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Nondestructive Allometric Model to Estimate Aboveground Biomass: An Alternative Approach to Generic Pan-Tropical Models

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ABSTRACT

Biomass and carbon stock analysis and estimations are performed with the use of mathematical allometric models. Developing countries in Sub-Sharan Africa such as Ethiopia lack the expensive resources to develop such costly models destructively. As a result, they are left with the only option to adopt models formulated from unrelated geographic areas which usually bears error in estimation. This study estimates the biomass of indigenous trees and develop allometric model for the Egdu Forest located Oromia region, Ethiopia. Nondestructive sampling is used to collect samples where Diameter at Breast Height (DBH), local wood density (ρ), and Tree Height (H) are the estimator variable for total dry Above Ground Biomass (AGB). Trees are selected based on DBH variability on the study site and located in a delineated area of quadrat plot. A set of species-specific models to relate AGB to estimator variables are fitted to the data. The allometric equation that fit the linear models has a significant p-value ($p<0.000$). Model comparison and selection are based on the Akaike Information Criterion (AIC), adjusted coefficient of determination (R^2) and Residual Standard Error (RSE) of the regression. Comparison of our results with those obtained using generalized pan-tropical model revealed differences in biomass estimations. The developed equations can be used for greater accuracy by researchers, forest managers and/or organization like REDD+ to calculate aboveground biomass and carbon stock of the studied species in Ethiopia.

Keywords: Allometric model, Biomass, Species-specific, Egdu Forest, Nondestructive

INTRODUCTION

Accurate estimation of biomass in tropical forests are lacking in many areas due to a lack of appropriate allometric models developed destructively for predicting biomass in species-rich tropical ecosystems, making estimations of the value of these species as carbon reservoir difficult [1]. This results in enormous uncertainty in the amount and spatial variations of aboveground biomass in Africa [2]. In addition, the use of generalized biomass equations across a wider unrelated ecological location can lead to a bias and error in estimating biomass for a particular species and sites because species vary in wood specific gravity, tree sizes, and growth stage, and their accuracy is limited to the developed geographic areas [3-4].

Moreover, applying direct destructive techniques for biomass estimation and develop allometric models are time-consuming, demand specialized labor and are very expensive [5]. In most cases such destructive studies are restricted to small trees for cost reasons and harvesting trees requires special authorization which is habitually difficult to acquire, and consequently only a few valid equations are available [6]. Generic equations ignore key innate differences arising from species diversity and variation in species parameters such as local wood density as a main ecological trait [7]. In addition, researchers argue that before pan-tropical allometric equations are used their validity within a particular geographic location needs to be tested [8-9].

Conversely, the use of locally developed equations permits estimation of total aboveground biomass of a specific tree species as a composite of biomass components such as trunks, large branches, small branches, etc. [10-11]. Species-specific allometric equations estimate biomass based on locally measured tree variables such as height, diameter, wood density, and crown, etc. Advantage of such equations are explicit to species, sites, tree age and management and possess higher levels of accuracy and are becoming preferred means of biomass estimation in temperate and some tropical regions [12-14]. This particular research estimated the biomass and developed a set of species specific allometric equations nondestructively and evaluated the biomass data against existing generic pan-tropical equation**.**

MATERIALS AND METHODS

Study site

The study was conducted in Welmera District, Oromia regional state, central highlands of Ethiopia in a forest at about 30 km west of Addis Ababa and 5 km from Menagasha town to the south. Egdu Forest is one of the dry afromontane forests in central Ethiopia and ranges from 2,580 m to 2,910 m above sea level. The forest covers a total area of 486 ha [15]. The forest has a mean annual temperature of 17.1ºC and mean annual rainfall of 1314 mm EMSA. The dominant species in the study area are *Bersama abyssinica* Fresen*, Cupressus lusitanica* Mill*, Maytenus arbutifolia* Sebsebe*, Rhamnus staddo* A.Rich, were chosen for the study.

Sampling method

Preferential sampling was adopted because geographic location and the process being modeled are stochastically dependent [16]. After plots were established at the study site, preferential sampling was applied by starting a rapid screening of DBH class variability in the landscape, thereby delimiting the vegetation and DBH classes, which is considered an informal way of stratifying the population [17].

