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Allometric models for estimating aboveground biomass of shade trees and coffee bushes grown together

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Abstract Allometric models for dominant shade tree species and coffee plants (*Coffea arabica*) were developed for coffee agroforestry systems in Matagalpa, Nicaragua. The studied shade tree species were *Cordia alliodora*, *Juglans olanchana*, *Inga tonduzzi* and *I. punctata*. The models predict aboveground biomass based on diameter at breast height (for trees), and the stem diameter at a height of 15 cm and plant height (for coffee plants). In addition, the specific gravity of the studied species was determined.The total aboveground biomass of the shade trees varied between 3.5 and 386 kg per tree, and between 0.005 and 2.8 kg per plant for coffee. The aboveground biomass components (foliage, branch, and stem) are closely related with diameter at breast height ($r > 0.75$). The best-fit models for aboveground biomass of the shade trees were logarithmic, with adjusted R^2 between 0.71 and 0.97. In coffee plants, a high correlation was found ($r = 0.84$) with the stem diameter at 15 cm height, and the best-fit model was logarithmic, as well. The mean specific gravity was 0.52 (± 0.11) for trees and 0.82 (± 0.06) for coffee plants.

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Introduction

Biomass equations form a basis for estimating carbon sequestration in forest and agroforestry systems (Eamus et al. 2000; Albrecht and Kandji 2003). Biomass is frequently estimated employing allometric models, which express the tree biomass as a function of easily measurable variables such as diameter at breast height (dbh), total height (*h*) and/or basal area (BA) (Parresol 1999).

Allometric models have mainly been developed for their application in natural forests and forest plantations. There are limitations for their use in agroforestry systems (AFS) due to natural differences in tree shape and due to alterations in their shape and architecture caused by management of trees in AFS. For this reason, there is a need for developing models for more accurate and confident estimations of biomass in AFS (Lott et al. 2000). The aims of this study is specifying model parameters for estimating aboveground biomass for individual shade trees and coffee plants in agroforestry systems from linear dimensions such as stem diameter or height in Matagalpa, Nicaragua.

Materials and methods

This study was carried out in the Yassica Sur district (85°50′00″ N and 12°55′30″ W; 400–1000 masl), municipality of San Ramón, in the northeast region of the department of Matagalpa, Nicaragua. The area corresponds to a subtropical humid forest (Holdridge 1996) with annual precipitation between 600 and 2000 mm year^{-1}, and temperature between 23 and 35°C. The soils are alfisols and molisols with texture clay loam, silty loam and silty clay. This zone is one of the most important regions for coffee production in the country.

A list of coffee producers was compiled with support of institutions, projects and organizations operating in the area. Based on this list, 37 coffee producers with coffee plantations (≥0.7 ha) were randomly selected for estimating the botanical composition and dominance of shade tree species in these agroforestry systems. The selected production systems varied in several aspects: density and botanical composition of the shade strata, management of trees, age, and variety and density of coffee (*Coffea arabica*) plants.

In each coffee plantation (farm), one or two temporal rectangular sampling plots of 1000 m^2 were established depending on the size of the plantation. In total 66 temporal sampling plots were established in 37 farms. In these plots, the trees were identified, and their dbh and *h* was measured.

The shade tree species selected to be analyzed for allometric relationships were the four most dominant species in terms of basal area (equaling 54% of total BA in the study plots): two species of *Inga* (*Inga punctata*, 18% of total BA; *I. tonduzzi*, 17%), *Cordia alliodora* (13%) and *Juglans olanchana* (6%).

In total 34 individuals (5–44 cm diameter at breast height—dbh) of different sizes of the four most dominant species were selected from 22 farms for destructive biomass analysis. The trees were measured (dbh and total height—*h*) and felled. Each tree was divided into four biomass components: foliage, branch, stem (until the first branch), and stump (lowest part of the plant aboveground). The foliage, branches and stem were weighted separately and one sub sample from each component per tree was taken to obtain dry matter content (60°C, 48 h or until constant weight). For the stumps, stump height and diameter was measured, and their volume was calculated using the Huber equation $V = d^2 * \pi/4 * h$ (Loetsch et al. 1973).

