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ORIGINAL PAPER

Aboveground biomass equations for sustainable production of fuelwood in a native dry tropical afro-montane forest of Ethiopia

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Abstract

· ***Key message*** **Biomass equations are presented for five tree species growing in a natural forest in Ethiopia. Fitted models showed more accurate estimations than published generalized models for this dry tropical forest.**

· ***Context*** Biomass equations are needed to correctly quantify harvestable stock and biomass for sustainability efforts in forest management, but this kind of information is scarce in Ethiopia.

· ***Aims*** This study sought to develop biomass models for five of the most common native tree species in the Chilimo dry afro-montane mixed forest in the central highlands of Ethiopia: *Allophyllus abyssinicus*, *Olea europaea* ssp. *cuspidata*, *Olinia rochetiana*, *Rhus glutinosa*, and *Scolopia theifolia.* Comparison with generalized models was intended to show the greater accuracy of the specific models.

· ***Methods*** A total of 90 trees from different diameter classes were selected, felled, and divided into different biomass compartments. Biomass equation models were fitted using joint-generalized least squares regression to ensure the additivity property between the biomass compartments and total biomass.

· ***Results*** These were the first models developed for these species in African tropical forests. Models were including diameter at breast height and total height as independent variables, obtaining more accurate biomass estimations using these models than from generalized models.

· ***Conclusion*** Fitted models are reliable for estimating aboveground biomass in the Chilimo forest and for more general application in similar forest types. Model applicability for biomass or carbon estimation is high within forest inventory data contexts.

Keywords Chilimo forest · Tropical forest · Biomass models · Fuelwood · Carbon stock

1 Introduction

Forests play an important role in mitigating global climate change. Forests cover over $4 \cdot 10^9$ ha of the earth's surface (IPCC 2007), with an estimated carbon (C) stock of 363 Pg C in living biomass (Pan et al. 2011). Tropical forests are especially important; they account for about 60 % of global

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forest cover and store from 229 Pg C (Baccini et al. 2012) to 263 Pg C (Pan et al. 2011) in aboveground biomass, roughly 20 times the annual emissions from combustion and changes in land use (Friedlingstein et al. 2010). Intact tropical forests contributed 1.2 Pg C ha^{-1} to the global carbon sink, which represents half the contribution of all established world forests (Pan et al. 2011). Tropical dry forests represent around 42 % of all tropical forest ecosystems (Miles et al. 2006) and possess great potential for carbon sequestration, especially through protection, conservation, and forest management in light of the high existing degradation and deforestation rates.

Biomass and carbon stock estimates for tropical forest species enhance our understanding of the importance of tropical forests in the global carbon cycle and how to manage these forests for sustainable production and fuelwood harvesting. In developing countries, about 38 % of primary energy consumption comes from forest biomass (Sims 2003); in Ethiopia, biomass supplies 93 % of total household energy consumption (Shiferaw et al. 2010). To successfully implement mitigating policies and take advantage of the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program of the United Nations Framework Convention in Climate Change (UNFCCC) (Chaturvedi et al. 2011), these countries need well-authenticated estimates of forest carbon stocks.

Consequently, there is an urgent need to quantify tree biomass through direct or indirect methods (Brown 2002). Destructive methods calculate biomass directly by harvesting the tree and measuring the actual mass of each of its compartments (Kangas and Maltamo 2006). Though very accurate (Henry et al. 2011), cutting down trees is both costly and time consuming. Indirect methods using biomass models and biomass expansion factors (BEFs) to estimate tree biomass are time efficient (Peltier et al. 2007). However, tools for biomass estimation remain scarce in the tropics and existing generalized models do not accurately represent biomass in the actual forests (Henry et al. 2011). Most existing models for tropical species were developed in Latin America and Asia. Though great efforts have been made to develop models for several tropical species in recent years, particularly in Africa (e.g., Henry et al. 2011; Fayolle et al. 2013; Mate et al. 2014; Ngomanda et al. 2014), attempts to develop biomass equations for sub-Saharan Africa have been very limited (Henry et al. 2011). To obtain precise and accurate biomass and carbon stock estimates in forests, different models must be developed for different species and forest types. Most of the recent biomass models in Africa have been developed for wet or moist forests (e.g., Djomo et al. 2010; Fayolle et al. 2013; Ngomanda et al. 2014), leaving dry forests poorly studied. The 2011 review of Henry et al. reported biomass equations for only six forest species in Ethiopia.

Biomass partitioning is an important factor in quantifying exploitable dendromass (for timber yield or firewood). Data that accurately reflects biomass amounts and distribution between compartments for different species in tropical forests can aid in the application of sustainable forest management for these resources.

Deforestation has reduced Ethiopia's forest cover in the last century. Forest policies aimed at stopping this process are being implemented due to the important ecosystem services that the forest provides (timber, firewood, soil erosion reduction, carbon sink…). Carbon stock estimates in Ethiopia range from 153 Tg C (Houghton 1999) to 867 Tg C (Gibbs et al. 2007). Estimates of mean aboveground biomass carbon stock density vary from 26 Mg C ha^{-1} (Brown 1997) to 18 Mg C ha^{-1} (FAO 2010) depending on the methodology and tools used. Mean values as high as 278 and 414 Mg C ha^{-1} have been found in dense forests such as the Egdu Forest (Feyissa et al. 2013) and the Arba Minch Ground Water Forest (Wolde et al. 2014), respectively. Localized carbon stocking capacity studies are urgently needed to aid sustainable management of the existing forest (IBC 2005).

