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Research Article

Aboveground Biomass Models for Indigenous Tree Species in the Dry Afromontane Forest, Central Ethiopia

Tamiru Lemi ,[1] Abeje Eshete ,[1] Getinet Seid ,[2] Sinke Mulugeta,[1] Dereje Egeta ,[1] and Mindaye Teshome [1]

[1]Ethiopian Forestry Development, P.O. Box 30708, Code 1000, Addis Ababa, Ethiopia
[2]Jimma University, P.O. Box 378, Jimma, Ethiopia

Correspondence should be addressed to Tamiru Lemi; lemitam671@gmail.com

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The application of biomass models for quantifying forests' above-ground biomass is essential for sustainable forest management. However, lack of knowledge in modelig biomass of individual tree growth hinders the sustainable management of Dry Afromontane forests. In this study, models to estimate above-ground biomass were developed for *Rhus ruspolii*, *Ekebergia capensis*, and *Nuxia congesta*. To develop the models, a total of 45 trees from different diameter classes were selected, felled, and divided into different biomass compartments. For the model's development, diameter at breast height (DBH), total height (TH), diameter at stump height (DSH), and wood density (WD) were used as independent variables. Models' performances were evaluated using RSE, adjusted coefficient of determination, and AIC. Also, model validations were done by using rRMSE, mean absolute deviation, bias, and coefficient of variation. Models 5 (Adj-$R^2 = 0.92$), 6 (Adj-$R^2 = 0.97$), and 8 (Adj-${R_2}^2 = 0.82$) were the best fitted models for *Nuxia congesta*, *Ekebergia capensis,* and *Rhus ruspolii,* respectively. The average wood densities of *Ekebergia capensis*, *Nuxia congesta,* and *Rhus ruspolii* were 0.59, 0.50, and 0.69, respectively. The variation between observed biomass and estimated biomass using new models was statistically not significant ($p > 0.05$). Thus, the biomass models developed here can be important tools to accurately estimate above-ground biomass in the Menagesha Suba forest and can be integrated into decision support tools.

1. Introduction

To understand the role of forest ecosystems in the global carbon cycle and to manage forest systems sustainably, quantifying biomass and carbon stocks in tropical forest species is very essential. Biomass estimation is specifically important to understand the role of forests as a carbon sink and for sustainable forest management [1]. The availability of tree biometric data like wood density (WD), total tree height (TH), diameter at breast height (DBH), volume, and biomass are critical for supporting forest management decision-making and reducing costs for ground-based forest resource assessment [2, 3].

Above-ground biomass (AGB), which is vital to measure forest stocking, is considered within the framework of sustainable forest management and carbon accounting purposes [4]. Also, it is a useful tool for comparing structural and functional attributes of the forest across a wide range of environmental conditions [5]. Furthermore, forest biomass and wood basic density (WBD) are crucial to effectively implementing climate change mitigation policies and reducing emissions from deforestation and forest degradation (REDD+) under the United Nations Framework Convention on Climate Change (UNFCCC) [6]. Hence, wbd of standing trees has become a fundamental component of biomass determinations in ecosystem studies.

Destructive sampling is the most accurate and direct method of estimating tree biomass [7]. Nonetheless, it is limited to small areas or small tree sample sizes and not suggested for endangered tree species [8]. In such cases, using generic models becomes preferable. But generic models may underestimate or overestimate the biomass in the tropical forest due to the high diversity of the species. Using generic models at the site level may lead to the production of systematic errors [9–11]. This error could have occurred due to environmental variation among different forests [9, 11, 12]. Besides, the variation in wood anatomy in the tropical forest is also another source of error. To minimize the error produced due to environmental variability and variation in wood anatomy, site-species-specific biomass becomes imperative. However, biomass estimation models specific to tropical Africa remain limited [13–15]. Even though some efforts have been made to develop biomass equations in tropical Africa [11, 16, 17], attempts to develop biomass models for sub-Saharan tropical species still remain scarce [18]. These led to biomass estimates in Africa relying on generic models [19–21].

Ethiopia is one of the sub-Saharan countries endowed with diverse vegetation types. The Ethiopian highlands constitute large parts of the Afromontane regions in Africa [22, 23]. These regions are dominated by dry afromontane forests, which are a complex ecosystem characterized by a variable rainfall pattern and a prolonged dry season [24]. It is the second-richest vegetation type, with about 460 species, next to Acacia-Commiphora woodland [25]. However, deforestation and forest degradation in the dry Afromontane forest ecosystem due to landscape fragmentation and land-use pressure are serious challenges in the forest system [22, 26]. Thus, Ethiopia has proposed and implemented a Climate Resilient Green Economy (CRGE) strategy to reduce GHG emissions [27]. Accordingly, to achieve the CRGE strategies, numerous forest resource assessment campaigns have been undertaken to understand the AGB status and management options of the forest resources [28]. Measurement, reporting, and verification (MRV) is one of the forest resource assessment methods established to quantify greenhouse gases (GHGs) emissions [29]. Biomass models are an important tool to facilitate the implementation of MRV in different forest systems across the country. To specifically, site-and species-specific biomass model is a crucial to accurately quantify biomass and carbon stocks by compromising the species diversity and environmental variability. Though efforts have been made to develop species-specific biomass models in dry Afromontane forests e.g. [12, 30–34]; models and data which are basic for decision-making and facilitating forest management in dry Afromontane forests in Ethiopia, however, are very scarce [35].