Tree selection

Forty trees were used for the study. Sampling error were minimized by grouping plants into DBH classes (2 cm-10 cm, 15 cm-20 cm, 21 cm-30 cm and 31 cm-50 cm). Trees were placed in the immediate delineated quadrat plot of 20 × 20 m and all individuals DBH classes were measured with a caliper.

Statistical analysis

Data were analyzed using one-way Analysis of Variance (ANOVA) with a confidence level of 0.05 to test the statistical significance. R-software, version 3.2.2 (R Foundation for Statistical Computing, Vienna, Austria) was used for all analyses and ggplot2 package was used for graphing.

Before the equations were established, scatter plots were used to see whether the relationship between independent and dependent variables was linear. Furthermore, several allometric relationships were tested. The independent variables included DBH, height, and local wood density, whereas the dependent variable was the Total dry Above Ground Biomass of the study species (TAGB). Because the data exhibited heteroscedasticity, we used a linear regression analysis.

Model comparison and selection were based on adjusted coefficients of determination, residual standard error, and the penalized likelihood criterion AIC [18]. The expression of AIC as a criterion for model selection was AIC=2ln L+2p, where L is the likelihood of the fited model and p is the total number of parameters in the model.

Nondestructive biomass measurement

Fresh biomass was divided into two parts for measurements: Trimmed fresh biomass and Untrimmed fresh biomass. Tree architectures were divided into different architectural elements for ease of analysis, as trimmed branches, untrimmed small branches, untrimmed large branches and trunks for measurement and analysis (Figure 1). Trunks and large branches were not trimmed only small branches were removed. Fresh biomass of small untrimmed branches was calculated from their basal circumference and a biomass table.

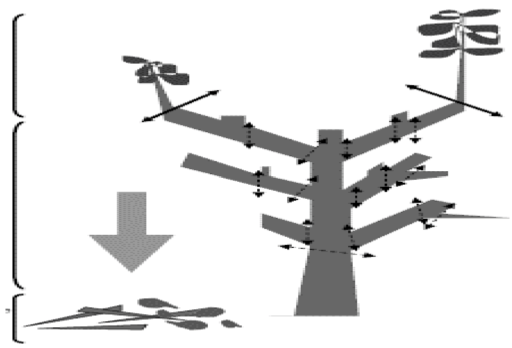

Figure 1: Determination of total fresh biomass, separation and measurement of trimmed and untrimmed biomass

Fresh biomass of large untrimmed branches and trunk calculated from volume and density measurements. Tree sections cuts were considered to be cylindrical, and density was considered to be the identical in all compartments of the tree. Fresh biomass of the trimmed branches was weighed in the field.

Trimmed fresh biomass measurement

Two secondary branches per plant were removed. Trunk mass was estimated from serial measurements of height, diameter and section volume using a parabolic estimation of trunk shape; these estimates were then used to develop whole-tree allometric equation. The diameter at the base of each branch to be trimmed was measured using a caliper, then branches were trimmed in compliance with local practices using a machete. Then the leaves were separated from the trimmed branches. Fresh leaves (B) and wood from the trimmed branches (BTFW) were weighed separately in the field. Random subsamples of the leaves from the trimmed branches were then weighed (BsubFL, in g). Similarly, an aliquot of the wood at random from the trimmed branches were taken without debarking and measured for its fresh mass (BsubFL, in g) in the field, immediately after cutting (Equations 1-4).

Untrimmed fresh biomass

Untrimmed biomass was measured indirectly. The different branches in the trimmed tree were numbered first. The small untrimmed branches were processed differently from the large branches and the trunk. For the small branches, only basal diameter was measured with caliper. Fresh biomass of small untrimmed branches was calculated from their basal diameter and a model developed from the trimmed branches biomass and their basal diameter (Equations 5-9).

The biomass of the trunk and large branches was estimated from measurements of trunk and large branches volume (V_i in cm^3) and mean wood density (ρ in g cm^{-3}). The volume V_i of each section [i] was obtained by measuring its diameter and its length. Sections about 1 m long were preferred to consider diameter variations along the length of the trunk and large branches (Equation 6). Wood specific gravity/density was defined as the oven-dried mass of wood sample (101ºC-105ºC) divided by the green volume of the sample, which is an important predictor of ABG [19]. The green volume of the sample was measured in the field by water displacement and the value of oven-dried wood mass was used to determine mean wood density or wood specific gravity.