Located in the central highland plateau of Ethiopia, the Chilimo-Gaji forest is one of the few remaining dry afro-montane mixed forests, composed of broad-leaf and predominantly coniferous species (Kassa et al. 2009). The forest represents a vital ecological space for birds, mammal species, and water supply. It is the source of several large rivers, including the Awash River. However, the Chilimo-Gaji forest has been subjected to human impact for over 2000 years. The current rate of deforestation is extremely high due to clearing for fuelwood, agricultural land expansion, lumber, and farming. Chilimo forest cover has shrunk from 22,000 ha in 1982 to its present-day size of 6000 ha (Dugo 2009; Teshome and Ensermu 2013). In order to preserve this area and the important environmental services it provides, the Ethiopian government has moved to protect this woodland by proclaiming it a National Forest Priority Area. Although some species were protected by law, other species are under increased pressure from the local human population in search of wood for fuel, construction, farm implements, and charcoal (Teshome and Ensermu 2013).

Given the lack of aboveground biomass estimates for most Ethiopian species (see the review of Henry et al. 2011), the main objective of this study was to develop biomass and carbon stock estimation models for use in sustainable biomass harvesting practices and carbon stock estimation for five of the most common native broadleaf species in a dry tropical afro-montane forest: *Allophyllus abyssinicus* (Hochst.) Radlk., *Olea europaea L.* ssp. *cuspidata* (Wall. ex G. Don) Cif, *Olinia rochetiana* A. Juss, *Rhus glutinosa* Hochst. ex A. Rich., and *Scolopia theifolia* Gilg. Although the coniferous *Juniperus procera* Hochst. ex Endl. and the broadleaf *Podocarpus falcatus* (Thunb.) R.Br. ex Mirb. are the most abundant and dominant tree species in this forest, cutting them down is prohibited by law and it was therefore not possible to develop biomass-based equations for these endangered species.

2 Materials and methods

2.1 Study site location

The experimental site was located in the Chilimo-Gaji dry afro-montane forest of the West Shewa zone, in the Dendi district of the central highlands of Ethiopia (38° 07′ E to 38° 11′ E longitude and 9° 03′ to 9° 06′ N latitude), at an altitude of 2170–3054 m above sea level (Fig. 1). The mean annual temperature ranges between 15 and 20 °C, and average annual precipitation is 1264 mm (Dugo 2009) with a bimodal rainfall distribution of lower precipitation from November to January and a higher rainy season from May to September. Köppen's typology classifies the Chilimo-Gaji forest as a temperate highland climate with dry winters (Cwb, subtropical highland variety) (EMA 1988). The main rock type in the area is basalt, and some areas are covered with other volcanic rocks of more recent formation.

2.2 Exploration and pilot study

This study included a stratification of the Chilimo-Gaji forest based on dominant species composition, representativeness, and accessibility. Due to the lack of data, a pilot survey was taken prior to biomass data collection in order to compile information about species composition, diameter distribution, and general forest conditions. A total of 35 20×20 m square sample plots were established (Fig. 1) between the altitudes of 2470 and 2900 m, based on the Neyman optimal allocation formula (Köhl et al. 2006). Thirty-three different native species (22 tree and 11 shrub species) were recorded in the Chilimo-Gaji forest. Tree density (N) was 591±39 tree ha^{-1} (stand basal area (G) of 24.5±2.3 m^2 ha^{-1}), and the most abundant species were *J. procera* and *P. falcatus* (136±28 and 116±24 tree ha^{-1}, respectively; 42 % of N and 50 % of G). The five next most abundant species accounted for one third of the total tree population in terms of mean density and 27 % of total basal area: *A. abyssinicus* 36.4±11.1 tree ha^{-1} (6 % of total N) and 0.8±0.3 m^2 ha^{-1} (3 % of total G), *O. europaea* 54.3±13.0 tree ha^{-1} (9 % of N) and 3.0± 0.7 m^2 ha^{-1} (12 % of G), *O. rochetiana* 59±16 tree ha^{-1} (10 % of N) and 2.1±0.6 m^2 ha^{-1} (8 % of G), *R. glutinosa* 16±5 tree ha^{-1} (3 % of N) and 0.5+0.2 m^2 ha^{-1} (2 % of G), and *S. theifolia* 34±11 tree ha^{-1} (6 % of G) and 0.4±+ 0.2 m^2 ha^{-1} (2 % of G).

2.3 Data

2.3.1 Data collection

The five most abundant and dominant broadleaf tree species in the natural forest (after the endangered and protected coniferous species *J. procera* and *P. falcatus*) were selected for developing aboveground biomass-based equations for sustainable fuelwood production: *A. abyssinicus*, *O. europaea*, *O. rochetiana*, *R. glutinosa*, and *S. theifolia*.

Trees of each species were randomly selected along a forest transect, based on diameter classes at 5-cm intervals that had been obtained from the pilot inventory data. The trees were dendrometrically representative of the population, with typical shape and development for each species studied. A total of 20 trees were felled for each of the most abundant species, in which it was possible to complete a suitable diameter range (*O. europaea*, *O. rochetiana*, and *R. glutinosa*), while 15 trees were for each of the other species (*A. abyssinicus* and *S. theifolia*) (Table 1). Prior to felling, diameter at breast height (dbh at 1.30 m), stump diameter (db), crown diameter (cd), and crown length (cl) were measured for each tree. After the trees were cut down, diameter at each meter interval, total height (h), commercial height (hc) (height up to a stem diameter of 7 cm), and height at branching stems (hb) were measured. Several biomass compartments were considered: stem with bark and thick branches (diameter greater than 2 cm) and thin branches (diameter less than 2 cm) with leaves. Trees were felled and divided in the field into the compartments mentioned. Stem biomass was estimated using stem volume (calculated through Smalian's formula in logs 2 m length) and wood density (Picard et al. 2012) because it was not possible to weigh heavier logs. Although this indirect method might overestimate stem biomass (Moundounga Mavouroulou et al. 2014), the short length of the logs would minimize this tendency. Fresh weights of each compartment were recorded in the field and then samples were taken to the laboratory and oven dried at 102 °C until constant weight was reached. The main dendrometric variables for the sampled trees are listed by species in Table 1. Sampling of larger trees was not possible due to the prohibition on felling trees in this natural forest (this research was an exceptional case agreed upon with the local forest user groups) and the fact that trees with diameter greater than 30 cm were not abundant in the forest.