The Menagesha Suba forest is one of the few remaining natural high forests in central Ethiopia [36]. This forest is dominated by multispecies stands, and about 97 plant species grow in this forest area [36, 37]. Of which, 46 species are woody plants [38]. They have been subjected to selective harvesting for more than a century to provide a mix of services to local communities [36, 39]. To preserve the forest and its environmental services, the Ethiopian government designated it a National Forest Priority Area in the 1980s. In addition to timber production, emphasis is being given to the concepts of ecological sustainability and biodiversity [36, 40, 41]. Even though the forest is considered a forest priority area, the current rate of deforestation is extremely high due to clearing for fuelwood, agricultural land expansion, and lumber. As a result, the forest cover was reduced from 7,360 ha to 2,720 ha [37]. Thus, developing a species specific biomass model is imperative to developing the management plan to sustainably conserve this forest. The overall aim of this study was therefore to develop species specific biomass models to estimate biomass and carbon stock of three codominant native species (i.e., *Rhus ruspolii* Engl, *Ekebergia capensis* Sparrm, and *Nuxia congesta* (R. Br. ex Fresen.) in Menagesha Suba dry Afromontane Forest.

2. Materials and Methods

2.1. Description of Study Area. The study was conducted in Menagesha Suba forest located in Oromia regional state, central highlands of Ethiopia, which is about 45 km southwest of Addis Ababa. Menagesha Suba Forest is one of the 58 National Forest Priority Areas (NFPAs) in Ethiopia which need management intervention to maintain the service provided by the forest. The forest supplies a wide range of ecosystem services, including carbon storage. It is also home to many bird species. This forest is also identified as one of the candidate areas for implementing the international climate change mitigation policy, Reducing Emission from Deforestation and Forest Degradation Plus Sustainable Forestry (REDD+). It is situated between 38°31′30″E and 38°34′30″E and 8°57′0″N and 9°0′N (Figure 1) with an altitude of 2200–3385 m a.s.l. [42]. The annual rainfall ranged between 900 mm and 1500 mm, while the mean average temperature of the forest is estimated at 16.5°C.

According to Zewdie's [43] report, a total of 82 vascular plant species representing 44 families were recorded in the Menagesha Suba forest. Moreover, Feleke [44] reported that 135 vascular plant species belonging to 67 families were recorded in the Menagesha Suba forest. Oromia Wildlife and Forest Enterprise's (OWFE) [45] report also indicated that about 46 woody species were recorded in Menagesha Suba's natural forest. Based on the Important Value Index (IVI), *Juniperus procera* (Hochst. Ex. Endlicher), *Olea europea subsp* cuspidata (Wall. Ex. DC.), *Prunus africana* (Hook. f.) Kalkman, *Podocarpus falcatus* (Thunb.) Mirb, *Nuxia congesta*, *Rhus ruspolii*, *Ficus sur* Forssk., *Acacia lahai* Steud. and Hochst. Ex Benth, *Ficus sycomorus* L, and *Ekebergia capensis* are the top ten dominant woody tree species in the natural forest of Menagesha Suba (Table 1). The understory of the forest is dominated by *Olea europea subsp* cuspidata, *Allophylus abyssinicus* (Hochst. Radlk.), *Maytenus* sp., and *Euphorbia ampliphylla* Pax, and at higher altitudes, the smaller *Juniperus procera* Hochst. ex Endlicher is mixed with *Erica arborea* L., *Rosa abyssinica* R. Br., and the endemic *Asminum stans* Pax [43].

The harvest of economically important and endangered indigenous woody tree species such as *Juniperus procera*, *Podocarpus falcatus* (Thunb.) Mirb, *Hagenia abyssinica*, *Prunus africana,* and *Olea europea, which* were legally protected by the Forest Proclamation, was prohibited from the cut. *Ficus sur*, *Acacia lahai,* and *Ficus sycomorus* are not accessible to cut. Nevertheless, biomass equations for *Olinia aequipetala and Scolopia theifolia* Gilg were developed by

