 6). This may be caused by variation in floristic composition [62]. According to our findings, *Apodytes dimidiata* and *Ilex mitis* had wood densities of 0.74 and 0.53 $g{\cdot}cm^{-3}$, respectively (Table 6). But this result is far from the reports of Merti et al. [63] of 0.53 and 0.45 $g{\cdot}cm^{-3}$, respectively. These variations may result from the type of vegetation and the estimating technique (the semi-destructive technique).

Cassipourea malosana has a basic wood density of 0.71 $g{\cdot}cm^{-3}$. This outcome differs significantly from the Genus average, which was reported as 0.673 $g{\cdot}cm^{-3}$. The number of trees we sampled and the stem positions we sampled may be to blame for this discrepancy. The basic wood density of *Celtis africana* is 0.74 $g{\cdot}cm^{-3}$ which is in line with the report of https://db.wordagroforestry.org//wd/species/Celtisafricana and Getachew et al. [64]. *Ilex mitis* has a basic wood density of 0.53 $g{\cdot}cm^{-3}$, which is much lower than the findings of Vreugdenhil et al. [65]. Finally, *Myrica salicifolia's* basic wood density was 0.55 $g{\cdot}cm^{-3}$, which was much less than the number given by https://db.wordagroforestry.org//wd/species.

The overall average wood density for the studied tree species was 0.656 $g{\cdot}cm^{-3}$. This outcome is comparable to that of Chave et al. [62] who discovered that the average weight of 2456 Central and South American tree species was 0.645 $g{\cdot}cm^{-3}$.

4.2.4. Species-Specific Comparison with the Pan Tropical Model. Brown and Lugo [30–33] discovered that the actual biomass and general model were comparable to, but not identical to, the actual mean value. This similarity is probably due to the allometry of the trees in the Brown and Lugo [30–33] sample, which may have included trees with similar allometry to the trees in our study area. The result is similar to that of Ares and Fownes [66]. When the equations of Brown and Lugo [30]; Chave et al. [31, 32]; Djomo et al. [33]; and Asrat et al. [12] were applied to our dataset, the predicted values were over- and underestimated (Table 4). The numerical differences in the results might arise because of agro-ecology and diameter range.

5. Conclusions and Recommendations

The incorporation of a diverse set of independent tree variables including diameter at breast height, total tree height, wood density, and average crown diameter significantly improved the precision of the models. The coefficients of determination were greater than or equal to 84% for both species-specific and mixed tree species for total biomass estimation. Among selected tree species, the maximum biomass expansion factor was recorded for *C. malosana* tree species, and wood density was recorded for *A. dimidiata*. Species-specific allometric equations were better than both pan tropical and mixed allometric equations for the estimation of total above-ground biomass. Generally, the selected models and computed wood density and biomass expansion factors in this study are believed to be applied by both government and nongovernment organizations to estimate the total biomass and carbon stock of selected tree species. To use the developed allometric equations, we have to consider the species composition and type of the forest ecosystem.

Data Availability

The data used during current study are available from the corresponding author based on reasonable request.

Disclosure

This paper was published in preprint form [67] (https://assets.researchsquare.com/files/rs-1521815/v1_covered.pdf?c=1649441771).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

List of the fitted species-specific allometric equations for studied tree species. (*Supplementary Materials*)

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