For the development of models for coffee, 96 coffee plants of different sizes and shapes were randomly selected in the plots. The *h*, and diameter at 15 cm of height (d_{15}) of these plants was measured. Coffee plants were felled, and foliage, branches and stem were weighted separately and one sub sample from each component per tree was taken to obtain dry matter content. The volume of stumps was converted to biomass using the values of specific gravity.

Table 1 Number samples per section collected from shade trees and coffee plants for biomass estimation and for specific gravity

Species	Biomass					Specific gravity	
	Foliage	Branch	Branch + foliage	Stem	Total	Stem	Branch
Inga punctata	6	7	7	7	7	4	4
Inga tonduzzi	8	10	10	10	10	6	3
Cordia alliodora	4	10	10	10	10	3	2
Juglans olanchana	7	7	7	7	7	3	1
Total of samples or tree	25	34	34	34	34	16	10
Coffea arabica unpruned					78	29	n/a
Coffea arabica pruned					18	n/a	n/a
Total of plants of coffee					96	29	n/a

A total of 55 samples were taken to estimate specific gravity for all the studied species including coffee (Table 1). These samples were taken in the lowest part of the main stem (close to the stump), and in branches for tree species and in the stem for coffee. The samples were dried (60°C until to constant weight) and they were submerged in distilled water in a container placed on a pan balance. The mass of the sample was obtained using water displacement method (ASTM 1983).

The total aboveground biomass (B_T) for each plant was calculated as a sum of the biomass of all the components. The biomass expansion factor (BEF) was calculated as a ratio between the total aboveground biomass and the biomass of the stem.

Descriptive statistics (means and standard deviations) for the specific gravity values were calculated for each section per species and for all the species combined. The data were examined for normality and homogeneity. Analysis of variance (ANOVA) was carried out to evaluate the variation in specific gravity among sections per species (branches and stem) using SAS Statistical Software.

Correlation analysis between dependent variables (biomass components) and independent variables (dbh, h, and d_{15}) was carried out by species individually and for the two species of *Inga* combined as a group. Linear and non-linear regression analyses were used to predict biomass based on independent variables (dbh, h, and d_{15}). The models were selected according to adjusted determination coefficient (adjusted R^2), F test, mean square error (MSE), root mean square error (RMSE), Furnival index (FI) (Furnival 1961), the predicted residual (PRESS) and the biologic logic of the model.

Results

Aboveground biomass models for shade trees

It was found in total 67 tree species in the shade strata in the 66 sampling plots. In small coffee plantations (<14 ha), the shade strata is composed of a high diversity of species, such as *Musa* spp., *Persea americana*, *Citrus* spp., *Mangifera indica*, timber species such as *C. alliodora*, *J. olanchana*, *Platymiscium dimorphandrum*, *Albizia* sp. and service species such as *I. tonduzzi* and *I. punctata*. In large coffee plantations (>35 ha), species of genus *Inga* dominate the shade strata associated to *Musa* spp. and/or trees from natural regeneration with less variability. In medium plantations (14–35 ha), the shade strata may have the characteristics of small or large plantations, or a mixture of them.

The mean specific gravity for shade species was 0.52 (±0.11). *I. punctata* was the species with the highest value (0.63 ± 0.10), followed by *I. tonduzzi* (0.51 ± 0.06), *C. alliodora* (0.45 ± 0.06) and *J. olanchana* (0.39 ± 0.04; Fig. 1). In *Inga* sp., the highest specific gravity was found in the lowest section of the stem; whereas in *J. olanchana* and *C. alliodora*, this was found in the branches.

The specific gravity of the stem was statistically different among species ($P < 0.01$). However, branch specific gravity was similar among species ($P > 0.05$). The mean specific gravity of *I. punctata* and *I. tonduzii* is statistically different from the mean specific gravity of *C. alliodora* and *J. olanchana*. In coffee plants, the mean specific gravity of stems was 0.82 (±0.06) (Fig. 1).