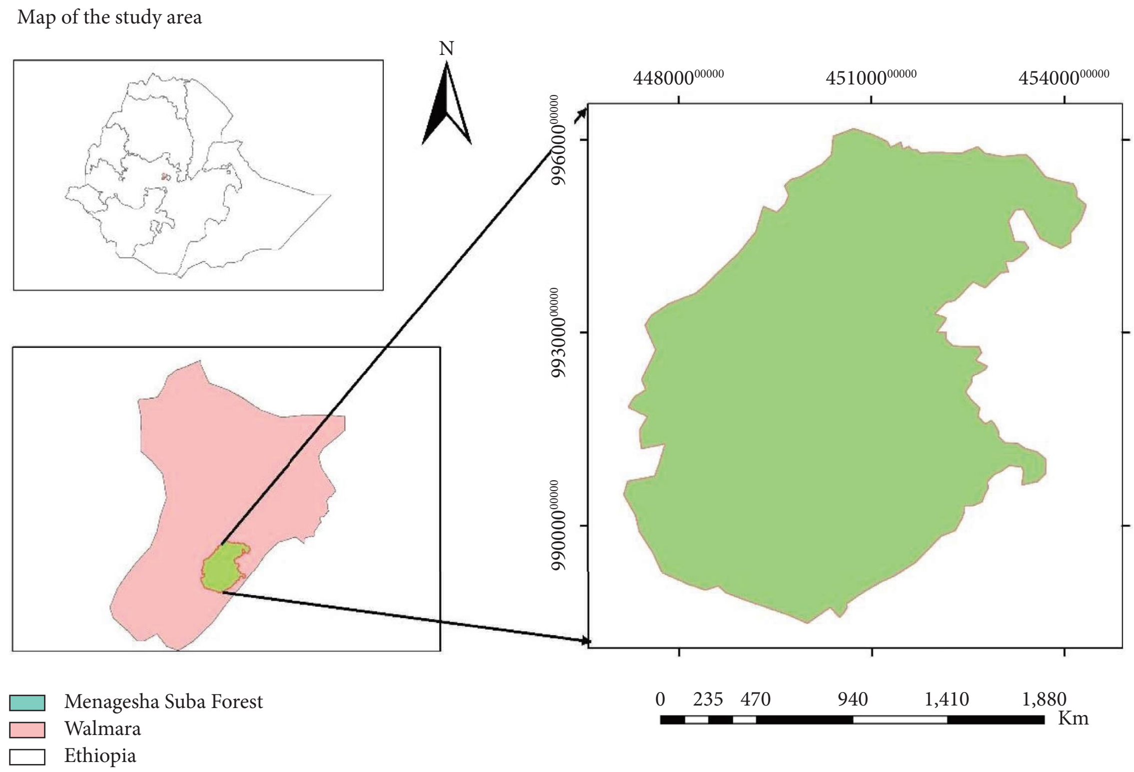

Figure 1: Location map of the study area: Menagesha Suba, central Showa, and Oromia national regional state, Ethiopia.

Table 1: Basal area, density, and importance value index of native tree species in Menagesha Suba natural forest (inventory conducted by [45]).

Species	BA	Density	RD	RF	AF	Rd_o	IVI
Juniperus procera	0.015	34122	12.26	12.42	1071.43	4.19	28.87
Olea europea	0.005	20949	7.53	7.62	657.81	1.56	16.72
Prunus africana	0.037	180	0.06	0.07	5.65	10.7	10.83
Podocarpus falcatus	0.002	11194	4.02	4.07	351.5	0.69	8.79
Olea capensis subsp. Hochstetteri	0.027	95	0.03	0.03	2.99	7.73	7.8
Nuxia congesta	0.005	2550	0.92	0.93	80.07	1.51	3.36
Rhus ruspolii	0.001	3989	1.43	1.45	125.25	0.29	3.18
Ficus sur	0.011	53	0.02	0.02	1.66	3.05	3.09
Acacia lahai	0.009	148	0.05	0.05	4.65	2.69	2.8
Ficus sycomorus	0.004	1492	0.54	0.54	46.84	1.15	2.23
Ekebergia capensis	0.003	561	0.2	0.2	17.61	0.99	1.39
Hagenia abyssinica	0.004	243	0.09	0.09	7.64	1.14	1.31
Celtis africana	0	1132	0.41	0.41	35.55	0.13	0.95
Croton macrostachys	0.002	317	0.11	0.12	9.97	0.62	0.85
Albizia schimperiana	0.001	487	0.18	0.18	15.28	0.32	0.67
Cordia africana	0.002	32	0.01	0.01	1	0.49	0.51
Olea welwitschii	0.001	286	0.1	0.1	8.97	0.29	0.5
Buddleja polystachya	0.001	85	0.03	0.03	2.66	0.19	0.25

Tesfaye et al. [33]. Consequently, among the dominant woody tree species, three codominant woody tree species (i.e., *Ekebergia capensis, Nuxia congesta,* and *Rhus ruspolii*) were selected for the aforementioned purposes based on their IVI and accessibility to cut down. These species have ecological and socio-economic importance for the surrounding community.

2.2. Sampling Design and Techniques. Menagesha Suba natural forest was stratified to avoid heterogeneity of the natural forest based on diameter distribution, accessibility, and representativeness. The stratification of the forest was done following the distribution of selected woody tree species in the forest. The selected species were not evenly distributed across the forest. Moreover, the number of species in each diameter range also varies from species to species. To accommodate the variation and get the targeted species, systematic random sampling was applied to select the sampled trees from the forest. A total of 45 sample trees and 15 trees for each tree species were selected following the study of Tesfaye et al. [33]. The diameter classes were formulated with 10 cm-diameter intervals. The basal area was used to determine the number of sample trees in each diameter class. Accordingly, 6, 6, and 3 trees were cut from diameter ranges of 5–15 cm, 16–25 cm, and 25–35 cm, respectively for *E. capensis*, whereas 6, 7, and 2 trees were cut from diameter classes of 5–15 cm, 16–25 cm, and 25–35 cm, respectively, for *R. ruspolii,* and 5, 8, and 2 trees were selected to be cut from diameter ranges of 5–15 cm, 16–25 cm, and 25–35 cm, respectively, for *N. congesta*. Representative sample trees were systematically marked [7, 46]. In each sampled tree across the forest, all trees with DBH >5 cm were recorded. Trees with DBH <5 cm were excluded from our data set [10] because such trees hold a small fraction of AGB in forests. Big trees with DBH >35 cm were excluded due to the OWFE prohibition om felling trees from natural forests by OWFE.

2.3. Field Data Collection. Diameter at breast height (DBH at 1.30 m) and diameter at stump height (DSH at 30 cm from the ground) of all tree species were measured before tree felling, whereas total height (TH) was measured after a tree was cut down as used in Tesfaye et al. [33]. The selected trees were felled at a height of 30 cm from the ground. The minimum distance between sampled tree species to be cut was 100 m from each other. The first tree was cut down randomly from one corner of the forest, and the other trees were cut down at a minimum distance of 100 m from each other. The felled tree species were separated into stems (from the stump to the top ≥7 cm diameter), branches (diameter >2 cm), and foliage (diameter < 2 cm + leaves) [33]. The stem and branches were crosscut into manageable pieces (logs), whose length is 2 m, to have a uniform shape to facilitate the volume and weight measurements, respectively. The real volume was calculated by using the Smalian formula. The total green weight of branches and foliage components was measured in the field by a beam balance of 100 kg (±0.01 kg) [47]. About 200 g of foliage and branches were collected for laboratory analysis. Their fresh weight was measured in the field. Three discs with 5 cm thickness were taken at the base, mid, and top of each stem. The fresh weight of each disc was measured at the field. The volume of the discs was measured via water displacement methods.