2.3.2 Data analysis

A correlation analysis between the biomass dry weight of the different compartments and the biometric tree measurements was carried out using the Spearman method. To fit the biomass models, different linear and non-linear equations (Table 2) with additive error term were evaluated for each dry biomass weight compartment. The best one was selected based on the statistics calculated for

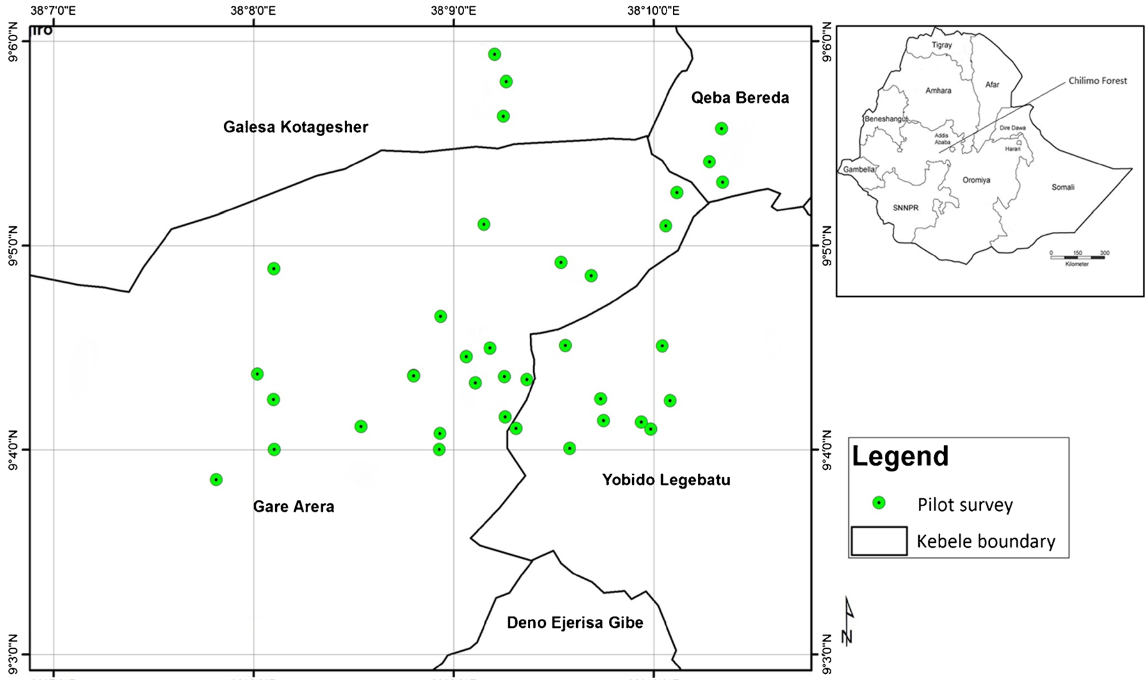


Fig. 1 Location map of Chilimo dry afro-montane forest in Ethiopia and pilot survey plots

each equation: bias (MRES), root mean square error (RMSE), adjusted coefficient of determination (R^2_{adj}) (Pérez-Cruzado and Rodríguez-Soalleiro 2011), and a graphical analysis of the biological behavior of the models and the residuals. The selected models were then simultaneously fitted using joint-generalized least squares regression (also known as seemingly unrelated regression-SUR), where cross-equation error correlation was taken into consideration to ensure the additivity property between biomass compartments and total aboveground biomass (Parresol 1999, 2001; Balboa-Murias et al. 2006; Pérez-Cruzado and Rodríguez-Soalleiro 2011; Ruiz-Peinado et al. 2011, 2012). Weighted regression was used to avoid heteroscedasticity: each observation was weighted by the inverse of its variance to homogenize the variance of residuals. Models were fitted using the MODEL procedure included in SAS/ETS software (SAS Institute Inc. 2012).

In order to determine how biomass is partitioned between compartments for the species studied, models were applied to the mean value of each diameter class and the mean height for each class (calculated in a dbh-height relationship using field data).

To compare the predictive accuracy of the main general equations developed for tropical dry forests (Brown et al. 1989; Brown 1997; Brown and Lugo 1992; Chave et al. 2005; Chave et al. 2014), the Ethiopian site-specific fitted models were evaluated using relative bias (RB) [Eq. 1], average deviation (S) [Eq. 2], relative root mean square error (rRMSE) [Eq. 3], and a paired *t* test for estimation values.

$$\mathrm{RB} = \frac{\sum_{i=1}^{n}\left[\frac{Y_i - \hat{Y}_i}{Y_i}\right]}{n} \tag{1}$$

$$\mathrm{S}(\%) = 100 \cdot \left| \frac{\sum_{i=1}^{n}\left[\frac{\left|Y_i - \hat{Y}_i\right|}{Y_i}\right]}{n} \right| \tag{2}$$

$$\mathrm{rRMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\frac{Y_i - \hat{Y}_i}{Y_i}\right]^2} \tag{3}$$

where Y_i is the observed value, $\hat{Y}_i$ is the predicted value, and n is the number of observations.

3 Results

3.1 Correlation of dendrometric variables to biomass compartments

The aboveground, stem and thin branches plus foliage dry weight biomass compartments for all five species were strongly correlated to dbh and stump diameter (Table 3).