The dbh of studied shade trees varied between 5 and 44 cm, h between 5.4 and 22 m, and total aboveground biomass between 3.5 and 386 kg.

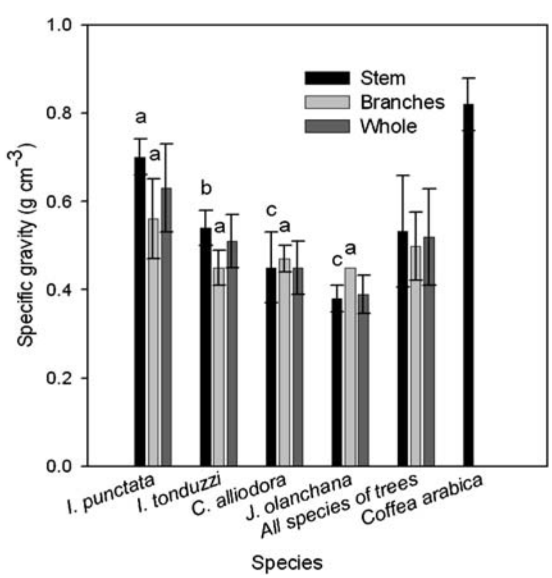

Fig. 1 Specific gravity (mean and standard deviation) by component among species in coffee agroforestry systems. Means with the same letter are not significantly different

The total aboveground biomass for all evaluated species was distributed as: 57% stem, 36% branches, and 7% foliage.

The mean BEF for all species was 2.1 (±1.0). The highest BEF was found in *I. tonduzzi* (2.6 ± 1.4), followed by *I. punctata* (2.1 ± 8.9), *C. alliodora* (1.7 ± 0.6) and *J. olanchana* (1.8 ± 0.4). However, BEF decreases with increments in stem biomass (Fig. 2f). The correlation between stem biomass and BEF was low for each of the species studied, varying between −0.70 (*I. punctata*) and −0.14 (*C. alliodora*). For the two *Inga* sp. species combined, $r = -0.51$, and for all the species combined, $r = -0.33$, respectively.

The total aboveground biomass and the dbh were highly correlated for each species separately and combined ($0.95 < r < 0.99$; $P < 0.001$; Fig. 2e). These results are similar to other studies (Saldarriaga et al. 1994). The correlation between B_T and h was positive and high for *I. tonduzzi*, *J. olanchana* and *C. alliodora*, varying between 0.76 and 0.81 ($P < 0.001$), but negative and low for *I. punctata* ($r = -0.12$; $P < 0.001$). For all species combined, it was relatively low ($r = 0.55$; $P < 0.001$).

The models with logarithmic transformations ($Log_{10} - Log_{10}$) presented the best-fit ($0.71 > R^2 < 0.97$) compared to the lineal and exponential models (Table 2) for all the species, for total above ground biomass, and for each biomass component (foliage, branch, stem).

The $Log_{10} - Log_{10}$ models gave the best fit for branch and foliage biomass for all the species (Fig. 2a–c), R^2 varying between 0.71 and 0.96, PRESS varying between 0.1 and 2.9, and FI between 1.2 and 3.0 (Table 2).

The stem and total aboveground biomass is better estimated with the $Log_{10} - Log_{10}$ models for each species either separately of grouped (Fig. 2d, e). These equations presented the highest adjusted R^2 values (0.93–0.97; Table 2) and the lowest square mean error, FI and PRESS values.

Aboveground biomass models for coffee plants

The selected coffee plants covered a wide range of dimensions. The h varied between 0.3 and 3.3 (m), d_{15} between 0.3 and 7.4 cm, and total aboveground biomass between 0.005 and 2.8 kg. Non-pruned coffee plants constitute 81% of the total sample. In this case, the distribution of total aboveground biomass is the following: stem 63.1%, branches 19.8%, and foliage 17.0%, respectively. In the pruned coffee plants (19% of the sample), two or more stems (re-growth) originated from the main stem. In this case, the distribution of biomass was the following: re-growth stems 30.7%, main stem 38.1%, branches 16.6%, and foliage 14.6%, respectively.