2.4. Laboratory Measurement. To determine the dry matter contents of the sampled trees, representative subsamples of the three components were taken to the laboratory for dry weight determination. In the laboratory, foliage samples were dried at 70°C, whereas woody parts or collected discs and branches were dried at a temperature of 105°C for all sample categories until a constant weight is reached, as used in [48, 49]. The weight of each dried disc, branch, and piece of foliage was measured using a beam balance weighing 100 kg.

Table 2: The general equations used in the AGB model development for *E. capensis*, *N. congesta*, and *R. ruspolii*. Where ht: total tree height, dbh: diameter at breast height and dsh: diameter at stump height.

Model code	Model form
1	$\ln(\text{AGB}) = \alpha + \beta1 \ln(\text{DBH}) + \varepsilon$
2	$\ln(\text{AGB}) = \alpha + \beta3 \ln(H) + \varepsilon$
3	$\ln(\text{AGB}) = \alpha + \beta2 \ln(\text{DSH}) + \varepsilon$
4	$\ln(\text{AGB}) = \alpha + \beta2 \ln(\text{DSH}) + \beta4 \ln(\text{WD}) + \varepsilon$
5	$\ln(\text{AGB}) = \alpha + \beta1 \ln(\text{DBH}) + \beta3 \ln(H) + \varepsilon$
6	$\ln(\text{AGB}) = \alpha + \beta1 \ln(\text{DBH}) + \beta4 \ln(\text{WD}) + \varepsilon$
7	$\ln(\text{AGB}) = \alpha + \beta3 \ln(\text{H}) + \beta4 \ln(\text{WD}) + \varepsilon$
8	$\ln(\text{AGB}) = \alpha + \beta1 \ln(\text{DBH}) + \beta3 \ln(H) + \beta4 \ln(\text{WD}) + \varepsilon$

Where, $\beta1$, $\beta2$, and $\beta3$ are estimated parameters of the fitted models respectively, whereas α is an intercept, ε the residual and WD is wood density (g cm-3) for a given tree, DBH is the diameter at breast height, DSH represent diameter at stump and H is tree height.

2.5. Data Analysis. Due to several effect variables, multiple linear regression models were used [49] to develop biomass equations from independent variables DSH, DBH, H, and wood density. The summary of the variables used for biomass models is summarized in (Table 2). The general model is written as the following:

$$Y = a_0 + a_1X_1 + a_2X_2 + \cdots + a_pX_p + \varepsilon, \quad (1)$$

where Y is the response variable, $X_1, \ldots, X_p$ the p effect variables, $a_0, \ldots, a_p$ the coefficients to be estimated, and ε the residual error. General biomass models used for developing species-specific biomass equations were summarized in Table 2.

Fitting biomass models by using simple linear regression as the variable is generally rarely used in the case of biological data, such as tree volume or biomass because heteroscedasticity is the rule and homoscedasticity the exemption [49]. Therefore, the log transformation was applied to resolve this problem. The best-fitting models for each component were selected by evaluating their goodness-of-fit based on the residual standard error (RSE), their adjusted coefficient of determination (Adj. R^2), and their akaike information criterion (AIC) based on the work of [19, 50, 51]. Thus, the model with the lowest value of RSE and AIC and the higher values of the adjusted coefficient of determination (adj. R^2) were selected as the best-fitted biomass and volume regression models. All statistical analyses were carried out with the R3.5.3 software package. The AIC is as follows:

$$\text{AIC} = n * \ln\left(\frac{\textbf{RSS}}{n}\right) + 2K, \quad (2)$$

where n: number of samples, RSS: the residual sums of squares, and K: parameters of the model including the p the parameter for error estimates (for example, the model $y = a + bx$, then $k = 3$).

Table 3: Summary of wood density and ANOVA for each studied species. Where StDv is the standard deviation and N is the number of observations.

Species	N	Min	Mean	Max	StDv	p value
R. ruspolii	15	0.45	0.69	0.90	0.13	<0.05
E. capensis	15	0.43	0.59	0.92	0.116	
N. congesta	15	0.33	0.50	0.70	0.09	

Relative bias (RB), average deviation (S%), relative root mean square error (rRMSE), and a paired t-test were used to compare the predictive accuracy of the general equations developed for tropical dry forests by [4, 10, 19] with species-specific fitted models. Average deviation S% is used to evaluate variation between observations and predictions. The smaller S% value is preferred

$$S\% = \frac{100}{n}\sum_{i=1}^{n}\frac{|yi - yilt|}{yi},$$

$$\mathrm{RB} = \frac{1}{n}\sum_{i=1}^{n}\frac{yi - yilt}{yi}, \tag{3}$$

$$r\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\frac{yi - yilt}{yi}\right]^2},$$

where $Yilt$: the predicted biomass; Yi: the observed biomass/carbon; n = number of observations

$$\mathrm{CF} = \exp\frac{\mathrm{RSE2}}{2}. \tag{4}$$

Then, the wood density was calculated as dry oven weight divided by the green volume of the sample

$$\mathrm{WD} = \frac{W_{\mathrm{ods}}}{V_{\mathrm{fresh.s}}}, \tag{5}$$

where WD represents wood density, W_{ods} oven-dry weight of the sample, and $V_{\mathrm{fresh.s}}$ fresh volume of the sample.