Calculations

The dry biomass of the tree was obtained as a sum of the trimmed dry biomass and the untrimmed dry biomass [20]:

$$B_{dry} = B_{trimmed\ dry} + B_{untrimmed\ dry} \quad (1)$$

Calculating trimmed biomass

From the fresh biomass B of the fresh wood subsample and the dry biomass B subsample of the dry wood, calculated as above, the moisture content of the wood including bark was calculated as: [20]

$$X_{wood} = B_{dry\ wood\ subsample} / B_{fresh\ \ wood\ sub\ sample} \quad (2)$$

Similarly, the moisture content of the leaves of the fresh biomass B of the subsample was obtained from the fresh leaf of the leaf subsample and its dry biomass B of the subsample of dry leaf was calculated as:

$$B_{trimmed\ dry\ wood} = B_{trimmed\ \ fresh\ wood} X_{wood} + B_{trimmed\ fresh\ leaf} X_{leaf} \quad (3)$$

Trimmed dry biomass was then calculated as:

$$B_{trimmed\ dry\ wood} = B_{trimmed\ \ fresh\ wood} X_{wood} + B_{trimmed\ fresh\ leaf} X_{leaf} \quad (4)$$

where $B_{trimmed\ fresh\ leaf}$ is the fresh biomass of the leaves stripped from the trimmed branches and $B_{trimmed\ fresh\ wood}$ is the fresh biomass of the wood in the trimmed branches.

Calculating untrimmed biomass

Two calculations were required to calculate the dry biomass of the untrimmed part (i.e. that is still standing): One for the small branches, the other for the large branches and the trunk. The untrimmed biomass was the sum of the two results [20].

$$B_{untrimmed\ dry} = B_{untrimmed\ dry\ branch} + B_{dry\ section} \quad (5)$$

According to a previously published method each section [i] of the trunk and the large branches may be treated as a cylinder to calculate volume using Smalian's formula:

$$V_i = \pi / 8\ Li(D^2_{1i} + D^2_{2i}) \quad (6)$$

where V_i is the volume of the section, L_i its length, and D_{1i} and D_{2i} are the diameters of the two extremities of section [i].

The dry biomass of the large branches and trunk is the product of mean wood density and total volume of the large branches and trunk:

$$B_{dry\ section} = \overline{\rho}\ \sum i\ Vi \quad (7)$$

where mean wood density is calculated as:

$$\rho = B_{\text{dry wood subsample}} / V_{\text{fresh wood subsample}} \quad (8)$$

The dry biomass of the untrimmed small branches was calculated using a model between dry biomass and basal diameter. This model was established by following the same procedure as for the development of an allometric model. Linear type equations are often used:

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

Using a model of this type, the dry biomass of the untrimmed branches is:

$$B_{\text{untrimmed dry branch}} = \sum_J (a + D_J) \quad (10)$$

where the sum was all the untrimmed small branches and D_J is the basal diameter of the branch J and a and b are model parameters (intercept and slope, respectively).

Estimation of belowground biomass

Belowground biomass estimation is much more difficult and time-consuming than estimating aboveground biomass [21]. The standard method is estimating belowground biomass (B_{GB}) as 20% of aboveground tree biomass (A_{GB}) [22]:

$$B_{GB} = 0.2A_{GB} \quad (11)$$

RESULT AND DISCUSSION

Local wood specific gravity is one of the principal estimators of A_{GB}, particularly when a broad range of vegetation type is considered. Most researchers have developed allometric equations through wood density/wood specific gravity as representative factor for the studied species [1, 4].

Here, we analyzed the branches from the trimmed section to obtain a local mean wood density for the study species (0.3584 g/cm^3 for *Bersama abyssinica*, 0.5313 g/cm^3 for *Cupressus lusitanica*, 0.4437 g/cm^3 for *Maytenus arbutifolia* and 0.4382 g/cm^3 for *Rhamnus staddo* (Figure 2). These values are then used to develop the multiple regression models for each species.