Table 1 Summary of main variables of the sampled trees for the five most dominant species in Chilimo-Gaji forest

Studied variables	*Allophyllus abyssinicus*				*Olea europaea* ssp. *cuspidata*				*Olinia rochetiana*				*Rhus glutinosa*				*Scolopia theifolia*			
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
dbh (cm)	11.3	3.9	6.4	21.3	14.5	5.9	6.3	28.8	14.9	6.68	6.2	27.5	15.6	4.9	9.0	23.5	11.8	4.1	6.4	22.0
db (cm)	13.9	6.2	0.2	27.3	18.2	6.3	9.9	31.9	17.9	8.36	7.6	34.8	18.8	5.0	12.7	27.5	14.6	4.1	8.0	22.9
h (m)	10.6	3.1	7.0	17.0	10.6	2.1	5.9	14.5	12.6	2.92	7.3	19.4	11.3	3.0	6.0	17.4	8.2	1.9	5.6	13.0
hc (m)	6.7	3.4	0.3	13.5	5.8	2.7	0.5	10.7	8.0	3.58	1.0	14.0	6.3	2.3	1.6	11.4	4.6	2.2	1.9	9.5
hb (m)	4.7	2.6	2.0	12.7	4.0	1.5	1.7	7.0	4.7	1.62	2.0	7.4	4.6	1.9	2.2	9.2	13.7	47.4	1.8	215.0
BS (kg)	32.3	35.6	0.0	130.4	84.2	83.5	4.9	302.9	93.5	97.33	0.0	349.9	65.2	50.4	9.0	168.8	36.3	37.2	5.3	129.3
Br27 (kg)	12.1	4.0	4.3	17.4	19.6	11.5	6.0	46.7	26.9	20.42	7.7	89.2	17.2	7.8	5.6	28.3	23.4	14.8	9.8	72.8
Br2 (kg)	7.7	3.5	1.5	13.2	16.7	12.2	1.4	37.9	19.2	14.05	3.0	48.3	8.8	5.7	2.4	22.5	22.6	14.8	6.3	79.1
Crown (kg)	19.8	6.5	5.8	28.3	36.3	22.7	7.4	84.6	46.1	32.19	11.7	129.8	26.0	12.1	8.1	49.6	46.0	28.2	17.8	151.9
Above (kg)	52.1	38.2	11.6	157.6	120.5	103.7	14.3	366.7	139.5	124.1	13.7	451.9	19.2	58.7	17.2	202.4	82.3	52.3	23.0	281.1
n	15	15	15	15	20	20	20	20	20	20	20	20	15	15	15	15	20	20	20	20

SD standard deviation, *dbh* diameter at breast height (1.30 m), *db* diameter at base, *h* total height, *hc* commercial height, *hb* branching height, *BS* biomass of stem, *Br27* biomass of thick branches (diameter between 2 and 7 cm), *Br2* biomass of thin branches (diameter <2 cm) plus foliage, *Crown* (kg) biomass of branches plus foliage, *Above* stem+thick branches (2–7)+thin branches+leaves biomass or stem+crown biomass, *n* number of observations

Similarly, most biomass compartments were also correlated to total height and commercial height. However, the thick branches compartment of *A. abyssinicus* and *R. glutinosa* were non-correlated to dbh and stump diameter and most biomass fractions were not significantly correlated to tree branching height, crown length, or crown diameter. Spearman's correlation results indicated that biomass models could use dbh and total height as independent variables.

3.2 Fitted models

Based on goodness-of-fit statistics and biological behavior, models 1, 2, 5, and 7 (Table 4) were selected for different compartments and species. Due to fitting problems, biomass for the different branch compartments were combined into a crown fraction for *O. rochetiana*, *R. glutinosa*, and *S. theifolia* and one model was fitted for this component. Similarly, the model that treated all compartments together as aboveground biomass provided the best fit for *A. abyssinicus*. The calculated model parameters were statistically significant at the 99 % confidence level ($p<0.001$) (Table 4). All fitted models for stem biomass showed R^2_{adj} values higher than 0.75. Due to high variability, branch or crown models presented lower values, ranging from 0.79 for the thick branches compartment in *O. europaea* to 0.55 for crown biomass in *S. theifolia*. Aboveground biomass models fitted with SUR (except for *A. abyssinicus*) showed high R^2_{adj} values ranging from 0.96 for *O. europaea* to 0.79 for *S. theifolia*.

The selected models were also tested for accuracy based on observed and predicted data. Figure 2 shows how observed and predicted aboveground biomass values are close to the 1:1 line and the simultaneous F test provided no evidence for rejecting the null hypothesis (intercept=0 and slope=1). Thus, bias was not revealed in the fitted models, though model efficiency varied among the species (Table 4).

3.3 Biomass partitioning

Aboveground biomass partitioning of *O. europaea*, *O. rochetiana*, *R. glutinosa*, and *S. theifolia* into stem and crown biomass compartments is summarized in Fig. 3. The biomass proportions were estimated by applying the fitted models to the sample diameter classes and the corresponding estimated total height. *O. europaea* and *O. rochetiana* exhibited similar biomass allocation: the stem compartment accumulated more biomass than the crown fraction (~60–70 %) in all diameter classes. *R. glutinosa* crown fraction accumulated more biomass (53 %) than stem compartment (47 %) in the 10-cm

Table 2 Biomass models evaluated for different tree compartments

Model	Equation	Model	Equation
1	$W=\beta\times(d\times h)$	7	$W=(\beta\times d^2)+(\lambda\times h)$
2	$W=\beta\times(d^2\times h)$	8	$W=(\beta\times d^2)+(\lambda\times h)+(\theta\times d^2\times h)$
3	$W=(\beta\times d)+(\lambda\times d^2)+(\theta\times d^2\times h)$	9	$W=(\beta\times d^2)+\lambda\times(d\times h)$
4	$W=(\beta\times d)+(\lambda\times h)$	10	$W=\beta\times(d^2\times h)+\lambda\times(d\times h)$
5	$W=(\beta\times d^2)+\lambda\times(d^2\times h)$	11	$W=\beta\times(d^\lambda)\times(h^\theta)$
6	$W=\beta\times(d^2\times h)^\lambda$	12	$W=\beta\times d+\lambda\times d^2$

W biomass weight (kg), *d* dbh (cm), *h* tree height (m), β, λ, θ model parameters

diameter class; but stem compartment accumulated more biomass than crown fractions in the 15 and 20 cm diameter classes (61 and 69 %, respectively). The *S. theifolia* crown fraction was always greater than the stem fraction for all sampled diameter classes.