Besides, an ANOVA was conducted to know whether there is variation in wood density among species and between trees' components or not.

2.6. Model Comparison. Model comparison was made using allometric models that were developed by [4, 10, 19]. Moreover, the model's adequacy and precision were evaluated and tested using sampled trees. These models are frequently used in the tropical forest. For this reason, the models were selected for comparison.

3. Results

3.1. Wood Density. The stem wood densities of the targeted species were summarized in Table 3. The mean wood density of *R. ruspolii* ranged from 0.45–0.90, that of *E. capensis* ranged from 0.43–0.92, and that of *N. congesta* ranged from 0.33–0.70. Thus, there was statistically significant variation among selected woody tree species (i.e., *R. ruspolii*, *E. capensis,* and *N. congesta*).

3.2. Tree Component Biomass. Total AGB of each selected species is the summation of stem biomass (SBM), branches biomass (BBM), and foliage biomass (FBM). About 75.67, 69.6, and 64.96% of total above-ground biomass was accumulated in the stem component of *E. capensis*, *R. ruspolii,* and *N. congesta*, respectively, whereas 3.61, 6.47 and 4.44% of biomass was stored in the leaf part of *E. capensis*, *R. ruspolii* and *N. congesta*, respectively, and 20.74, 23.90, and 30.60% were stored in the branches of *E. capensis*, *R. ruspolii,* and *N. congesta*, respectively. Significant variation was observed between all components ($p < 0.05$), except between branch and foliage biomass of *R. ruspolii* and *E. capensis* (Table 4).

3.3. Correlation between Tree Components' Biomass and Dendrometric Variables. When correlating the variables, we found strong correlation between AGB and DBH, AGB and DSH, DBH and DSH, and TH and DBH ($p < 0.001$; Corr. > 0.73; Figures 2(a)–2(c)) for all species, whereas the correlation between DSH and TH was medium in the cases of *N. congesta* and *R. ruspolii* and weak for *E. capensis*. Wood density was not correlated with all variables, including AGB.

3.4. Biomass Regression Models. A total of eight fitted equations were selected for *R. ruspolii*, *E. capensis*, and *N. congesta* (Table 5). Out of tested models, model 8 was found the best-fitted model for *R. ruspolii* (Adj. $R^2 = 0.91$, $p \leq 0.001$) and model 5 for *N. congesta* (Adj. $R^2 = 0.97$, $p \leq 0.001$) whereas model 6 was the best fitted model for *E. capensis* (Adj. $R^2 = 0.95$, $p \leq 0.001$). All tested models were statistically significant ($p < 0.05$). In most cases, the coefficients $\beta1$, $\beta2$, $\beta3$, and $\beta4$ were positive, which indicates that the aboveground biomass of each tree species would increase for every 1 unit increase in the value of other tree parameters used in the model.

Residual plots of the best-fitted height equations for our studied species generally indicate an even spread of residuals above and below the zero line with no systematic trend (Figure 3). This suggests that natural log-transformed multiple linear regressions are effective in stabilizing error variance, and this study appeared to be appropriate for reducing heteroscedasticity.

The best-fit models from all tested models were also tested for accuracy based on observed and predicted data. Observed and predicted above-ground biomass values are close to the 1 : 1 line (Figure 4).

3.5. Model Comparison. The mean observed values of *R. ruspolii*, *E. capensis*, and *N. congesta* were 111.9, 125.94, and 191.53 kg, respectively. Whereas the average predicted biomass of *R. ruspolii* through the species-specific model, Brown [4]; Chave et al. [10, 19] were 125.71, 111.40, 155.94, and 185.53 kg, respectively. The average predicted biomass of *E. capensis* via a species-specific model Brown [4]; Chave et al. [10, 19] was 190.69, 153.51, 247.30, and 309.77 kg, respectively.

Table 4: ANOVA of tree compartments biomass of *R. ruspolii*, *E. capensis,* and *N. congesta*.

Compartment	*R. ruspolii*		*E. capensis*		*N. congesta*	
	F value	*p* value	*F* value	*p* value	*F* value	*p* value
SBM-BBM	10.12	0.0008***	54.62	0.002***	20.82	0.0077**
SBM-FBM	0.625	0.00001***	53.86	0.000044***	9.597	0.000001***
BBM-FBM	1.515	0.34621	282.7	0.4363731	4.384	0.0238

Where SBM represent stem biomass, BBM is branch biomass and FBM is represent foliage biomass.