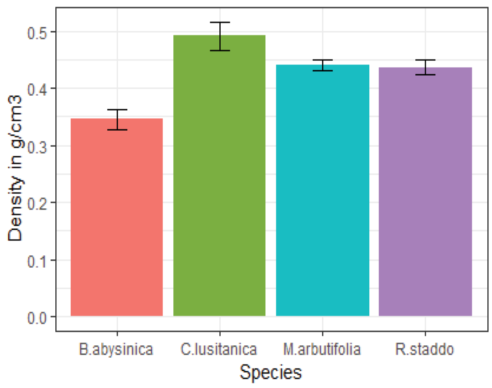

Figure 2: Locally developed mean wood density

All estimates of fresh and dry biomass and oven dried moisture content (X) of each tree component of *Bersama abyssinica, Cupressus lusitanica, Maytenus arbutifolia, and Rhamnus staddo* are given in Table 1.

Table 1: Biomass and moisture content (*X*) for tree components of study species.

Tree component	N	Maximum	Minimum	Range	Total	Mean
Bersama abyssinica						
Fresh wood mass (mg)	8	2100	500	1600	12,700	1587.5
Dry wood mass (mg)	8	979.09	233.12	745.97	5921.19	740.15
X wood	8	0.563	0.209	0.354	4.58	0.572
Fresh leaf mass (mg)	8	800	200	500	4500	562.5
Oven dry leaf mass (mg)	8	272.79	68.19	204.6	1534.45	191.81
X leaf	8	0.638	0.242	0.396	4.092	0.511
Trimmed dry biomass (mg)	8	1251.89	318.37	933.52	7455.64	931.95
Cupressus lusitanica						

Fresh wood mass (mg)	12	3500	1300	2200	28700	1700
Oven dry wood mass (mg)	12	1744.05	724.66	1019.36	13497.5	2052.79
X wood	12	0.657	0.329	0.327	5.7546	0.479
Fresh leaf mass (mg)	12	3000	900	2100	28700	2391.67
Oven dry leaf mass (mg)	12	1560.9	355.6	1205.3	9200.55	766.71
X leaf	12	0.6331	0.254	0.3791	5.411	0.45
Trimmed dry biomass (mg)	12	2965.45	1130.04	1835.41	22698.05	3299.44
Maytenus arbutifolia						
Fresh wood mass (mg)	12	1900	600	1300	12400	1033.33
Oven dry wood mass (mg)	12	1000	315.82	684.18	6526.94	543.92
X wood	12	0.686	0.222	0.464	6.15	0.513
Fresh leaf mass (mg)	12	600	200	400	4650	387.5
Oven dry leaf mass (mg)	12	216.6	72.2	144.4	1678.65	139.89
X leaf	12	0.63	0.223	0.407	4.132	0.344
Trimmed dry biomass (mg)	12	1216.69	388.02	828.67	8205.59	683.79
Rhamnus staddo						
Fresh wood mass (mg)	8	1000	400	600	5800	725
Oven dry wood mass (mg)	8	537.96	215.18	322.78	3120.77	390.02
X wood	8	0.698	0.357	0.341	4.22	0.528
Fresh leaf mass (mg)	8	400	100	300	1800	454.98
Oven dry leaf mass (mg)	8	115.49	28.87	86.62	519.74	64.96
X leaf	8	0.408	0.222	0.186	2.309	0.289
Trimmed dry biomass (mg)	8	653.45	272.93	380.52	3639.88	454.98

Samples of *Maytenus arbutifolia* had the highest trimmed fresh biomass while the other three species exhibit similar values (Figure 3). Wood and leaf samples were separated and oven dried to constant weight to calculate the moisture content of each species (Figure 4).

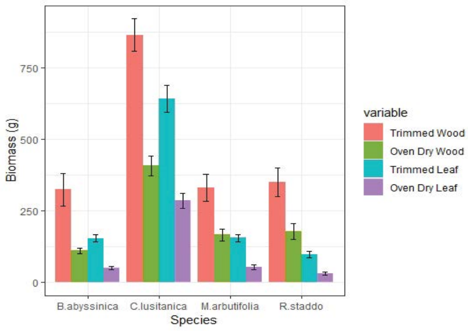

Figure 3: Trimmed and oven dried biomass for wood and leaf samples

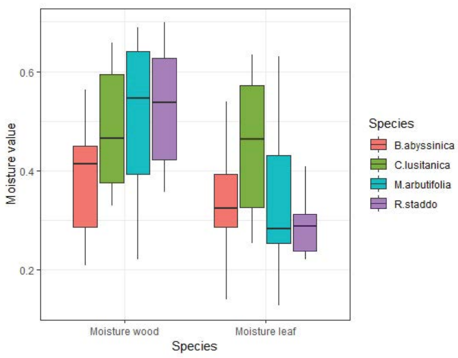

Figure 4: Moisture content per wood and leaf of species.