4 Discussion

The biomass models for these tropical dry forest species are valuable tools for policymakers and stakeholders, mainly in assisting forest managers in the necessary estimation of

Table 3 Spearman correlation coefficients between biomass compartments and dendrometric variables for the studied species

Species	Biomass comparments	Dendrometric variables						
		h	hc	hb	dbh	db	cd	cl
Allophyllus abyssinicus	Stem	0.72**	0.96***	0.32	0.85***	0.82***	0.13	0.46
	Thick branches	0.20	0.02	0.01	0.22	0.25	0.05	−0.08
	Thin branches+leaves	0.64*	0.58*	0.38	0.65**	0.64*	0.10	0.29
	Crown	0.48	0.36	0.19	0.54*	0.48	0.11	0.15
	Above	0.86***	0.93***	0.24	0.91***	0.89***	0.07	0.50
Olea europaea ssp. *cuspidata*	Stem	0.71***	0.81***	0.09	0.95***	0.89***	0.67**	0.48*
	Thick branches	0.70**	0.86***	0.08	0.89***	0.84***	0.81***	0.39
	Thin branches+leaves	0.54*	0.76***	−0.11	0.92***	0.88***	0.51*	0.36
	Crown	0.62**	0.84***	−0.02	0.95***	0.91***	0.67**	0.39
	Above	0.68**	0.85***	0.05	0.96***	0.93***	0.68*	0.48*
Olinia rochetiana	Stem	0.84***	0.87***	0.36	0.92***	0.93***	0.75***	0.69**
	Thick branches	0.69**	0.57**	0.41	0.76**	0.83***	0.64**	0.64**
	Thin branches+leaves	0.67***	0.56**	0.29	0.82***	0.82***	0.55*	0.62**
	Crown	0.69**	0.57**	0.37	0.83***	0.87***	0.62**	0.82***
	Above	0.83***	0.83***	0.40	0.94***	0.95***	0.74***	0.68**
Rhus glutinosa	Stem	0.49	0.88***	0.19	0.98***	0.94***	0.44	0.69**
	Thick branches	0.63*	0.36	−0.38	0.41	0.44	0.58*	0.59*
	Thin branches+leaves	0.61*	0.59*	0.04	0.68*	0.68*	0.14	0.73**
	Crown	0.61*	0.52	−0.26	0.68*	0.71**	0.47	0.73**
	Above	0.63*	0.83***	0.10	0.92***	0.89**	0.46	0.74**
Scolopia theifolia	Stem	0.90***	0.89***	0.14	0.92***	0.88***	0.34	0.48*
	Thick branches	0.79***	0.81**	0.02	0.73***	0.71**	0.35	0.47*
	Thin branches+leaves	0.49*	0.53*	0.17	0.70***	0.70**	0.33	0.39
	Crown	0.76***	0.81***	0.05	0.85***	0.88***	0.40	0.48*
	Above	0.87***	0.90***	0.16	0.89***	0.83***	0.41	0.53*

Thick branches: biomass of branches with diameter between 2 and 7 cm; thin branches+leaves: biomass of branches with diameter lower than 2 cm, including leaves biomass; crown: thick branches+thin branches+leaves biomass; above: stem+thick branches+thin branches+leaves biomass or stem+crown biomass

hc commercial height, *hb* branching height, *h* total height, *dbh* diameter at breast height, *db* stump diameter, *cd* crown diameter, *cl* crown length

*$p\leq0.05$; **$p\leq0.01$; ***$p\leq0.001$

Table 4 Simultaneous fit of biomass models for the studied species

Species	Compartment	MRES	RMSE	R^2_{adj}	Selected model	Estimated parameters	Pr>|*t*|
Allophyllus abyssinicus	Above	0.01	10.27	0.84	$W_{\text{above}} = \beta \times (d \times h)$	0.3937	<.0001
Olea europaea ssp. *cuspidata*	Stem	0.72	12.01	0.93	$W_{\text{stem}} = \beta \times (d^2 \times h)$	0.02746	<0.0001
	Br27	−0.53	4.47	0.79	$W_{\text{Br27}} = (\beta \times d^2) + (\lambda \times h)$	0.05744	<.0001
						0.6856	0.0008
	Br2	0.09	5.29	0.69	$W_{\text{Br2}} = \beta \times (d^2 \times h)$	0.006584	<.0001
	Above	0.27	12.03	0.96	$W_{\text{above}} = \sum W_i$		
Olinia rochetiana	Stem	0.25	35.06	0.76	$W_{\text{stem}} = \beta \times (d \times h)$	0.3990	<.0001
	Crown	1.31	14.41	0.58	$W_{\text{crown}} = (\beta \times d^2) + \lambda \times (d^2 \times h)$	0.4550	<.0001
						−0.02163	<.0001
	Above	1.56	33.38	0.85	$W_{\text{above}} = \sum W_i$		
Rhus glutinosa	Stem	3.34	10.57	0.79	$W_{\text{stem}} = \beta \times (d^2 \times h)$	0.01604	<.0001
	Crown	−1.24	6.28	0.68	$W_{\text{crown}} = (\beta \times d^2) + (\lambda \times h)$	0.04867	0.0017
						1.3033	<.0001
	Above	2.11	11.11	0.88	$W_{\text{above}} = \sum W_i$		
Scolopia theifolia	Stem	1.52	6.94	0.75	$W_{\text{stem}} = \beta \times (d^2 \times h)$	0.02107	<.0001
	Crown	0.65	7.67	0.55	$W_{\text{crown}} = \beta \times (d \times h)$	0.4253	<.0001
	Above	2.17	11.04	0.79	$W_{\text{above}} = \sum W_i$		