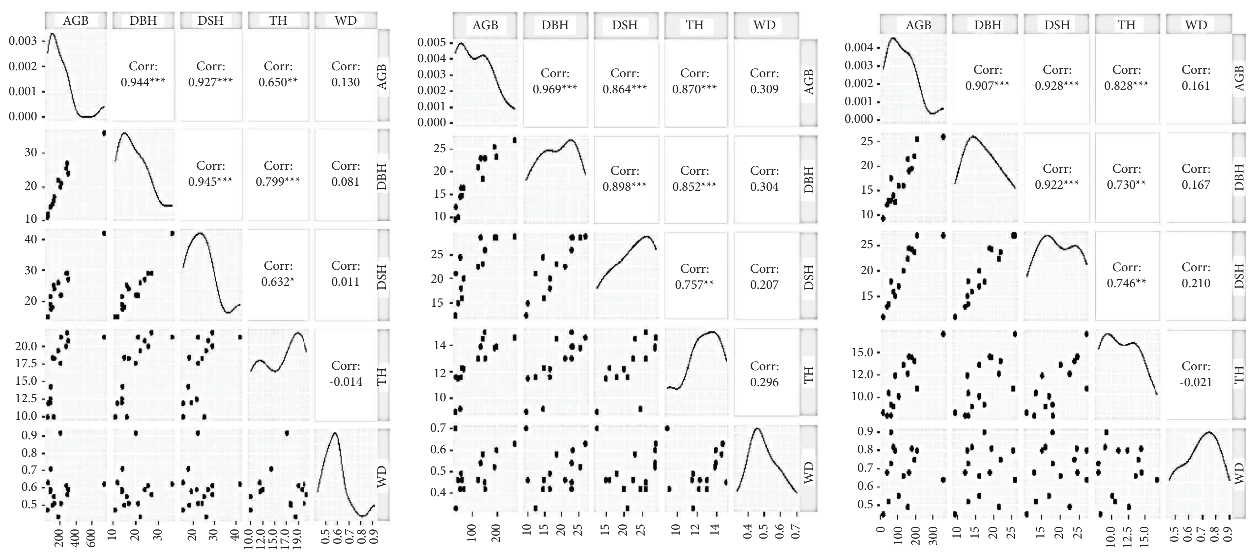

Figure 2: Scatter plot matrices showing correlation coefficients between tree variables and significance levels for (a) *E. capensis,* (b) *N. congesta,* and (c) *R. ruspolii* in Menagesha Suba dry afromontane forest, central highlands of Ethiopia. On the top of the diagonal, the value of the correlation (Corr.) is shown, plus the significance level of the *p*-values, which are indicated by asterisks, ***, <0.001; **, <0.01; and *, <0.05. The abbreviations AGB represent above ground biomass, TH = tree total height, DBH is diameter at breast height, DSH is diameter at stump height, and WD = wood density.

Consequently, the average predicted biomass of *N. congesta* through the species-specific model of Brown [4]; Chave et al. [10, 19] was 110.80, 134.54, 146.18, and 142.26 kg, respectively. Thus, the variation between observed and predicted biomass through a species-specific allometric equation was statistically not significant for all targeted species, while the variation between observed and predicted biomass via Chave et al. [10, 19] was statistically significant (Table 6). On the other hand, the estimated biomass using the biomass equation developed by Brown [4] underestimated the biomass of *R. ruspolii* and *E. capensis* but overestimated that of *N. congesta*. Except for *R. ruspolii,* the variation between the predicted biomass using Brown [4] and the observed one was statistically significant ($p < 0.05$).

4. Discussions

Estimating wood density (WD) for these co-dominant native tree species in Ethiopian dry afromontane mixed forests will contribute to developing biomass models and sustainable management of these forests. Wood densities were determined for each targeted species. The mean wood density of each species ranged from 0.5–0.69 g/cm^3. The WD of *E. capensis* reported by Desalegn et al. [52] is lower by 1% than that of this study. Consequently, the average WD of *Rhus ruspolii* was 0.51 [28], which is 18% lower than this study. The average WD of *Nuxia congesta* reported by MEFCC [28] was 12% higher than that of this study. The wood density of tropical woody species is between 0 and 1.5 [53] and 0.262–1.040 g/cm^3 in Ethiopia [28]. Thus, the mean average WD of each targeted species is found within this range. Furthermore, significant variation in WD was observed among selected tree species. This indicated that the anatomical structure of these species could be varied. Thus, determining the WD of targeted species has an indispensable role in estimating the above-ground biomass of Ethiopian's dry Afromontane forest. Tesfaye et al. [54] stated that determining WD for each species is essential rather than using a default value during the development of the biomass model. Henry et al. [55] also stated that tree species and stem position in a given forest influence wood density. For instance, Olmos and Lorena [56] found higher values of wood density in the bottom parts of a tree than in the top parts of

Table 5: Parameter estimates and statistics fit the AGB equations developed based on log-transformed linear models. Error: standard error; AIC akaike information criteria; RSE: residual standard error; and NA represents: not applicable or those variables represented by NA are not considered for that specific model development.