After computing the dry section, dry branch, untrimmed biomass and trimmed biomass, the total biomass was determined

(A_{GB}+B_{GB}). Aboveground biomass is the sum of all biomass components i.e. trimmed, untrimmed and small branches. Developed models for untrimmed small branches had the following statistical results, the p-value of Model-1 for *Bersama abyssinica* relating the basal diameter and trimmed dry biomass was 0.00294 for the predictor variable, basal diameter, indicating a strong statistically significant correlation between basal diameter and trimmed dry biomass at 95% confidence interval (Table 2). The accuracy of Model-1, given by R^2 (0.7038), shows that 70.21% of the variation of the output variable, trimmed dry biomass, is explained by variation of the input variable, basal diameter. The R2 for Model-2 for *Cupressus lusitanica* is 0.6039 (p=0.00294).

Table 2: Allometric equations for untrimmed small branches for each studied tree species

Species	Intercept	Slope	R^2	p-value
Bersama abyssinica (Model-1)	338.4	504.9	0.6039	0.00294
Cupressus lusitanica (Model-2)	179.9	654.1	0.7021	0.00294
Maytenus arbutifolia (Model-3)	359.13	126.49	0.6087	0.00276
Rhamnus staddo (Model-4)	66.65	204.63	0.6278	0.019

The R^2 for *Maytenus arbutifolia* was 0.6087 (p=0.002756) and 0.6278 for *Rhamnus staddo* (p=0.001904). As estimated by the linear regression model, the A_{GB} based on the basal diameter of the small untrimmed branches measured in the field was 559.22 kg for *Cupressus lusitanica* (mean 46.60 kg, range 72.15 kg). For *Bersama abyssinica*, total A_{GB} was 35.19 kg (mean 2.93 kg, range 3.980 kg) and likewise, *Maytenus arbutifolia*, total A_{GB} was 45.05 kg (mean 3.76 kg, range 3.39 kg) and 16.45 kg for *Rhamnus staddo* (mean 2.07 kg, range 2.02 kg).

Untrimmed biomass

Dry biomass of large branches and trunks ($B_{\text{dry section}}$)

Calculated estimates for the untrimmed biomass components for trees of *Bersama abyssinica, Cupressus lusitanica, Maytenus arbutifolia* and *Rhamnus staddo* are given in (Table.2).

After computing the dry section, dry branch, untrimmed biomass and trimmed biomass (Table 3), the total biomass was determined as a sum of aboveground and belowground biomass.

Table 3: Untrimmed biomass components (kg) for each tree species.

Tree biomass component	N	Maximum	Minimum	Range	Total	Mean
Bersama abyssinica						
Dry section (kg)	8	6.07	0.452	5.62	32.56	4.07
Dry branch (kg)	8	4.95	0.97	3.98	35.19	4.39
Untrimmed biomass (kg)	8	7.4	2.97	4.43	67.75	8.47
Cupressus lusitanica						
Dry section (kg)	12	608.06	49.94	558.12	3292.31	274.36
Dry branch (kg)	12	89.81	17.66	72.15	559.22	46.6
Untrimmed biomass (kg)	12	680.61	76.84	603.78	3851.53	320.96
Maytenus arbutifolia						
Dry section (kg)	12	27.23	0.805	26.43	118.02	9.84
Dry branch (kg)	12	5.65	2.26	3.39	45.05	3.76
Untrimmed biomass (kg)	12	32.87	3.06	29.81	163.08	13.59
Rhamnus staddo						
Dry section (kg)	8	22.04	0.45	21.59	64.96	8.12
Dry branch (kg)	8	3.29	1.27	2.02	16.45	2.07
Untrimmed biomass (kg)	8	23.84	1.71	22.13	81.41	10.18

Aboveground biomass is the sum of all biomass components, below ground biomass was obtained as estimate from aboveground biomass using a relationship (Table 4).