Stem (kg) stem biomass, *Br27* (kg) biomass of thick branches (diameter between 2 and 7 cm), *Br2* (kg) biomass of thin branches (diameter<2 cm) plus foliage, *Crown* (kg) biomass of branches plus foliage, *Above* (kg) stem+thick branches (2–7)+thin branches+leaves biomass or stem+crown biomass, W_i (kg) biomass weight of the different compartments, d dbh (cm), h tree height (m), β, λ parameters of the models, *MRES* mean residual (kg), *RMSE* root mean square error (kg), R^2_{adj} adjusted coefficient of determination

fuelwood or carbon stocks for sustainable management. The models developed in this study included *dbh* and total height as independent variables in all the biomass compartments (Table 4). Goodman et al. (2014) showed the importance of included crown variables to improve tropical biomass estimations. Nevertheless, correlations of crown variables with biomass were not high (Table 3) (with some exceptions) perhaps due to the lack of large trees in our dataset. Although commercial height showed a high correlation with biomass weight, accurate measurement of this variable in the field is very difficult (Segura and Kanninen 2005). For this reason, total height was selected as independent variable, together with dbh. Combining these independent variables provided better fit results and estimation values than the use of dbh alone, as several authors have advocated (e.g., Henry et al. 2011; Feldpausch et al. 2012). Total height could include information about competition or fertility of the site and may yield less-biased estimates. Though accurate measurement of total height may be challenging, Chave et al. (2005) observed a standard error reduction from 19.5 % when total height was not available to 12.5 % when total height was available, across all tropical forests types. The independent variables of the models developed here can be easily measured in the field or are commonly recorded in forest inventories, facilitating practical, timely, and virtually effortless application of these and similar models (Ketterings et al. 2001).

Equations were developed for each biomass compartment according to species (Table 4). Models were developed for all biomass compartments of *O. europaea*, but only an aboveground biomass equation could be developed for *A. abyssinicus*, possibly due to the low crown and foliage biomass weight of this species. For the other studied species (*O. rochetiana*, *S. theifolia*, and *R. glutinosa*), stem and crown biomass compartment models were developed. Combining thick branches and thin branches with leaves into a crown biomass compartment resulted in better fitting efficiency and accuracy than individual models for each compartment. The lower prediction potential of the branch and foliage biomass models over the stem model has been confirmed in other studies (e.g., Návar 2009; Ruiz-Peinado et al. 2011; Negash et al. 2013). Cole and Ewel (2006) argue that weather, herbivores, and inter-plant competition can affect the crown biomass compartment. In mixed forests, inter-specific competition due to the competition process itself or to facilitation could strongly influence crown geometry (Menalled et al. 1998; Dieler and Pretzsch 2013), resulting in high crown biomass heterogeneity. Moreover, although Chilimo-Gaji is a protected forest, pressure from local people pruning trees for firewood might also modify crown growth and biomass weight (Smektala et al. (2002), cited in Henry et al. (2010)).

All the estimator parameters for the biomass models showed positive coefficient values for all species and biomass

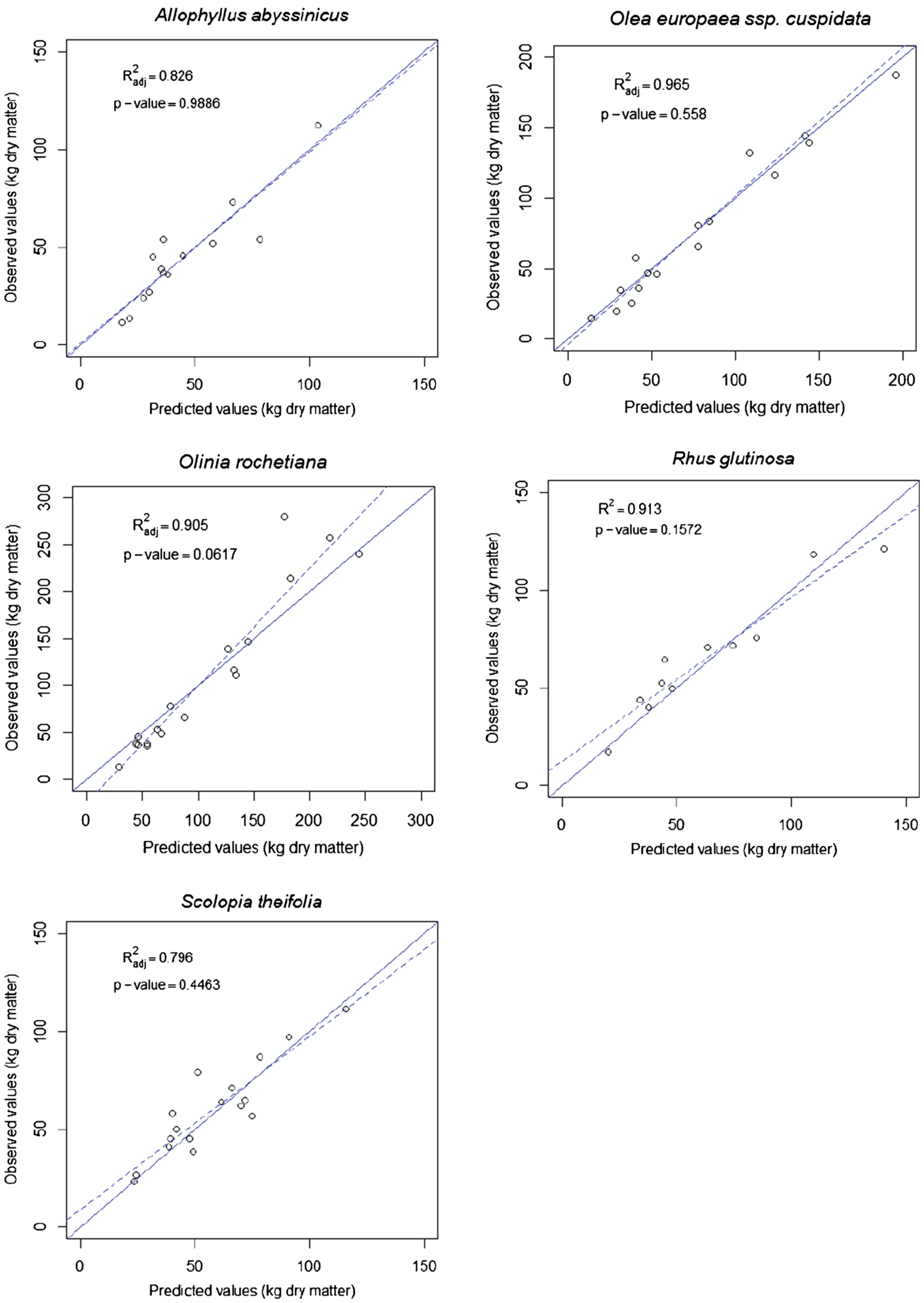
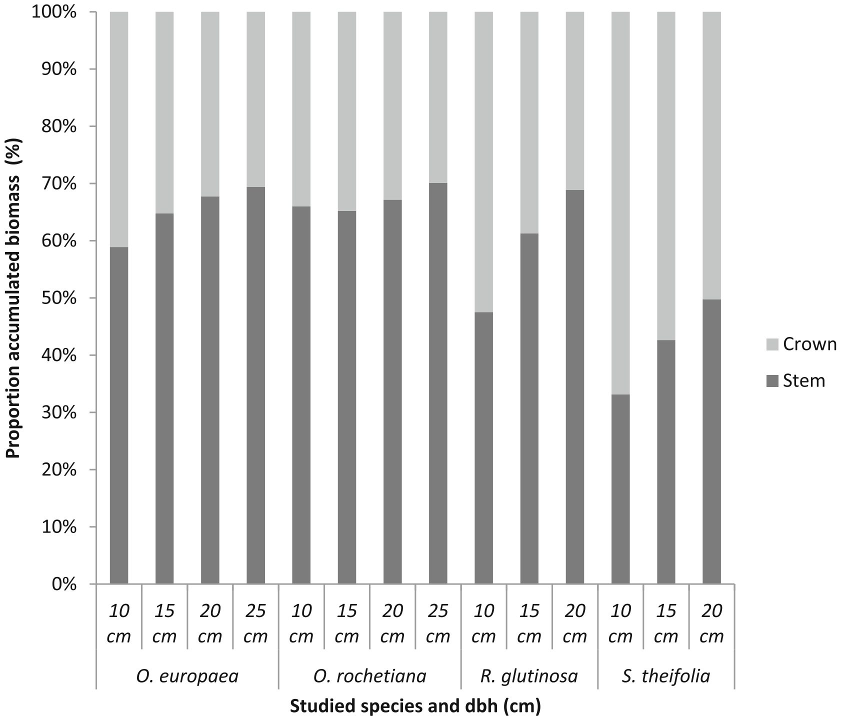