Species	M cod	Estimated parameters and respective std. error					Statistical performance				
		Bo	β1	β2	β3	β4	Adj. R^2	RSE	AIC	p-value	CF
E. capensis	1	−1.64	2.27 (0.19)	NA	NA	NA	0.94	0.16	−3.46	≤0.001	1.01
	2	0.08	NA	NA	1.75 (0.45)	NA	0.64	0.40	13.13	<0.05	1.08
	3	−3.40	NA	2.69 (0.68)	NA	NA	0.64	0.40	13.0	<0.005	1.08
	4	−2.77	NA	2.60 (0.70)	NA	0.60 (0.68)	0.63	0.41	13.9	<0.05	1.09
	5	−1.65	2.18 (0.38)	NA	0.10 (0.34)	NA	0.93	0.17	−1.58	≤0.001	1.01
	6	−1.24	2.21 (0.18)	NA	NA	0.40 (0.24)	0.97	0.14	−4.80	≤0.001	1.01
	7	0.65	NA	NA	1.71 (0.44)	0.75 (0.65)	0.65	0.40	13.30	<0.05	1.08
	8	−1.24	2.06 (0.34)	NA	0.17 (0.31)	0.42 (0.26)	0.95	0.15	−3.31	≤0.001	1.01
N. congesta	1	−3.11	2.61 (0.18)	NA	NA	NA	0.96	0.13	−6.38	≤0.001	1.01
	2	−12.8	NA	NA	6.82 (1.32)	NA	0.76	0.34	10.34	<0.01	1.06
	3	−4.23	NA	2.83 (0.66)	NA	NA	0.68	0.40	12.89	<0.05	1.08
	4	−0.84	NA	2.16 (0.50)	NA	1.69 (0.56)	0.85	0.27	6.73	<0.01	1.04
	5	−5.26	2.23 (2.22)	NA	1.28 (0.97)	NA	0.97	0.13	−6.66	≤0.001	1.01
	6	−2.44	2.46 (0.26)	NA	NA	0.29 (0.37)	0.96	0.14	−5.26	≤0.001	1.01
	7	−8.03	NA	NA	5.30 (1.43)	1.24 (0.69)	0.82	0.30	8.54	<0.01	1.05
	8	−4.63	2.04 (0.39)	NA	1.34 (0.98)	0.33 (0.35)	0.97	0.13	−6.08	≤0.001	1.01
R. ruspolii	1	−2.31	2.46 (0.27)	NA	NA	NA	0.84	0.30	10.91	≤0.001	1.05
	2	−1.92	NA	NA	2.69 (0.49)	NA	0.67	0.45	22.52	≤0.001	1.11
	3	−3.16	NA	2.64 (0.25)	NA	NA	0.88	0.26	6.87	≤0.001	1.03
	4	−3.25	NA	2.66 (0.28)	NA	−0.07 (0.38)	0.87	0.28	8.82	≤0.001	1.04
	5	−3.19	1.79 (0.31)	NA	1.13 (0.37)	NA	0.91	0.23	4.30	≤0.001	1.03
	6	−2.10	2.41 (0.3)	NA	NA	2.41 (0.42)	0.84	0.31	12.59	≤0.001	1.05
	7	−1.38	NA	NA	2.63 (0.45)	0.97 (0.53)	0.72	0.41	20.85	≤0.001	1.09
	8	−2.86	1.65 (0.31)	NA	1.23 (0.37)	0.42 (0.32)	0.91	0.23	4.08	≤0.001	1.03

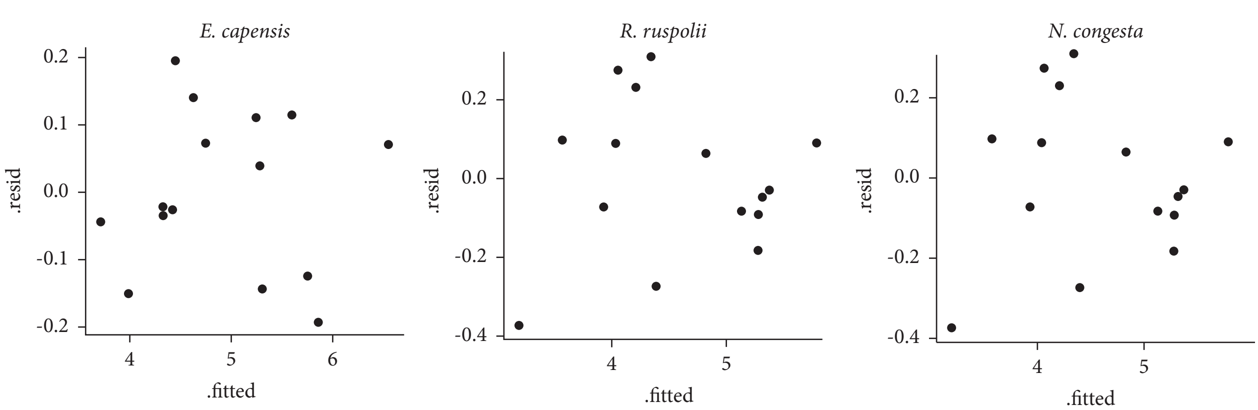

Figure 3: Best-fit AGB (kg) against the residual plot of models (i.e., the residual plot of model 8 for *R. ruspolii* and *N. congesta* and the residual plot of model 6 in the case of *E. capensis*).

a tree. Species with very thick-walled fibers had a significantly higher mean wood density than species with very thin-walled fibers [53].

We estimated the biomass of the stem, branches, and foliage of *E. capensis*, *R. ruspolii*, and *N. congesta*. For all targeted species, a larger proportion of carbon and biomass was stored in the stem than in the foliage and branches. Previous studies also confirmed that a large portion of biomass accumulated in the stem compared to other tree compartments [33, 55, 57–62]. For instance, larger biomass was accumulated in the stem part of *Casuarina equisetifolia* than in the branches, leaves, and roots [63]. Thus, to increase the above-ground biomass, different silvicultural activities which enhance stem growth become imperative. In contrast to this study, the highest biomass fraction was observed in branches of *Afzelia africana* [58], *Scolopia theifolia* [33], *Combretum glutinosum,* and *Terminalia laxiflora* [64]. Thus, the variation of biomass among components of the woody plants could be due to plant architecture and morphology, climatic and edaphic factors, and forest management

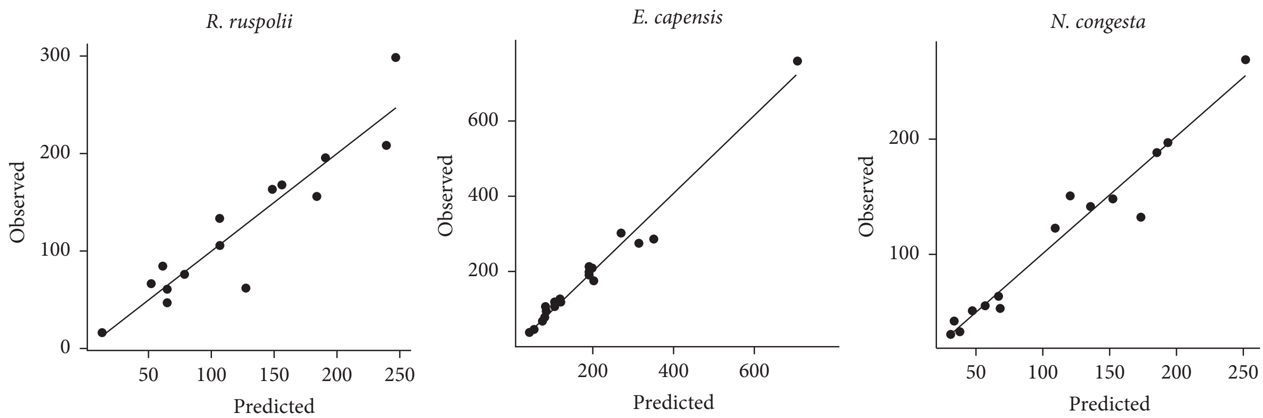

Figure 4: Observed against predicted above-ground biomass values for the studied species.