Table 4: Aboveground (A_{GB}), belowground (B_{GB}), and total biomass of each tree species

Tree component	N	Maximum	Minimum	Range	Total	Mean
Bersama abyssinica						
A_{GB} (kg)	8	8.36	3.31	5.05	75.21	9.4
B_{GB} (kg)	8	1.67	0.66	1.01	15.04	1.88
Total biomass (kg)	8	10.04	3.97	6.07	90.25	11.28
Cupressus lusitanica						

A_{GB} (kg)	12	682.78	78.05	604.73	3874.23	322.85
B_{GB}	12	36.56	15.61	20.95	774.85	64.57
Total biomass (kg)	12	819.33	93.65	725.68	4649.08	387.42
Maytenus arbutifolia						
A_{GB} (kg)	12	33.55	3.51	30.04	171.29	14.27
B_{GB} (kg)	12	34.26	0.7	33.56	34.26	2.85
Total biomass (kg)	12	40.26	4.21	36.05	205.55	17.25
Rhamnus staddo						
A_{GB} (kg)	8	24.2	2.09	22.11	84.45	10.56
B_{GB} (kg)	8	4.84	0.42	4.42	16.89	2.11
Total biomass (kg)	8	29.04	2.51	26.53	101.34	12.67

In the present study models developed using DBH as the sole explanatory variable provided a satisfactory estimation, since the total variation explained by the relationship was high (R^2) (Table 5). This indicates that DBH alone is a robust indicator of aboveground biomass, which implies the variability of biomass of trees in forest landscape is largely explained by variability in DBH. It is in agreement with previous reports [23].

Table 5: Statistical indicators, R^2, adjusted (Adj.) R^2, and p-values for models

Model	**Allometric equation**	**R2**	**Adj. R^2**	**p-value**
Model-5	A_{GB}= -258.30+20.57 (DBH)	0.9279	0.8207	4.939×10^{-7}
Model-6	A_{GB}= -1.1407+2.1262 (DBH)	0.9416	0.9058	1.7×10^{-5}
Model-7	A_{GB}= 4.1542+0.4830 (DBH)	0.5952	0.4448	0.01065
Model-8	A_{GB}=2.4031+1.9747 (DBH)	0.913	0.7985	0.000213
Model-9	A_{GB}=-143.492+26.387 (DBH)-16.93 (H)	0.9488	0.8474	1.56×10^{-6}
Model-10	A_{GB}= -3.33 +0.3656 (DBH) + 0.413 (H)	0.7961	0.7508	0.000781
Model-11	A_{GB}= -1.246+2.1 (DBH)+0.044 (H)	0.9416	0.9286	2.809×10^{-6}
Model-12	A_{GB}= -2.25+3.220 (DBH)-1.356 (H)	0.9253	0.8954	0.001526
Model-13	A_{GB}= -193.359 + 25.869 (DBH)-15.727 (H) + 90.952 (r)	0.95	0.9312	1.509×10^{-5}
Model-14	A_{GB}=9.996+0.51799 (DBH)-0.044 (H)-17.37 (r)	0.8383	0.7777	0.001568
Model-15	A_{GB}= 5.538+1.9545 (DBH)+0.316 (H) + 8.01 (r)	0.9421	0.9204	2.706×10^{-5}
Model-16	A_{GB}= -2.193+3.234 (DBH)-1.378 (H)-2.557 (r)	0.9253	0.8693	0.01019

Models 7, 10, and 14 are for *Bersama abyssinica*; Models 5, 9, and 13 for *Cupressus lusitanica*, Models 6, 11, and 15 for *Maytenus arbutifolia* and Models 8, 12, and 16 for *Rhamnus staddo*.

Moreover, DBH alone is a good estimator of biomass especially in terms of the multiple trade-offs between accuracy, cost and practicality of the measurements because DBH is always included in forest inventory data. Arguably the number of trees used in this study was low, which is usual for biomass studies due to the extensive, time-consuming and costly work required, especially for a heterogeneous landscape. Weighed 15 trees in Brazil, weighed 8 trees and 14 trees in Cameroon. Here we measured a total of 38 trees among four dominant species in the study site.