Fig. 2 Observed against predicted aboveground biomass values for the studied species. The *dashed line* is showing the adjusted line to the residuals, and the *continuous line* the 1:1 line

compartments, except one parameter for crown biomass in *O. rochetiana* involving the combination of square diameter and total height (d^2h) as an independent variable. This may indicate that taller trees allocate less biomass to the crown due to light competition processes for this species (the same tendency was found in *Pinus sylvestris* L. by Vanninen and Mäkelä 2000).

Although some authors have proposed the use of existing generalized equations to estimate aboveground biomass in African tropical forests (e.g., Brown et al. 1989; Brown and Lugo 1992; Chave et al. 2005), others report that generalized models are unsuitable for African tropical forests (e.g., Henry et al. 2010; Ngomanda et al. 2014). So, the use of species-specific and site-specific equations are encouraged (Cairns et al. 2003; Henry et al. 2011). Such equations reflect the great variability in tree architecture and wood gravity among and within species (Henry et al. 2011; Litton and Kauffman 2008), making it possible to more accurately quantify harvestable

Fig. 3 Biomass partitioning for the mean tree for the studied species and different diameter classes



biomass for fuelwood and other purposes. Comparison of generalized models (Brown et al. 1989; Brown 1997; Brown and Lugo 1992; Chave et al. 2005; Chave et al. 2014) to the fitted models for the species studied (Table 5) showed that accuracy varied according to species. All generalized models tested showed a high bias and that rendered them inappropriate for biomass estimation of *S. theifolia* (*p* value <0.0001). Similarly, Brown et al. (1989) and Brown (1997) models were unsuitable for four of the species studied (*p* value >0.05 on the *t* test only for *R. glutinosa*) having high average deviation values. Brown et al. (1989) model has already been described as unsuitable for tropical African species by Vieilledent et al. (2012) for a dry forest and Ngomanda et al. (2014) for a moist forest. Brown and Lugo (1992) model was applicable for three species (*A. abyssinicus*, *O. rochetiana*, and *R. glutinosa*), but showed poor statistics for the latter species. Chave et al. (2005) model proved unsatisfactory for two of the species studied (*R. glutinosa* and *S. theifolia*), but showed acceptable statistics for the other three species. This model was described as accurate for tropical species by Djomo et al. (2010) and Fayolle et al. (2013) in African moist forests and Vieilledent et al. (2012) in an African dry forest. Finally, Chave et al. (2014) model was unexpectedly unsuitable for the same two species as the 2005 model (*R. glutinosa* and *S. theifolia*) and also for *O. europaea*, although this model was developed with an ample dataset including trees in larger diameter ranges from tropical areas in America and Asia, including a new dataset of trees collected in Africa. In light of these results and the high species heterogeneity in tropical dry forests, the generalized models should be used judiciously and with full awareness of the potential for error in the estimations (Table 5).

In recent years, several site-specific models have been developed for tropical species in general. Although the number of site-specific models for sub-Saharan species in particular has been increasing in the last years (e.g., review by Henry et al. 2011; Mugasha et al. 2013; Mate et al. 2014), if possible, more site-specific models should be developed in order to obtain non-biased biomass (fuelwood or timber) or carbon estimates for REDD+ projects. So, estimations of carbon sequestration potential for Ethiopian afro-montane forests (Mokria et al. 2015) could improve accuracy using the developed biomass models.