Table 6: Comparison of the species-specific allometric equation and generalized allometric equations against the observed value.

Species	Model references	RB	S (%)	rRMSE	Paired t test	
					t statistics	p value
R. ruspolii	New	−0.02	2	0.19	0.049	0.96
	[4]	0.04	4	0.30	1.55	0.14
	[19]	−0.27	27	0.44	−3.158	0.0069
	[10]	−0.45	45	0.62	−3.757	0.002
E. capensis	New	−0.01	1	0.12	0.117	0.91
	[4]	0.18	18	0.21	2.831	0.01
	[19]	−0.28	28	0.37	−3.622	0.002
	[10]	−0.52	52	0.63	−3.610	0.002
N. congesta	New	−0.01	1	0.14	0.269	0.79
	[4]	−0.22	22	0.34	−3.383	0.004
	[19]	−0.28	28	0.36	−4.293	0.0007
	[10]	−0.22	22	0.32	−3.543	0.003

practices [7, 54, 58, 65, 66], availability of nutrients [67], age [68, 69], and spacing [70]. For example, annual maximum temperature and precipitation had a positive impact on stem biomass [71].

Developing biomass equations for tropical dry forest species is essential to quantifying biomass and carbon stock, which encourage sustainable forest management of dry Afromontane forests [33]. The biomass models developed in this study included DBH, DSH, TH, and WD as independent variables for all selected species. Above-ground biomass (AGB) of all targeted species was highly correlated with the aforementioned independent variables, except wood density. In line with this finding, the AGB of five native tree species was correlated with DBH, CH, and TH [54]. Previous findings also supported the idea that combinations of different dendrometric variables fit better than individual variables [12, 18, 33, 72]. For instance, DBH, crown diameter, and basal diameter were important variables to explain the biomass of *Vitellaria paradoxa* [73, 74]. Thus, combining these variables provides better fit results than using DBH and TH alone to accurately estimate AGB.

Despite some studies suggesting the importance of generic equation to estimate AGB of tropical African forests [5, 10, 19], others argued generic models are inappropriate for African tropical forests [11, 18, 30, 33]. Moreover, Goodman et al. [73] also emphasized that pan-tropical allometric models may underestimate the AGB of a very large tree by 20% due to sampling bias in the harvest data set. A comparison of generalized models [4, 10, and 19] to the fitted models for the species studied revealed that generalized models were not appropriate for all species to estimate biomass as compared to a newly developed model. All generalized models tested showed a high bias and were unsuitable for biomass estimation of selected tree species. The variation between observed biomass and predicted biomass through a generalized equation is due to unfair representation or a lack of sample trees from Ethiopia in their data set. For example, Tesfaye et al. [33] indicated that the generalized allometric models by Brown et al. [5] showed the poorest results, with 32–59% average deviation for AGB predictions of five tree species in Ethiopia. Correspondingly, the model developed by Chave et al. [19] was inappropriate for three species in Ethiopia, including *Allophylus abyssinicus, Olinia rochetiana, and Rhus glutinosa* [33]. Thus, compared to models developed by Brown [4] and Chave et al. [10, 19], the species-specific models can generate higher reliability biomass estimation for the studied species.

Overall, generalized models produce a larger bias for all species when estimating above-ground biomass. Due to the species diversity in tropical forests, species-specific biomass models are required to accurately estimate the biomass. Furthermore, 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. This study is the pioneer in the study area, and the models developed represent useful tools to support decision-making for selected ecologically and economically important tree species in Menagesha Suba natural forests. Thus, the biomass models developed here may help with the sustainable management of the dry forest of central Ethiopia.

5. Conclusions

We explored the applicability of species-specific biomass models to estimate the aboveground biomass of three economically and ecologically important indigenous woody species in Menagesha Suba, the central highlands of Ethiopia, which helped us understand the strategies to sustainably manage the dry Afromontane Forest. Furthermore, this study was used to indicate the gap in generic biomass equations used to estimate aboveground biomass in the study area. Moreover, the information generated by this study can be used for sustainable forest management, including REDD+ and MRV practices, in the dry Afromontane Forest of Ethiopia. The predictor variables used to develop biomass models of *Ekebergia capensis*, *Nuxia congesta,* and *Rhus ruspolii* were DBH, DSH, H, and WD. Despite the development of species-specific biomass being complex, the developed models are accurate in estimating the biomass of studied species in the study area. Including more variables improves the accuracy of the models to estimate the biomass. As compared to the general equation, the species-specific biomass equations measured biomass and carbon stocks accurately. The outputs of the model comparison showed that the application of generalized models for estimating AGB of selected species produced a very big bias. Generic equations highly deviated from the observed value, whereas species-specific equations deviated less from the actual value. Therefore, species-specific equations can accurately measure biomass as compared to general equations.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest on this work.

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