In addition, if total tree height is available, allometric models usually yield less-biased estimates. However, tree height has often been ignored in biomass estimation and carbon-accounting programs [24]. We found that including total tree height, measured serially and local wood density, improved biomass predictions when compared to using DBH alone as is evident from the increment in the adjusted coefficient of determination for each species (0.9312, 0.7777, 0.9204, and 0.8693) (Table 5). These findings corroborate with those reported by Isthmus of Panama and the humid lowlands of Costa Rica [25-26].

Model selection

The Residual Standard Errors (RSE) for *Bersama abyssinica* models 7, 10, 14 show very low values 1.15, 0.69, 0.73, respectively, indicating good fit of the models or a very minimal error value for A_{GB} estimation (Table 6). Although based on the AIC value, which penalizes parameter-rich models, we can say that model-7 is parsimonious with one variable, but any of the three models could provide a very good proximal estimation depending on the availability of forest inventory data such as height and density. Similarly, models for *Cupressus lusitanica* had close RSE values (52.23, 54.72, 58.76) for models 5, 9, and 13, but despite this closeness, their adjusted R^2 values had better capacity as explanatory variables in the model, indicating that model 13 could be used for better estimation of aboveground biomass for the study species depending on the availability of forest inventory data.

Table 6: Residual Standard Error (RSE), adjusted R^2 and Akaike Information Criterion (AIC)

Species	Models	RSE	Adjusted R^2	AIC
Cupressus lusitanica	A_{GB}= -258.30+20.57 (DBH)	58.76	0.8207	133.54
	A_{GB}= -143.492+26.387 (DBH)-16.93 (H)	52.23	0.8474	135.63
	A_{GB}=193.359+25.869 (DBH)-15.727 (H)+90.952 (r)	54.72	0.9312	135.3
Bersama abyssinica	A_{GB}=4.1542+0.4830 (DBH)	1.149	0.4448	39.57
	A_{GB}=3.33 +0.3656 (DBH)+0.413 (H)	0.6882	0.7508	40.34
	A_{GB}=9.996+0.51799 (DBH)-0.044 (H)-17.37 (r)	0.7273	0.7777	42.35
Maytenus arbutifolia	A_{GB}= -1.1407+2.1262 (DBH)	2.34	0.9058	58.26
	A_{GB}= -1.246+2.1 (DBH)+0.044 (H)	2.466	0.9286	60.27
	A_{GB}=5.538+1.9545 (DBH)+0.316 (H)+8.01 (r)	2.605	0.9204	62.16
Rhamnus staddo	A_{GB}=2.4031+1.9747 (DBH)	2.277	0.7985	39.57
	A_{GB}= -2.25+3.220 (DBH)-1.356 (H)	2.311	0.8954	40.35
	A_{GB}= -2.193+3.234 (DBH)-1.378 (H)-2.557 (r)	2.584	0.8693	42.35

Maytenus arbutifolia, all the three models (models 6, 11, 15) had RSE values of 2.34, 2.61, and 2.47, respectively, and the adjusted R^2gave slight improvement, and the AIC penalized model 15 more than model-6 and model-11 because it included three independent variables. Regardless, the model's application for estimating for the species is not limited in the presence of sufficient inventory data, and this study established local densities for the study species. However, in the absence of data for height, model-6 could effectively be used to estimate aboveground biomass.

Finally, models developed for *Rhamnus staddo*, revealed the same pattern, with a low residual standard error (2.28, 2.32, 2.58), models 8, 12, and 16 and adjusted R^2 of 0.7985, 0.8954, and 0.8693 (Table 6).

The coefficient of determination (R^2) is used in many biomass studies to evaluate simple linear regression models based on the ability to explain variance of the model compared to the total variance. However, when developing multiple regression models, it is necessary to check and evaluate R^2 against the adjusted coefficient of determination to overcome the limits of R^2, because whenever adding model variables in a regression, the R^2 is likely to increase by chance alone and thus, be misleading for the interpretation as a goodness of fit. Therefore, in this study the adjusted R^2 is used as explanatory power of variation in multiple linear regression because it is adjusted for the number of estimators in the model. It only increases if the new variable improves the model more than expected by chance [27]. In this study, the adjusted R^2 has increased for the studied species when adding more predictor variables into regression line.