The total aboveground biomass of coffee presented a high correlation with d_{15} ($r = 0.84$; Fig. 3a) and a low correlation with total h ($r = 0.62$; $P < 0.001$; Fig. 3b). The models for estimating the total aboveground biomass based on d_{15} and/or h presented good fit ($0.70 < R^2 < 0.94$). The equation 4 (Table 3), with $Log_{10} - Log_{10}$ transformation in its all variables, is the best predictor of the total aboveground biomass in coffee plants presenting the highest R^2 and the lowest MSE, FI and PREES values.

Discussion and conclusions

The specific gravity of *C. alliodora* and *J. olanchana* found in this study (0.34–0.49 g cm^{-3}) and is congruent with the values reported for Costa Rica (0.49) for Nicaragua (0.48) by Carpio (1992) and Herrera and Morales (1993). We did not find previous studies on specific gravity for *I. tonduzii*, *I. punctata* and *C. arabiga* in the literature.

In general terms, dbh is a good predictor of tree volume (Somarriba and Beer 1987) or total aboveground biomass, explaining well the variability of the data (Table 2). The h is not a good predictor of total aboveground biomass of the shade trees, due to natural differences in canopy architecture among species and due to modifications of tree canopy architecture by pruning for shade regulation.

In coffee plants, h and d_{15}, respectively, explained 82 and 94% of the variability in total aboveground biomass. A mixture of h and d_{15} explained 94%. These models have high accuracy and confidence to estimate the biomass. Many