Stem biomass proportions in *O. europaea* (58 % in the 10-cm- and 68 % in the 25-cm-diameter class) and *O. rochetiana* (66 % in the 10-cm- and 68 % in the 25-cm-diameter class) showed little increments across the sampled diameter classes (Fig. 3). For *R. glutinosa* (47 % in the 10-cm- and 69 % in the 20-cm-diameter class) and *S. theifolia* (33 % in the 10-cm- and 49 % in the 20-cm-diameter class), the stem compartment exhibited rapid growth along diameter. The crown biomass fraction of *S. theifolia* was generally greater than the stem compartment in the sampled trees. This might be due to the large, umbrella-shaped crown of this species, which tends to result in a greater proportion of biomass in the branches than in the stem. Tropical species vary greatly in leaf morphology and crown structure, leading to differences in biomass allocation among species (Poorter et al. 2006). Our findings for

Table 5 Comparison of models for aboveground biomass estimation (site-specific and generalized equations)

Species	Model reference	Relative bias (%)	Average deviation (%)	Relative RMSE	*t* test	
					t statistic	*p* value
Allophyllus abyssinicus	This study	−7.41	21.09	0.280	0.0040	0.9969
Generalized	Brown et al. (1989)	36.14	38.95	0.416	4.4287	0.0006
Generalized	Brown and Lugo (1992)	−2.58	23.36	0.342	−0.8096	0.4327
Generalized	Brown (1997)	18.45	25.31	0.287	24.4615	0.0286
Generalized	Chave et al. (2005)	−4.50	19.97	0.298	−0.8262	0.4236
Generalized	Chave et al. (2014)	7.21	23.38	0.303	0.1729	0.8654
Olea europaea	This study	−5.29	14.32	0.204	0.0955	0.9251
Generalized	Brown et al. (1989)	40.81	43.21	0.445	6.2926	<0.0001
Generalized	Brown and Lugo (1992)	15.12	18.41	0.216	4.0902	0.0008
Generalized	Brown (1997)	28.41	30.12	0.331	5.0996	0.0001
Generalized	Chave et al. (2005)	1.54	14.16	0.188	0.7807	0.4464
Generalized	Chave et al. (2014)	6.96	14.00	0.180	2.4653	0.0254
Olinia rochetiana	This study	−19.43	29.18	0.408	0.2015	0.8427
Generalized	Brown et al. (1989)	44.16	46.50	0.497	4.2731	0.0005
Generalized	Brown and Lugo (1992)	9.46	22.23	0.303	−0.2241	0.8253
Generalized	Brown (1997)	35.11	36.90	0.398	3.8545	0.0013
Generalized	Chave et al. (2005)	5.27	17.30	0.243	−0.1119	0.9122
Generalized	Chave et al. (2014)	12.09	21.84	0.287	0.2137	0.8333
Rhus glutinosa	This study	4.17	13.32	0.156	0.6595	0.5244
Generalized	Brown et al. (1989)	13.07	32.05	0.374	0.4016	0.6965
Generalized	Brown and Lugo (1992)	−22.89	29.77	0.390	−2.126	0.0593
Generalized	Brown (1997)	−4.19	31.22	0.340	−0.7757	0.4559
Generalized	Chave et al. (2005)	−44.03	44.03	0.532	−3.0834	0.0116
Generalized	Chave et al. (2014)	−34.32	37.04	0.472	−2.5783	0.0275
Scolopia theifolia	This study	2.43	13.59	0.168	0.4193	0.8290
Generalized	Brown et al. (1989)	55.45	58.71	0.582	10.1593	<0.0001
Generalized	Brown and Lugo (1992)	40.91	43.31	0.444	9.2180	<0.0001
Generalized	Brown (1997)	42.49	44.99	0.458	8.5675	<0.0001
Generalized	Chave et al. (2005)	36.78	38.94	0.401	8.4323	<0.0001
Generalized	Chave et al. (2014)	43.88	46.46	0.470	9.7447	<0.0001

biomass partitioning align with results of Mate et al. (2014) for three tropical species (of greater diameter than those sampled in this study): mean biomass partitioning values ranged between 46 and 77 % for stems and from 23 to 54 % for crowns. Henry et al. (2010) also reported mean figures indicating higher biomass accumulation in the stem (69 %) than in the crown compartment (28 %) for 16 tropical rainforest species in Africa. Likewise, these authors found that stem biomass proportion tended to decrease and crown biomass proportion increase with increasing tree size (from trees with diameter larger than 20 to 100 cm). The latter was not corroborated for the species we examined, where the stem percentage is increased with tree size for the sampled diameter range (up to the maximum sampled dbh which ranged between 21 and 29 cm according to the species).

5 Conclusion

Models developed in this study for five of the most important species of an Ethiopian dry mixed forest are using tree diameter and total height as independent variables to estimate biomass for different tree compartments. Crown biomass models were fitted for three of the five species studied (*O. rochetiana*, *R. glutinosa*, and *S. theifolia*) due to high variability in branch biomass compartments resulting from inter-specific competition in the mixed tropical forest. Similarly, an aboveground model was developed for *A. abyssinicus* based on its biomass heterogeneity and small crown biomass weight. These models were developed for trees in a fairly small diameter range (maximum sampled dbh, 28.8 cm; maximum sampled height, 19.4 m), and their use outside this range could be biased.

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

The biomass models developed here and information about biomass distribution patterns for these species could help in sustainable management of fuelwood harvesting. Sustainable fuelwood harvesting might help to develop local fuelwood markets having an important, positive socioeconomic and ecological impact. Moreover, this might lead to a deforestation reduction and avoiding degradation due to firewood collector preferences for deadwood, combined with identification of low competition sites and recognized access rights (Hiemstra-van der Horst and Hovorka 2009).

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