Models developed for *Bersama abyssinica* (model 7and model 10) resulted an improved adjusted R^2 of 0.4448, 0.7508, and 0.777, respectively. Models 5, 9, and 13 for *Cupressus lusitanica* yielded an adjusted R^2.

of 0.8207, 0.8474, and 0.9312, respectively. Models 6, 11, and 15 for *Maytenus arbutifolia* had a value of 0.9058, 0.9208, and 0.9204, and models 8, 12, and 16 for *Rhamnus staddo* had an adjusted R^2 of 0.7985, 0.8954, and 0.8693 respectively.

Comparison of biomass result estimated by models developed in this study against general pan-topicals revealed disparity with our findings (Figure 5 and Figure 6). It's attributable for reasons such as local wood density and ecological variables specific to the study location. Moreover, linear regression models are preferred for simplicity and usually yield the best fit for data. The pan-tropical models were general equation 2, A_{GB}= 34.4703-8.0671 DBH+0.6589 DBH^2, typically relates tree biomass with only DBH and ignores relevant biomass estimation variables such as tree density and height. As a result, this model overestimated the biomass of all the studied species.

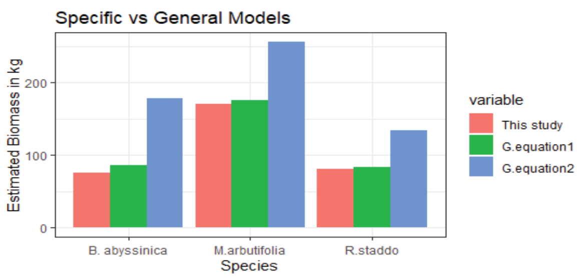

Figure 5: Comparison of biomass estimation models

The general equation 1 of incorporates tree height and density, and their best performing model is A_{GB}= 0.0559ρD^2H, this model has better estimated the biomass of the studied species than the model, mainly due to the incorporation of wood density and tree height [1,9]. For this model wood density developed in our study was used as for tree height for biomass estimation.

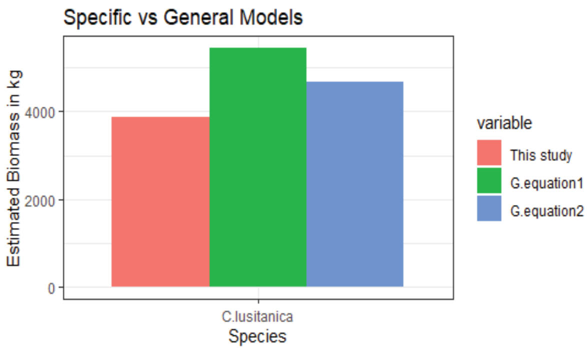

Figure 6: Comparison of biomass estimation models for *Cupressus lusitanica*

The total biomass estimated by general equation 1 provides an estimate comparable to this study; the model estimated similar values for *Maytenus arbutifolia* (176.11 kg) and for *Rhamnus staddo* (83.67 kg) and for *Bersama abyssinica* (85.55 kg). However, because tree height and DBH for *Cupressus lusitanica* was estimated as a higher value, and the model overestimated the biomass, predicting 5449.72 kg.

CONCLUSION

Locally developed allometric equations are fundamental for accurate estimation of biomass and/or carbon stock assessment. This study estimated the biomass and developed allometric equations that can be used by researchers, forest managers and/or organizations such as REDD+ to calculate aboveground biomass for estimation of carbon stock of the studied species in Ethiopia. This study also provided locally developed wood density for the study species. The best performing models were A_{GB}=9.996+0.518 (DBH)-0.044 (H)-17.37 (ρ), model 14 for *Bersama abyssinica*, A_{GB}= -193.359 + 25.869 (DBH)-15.727 (H)+90.952 (ρ), model 13, for *Cuprussus lusitanica*, and A_{GB}=5.538+1.9545 (DBH)+0.316 (H)+8.01 (ρ), model 15 and for *Maytenus arbutifolia*, and A_{GB}= -2.25+3.220 (DBH)-1.356 (H), model 12 for *Rhamnus staddo*.

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