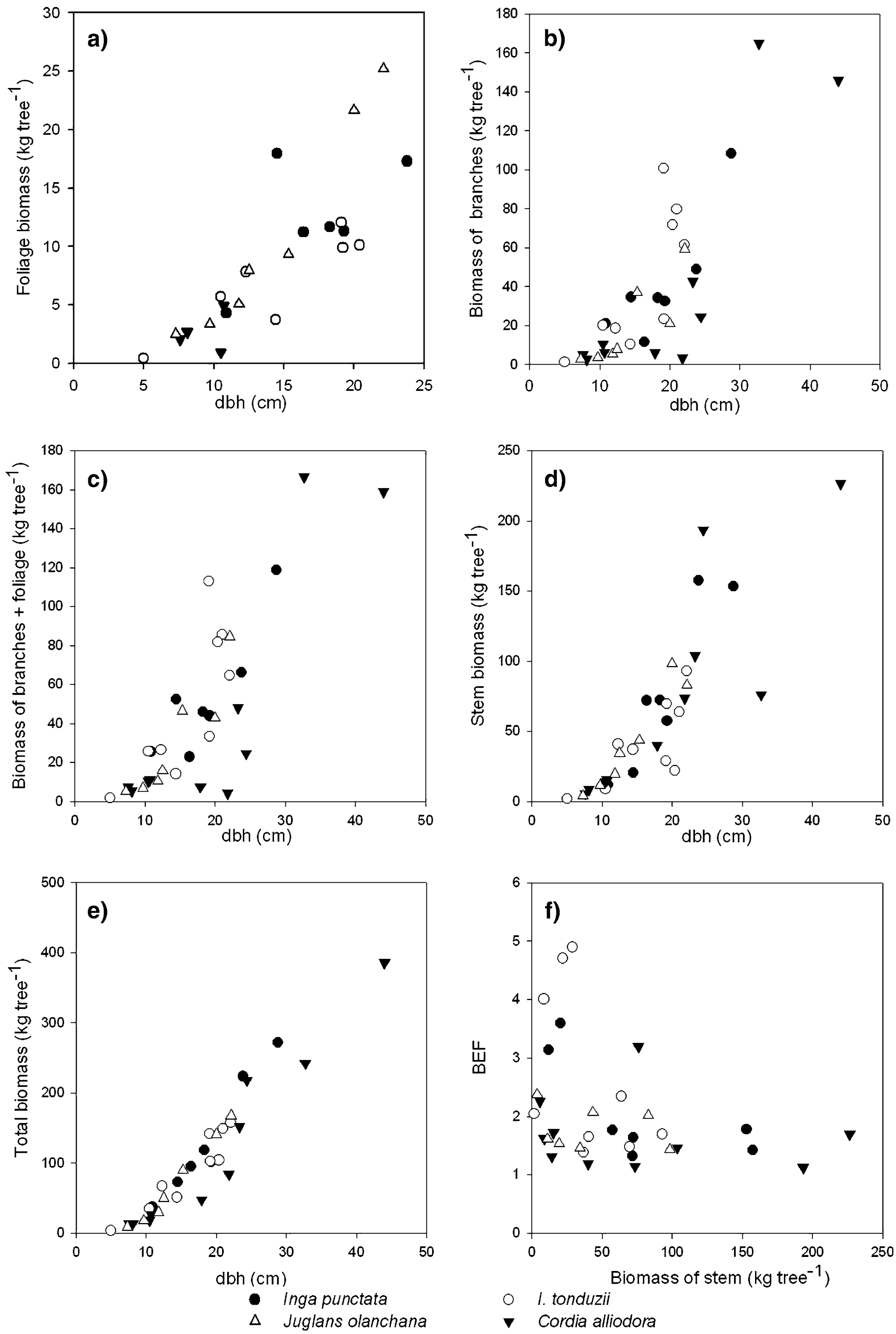

Fig. 2 Relation between (a) foliage, (b) branch, (c) branch + foliage, (d) stem, (e) total aboveground biomass and dbh, and (f) BEF and stem of biomass of the dominant shade species in agroforestry systems with coffee (*Coffea arabica*)

Table 2 Parameter values and regression statistics for the best allometric models for biomass components for all species and each species. Symbols used are: coefficient of adjusted determination (R^2), mean square error (MSE), root mean square error (RMSE); predicted residual (PRESS), furnival index (FI)

Model specie/s	Biomass component (kg)	Estimated coefficients		R^2	MSE	RMSE	PRESS	FI
		a	b					
For all		Equation 1: $Log_{10}Y$ = a + b * Log_{10}dbh (cm)						
1	Foliage	−1.557	2.098	0.78	0.04	0.20	1.11	1.73
2	Branch	−1.452	2.286	0.74	0.08	0.29	2.92	2.93
3	Branch + foliage	−1.008	2.029	0.71	0.07	0.27	2.63	3.02
4	Stem	−1.196	2.294	0.87	0.04	0.19	1.32	2.28
5	Total	−0.834	2.223	0.93	0.02	0.13	0.61	1.89
Inga punctata								
6	Branch + foliage	−1.825	2.704	0.73	0.05	0.22	0.61	2.82
7	Stem	−1.830	2.847	0.86	0.03	0.16	0.25	2.18
8	Total	−0.559	2.067	0.97	0.00	0.05	0.02	1.35
Inga tonduzzi								
9	Foliage	−1.471	1.964	0.81	0.04	0.21	0.63	1.64
10	Branch	−1.541	2.527	0.85	0.06	0.24	0.63	2.51
11	Branch + foliage	−1.252	2.362	0.85	0.05	0.22	0.58	2.45
12	Stem	−1.146	2.208	0.80	0.06	0.24	0.74	2.62
13	Total	−0.936	2.348	0.95	0.01	0.12	0.23	1.78
I. punctata + *I. tonduzzi*								
14	Foliage	−1.464	2.003	0.80	0.04	0.19	0.77	1.70
15	Branch	−1.287	2.275	0.79	0.05	0.23	1.00	2.56
16	Branch + foliage	−1.030	2.157	0.83	0.04	0.20	0.78	2.35
17	Stem	−1.347	2.419	0.84	0.05	0.21	0.85	2.52
18	Total	−0.889	2.317	0.96	0.01	0.10	0.24	1.64
Juglans olanchana								
19	Foliage	−1.599	0.964	0.96	0.01	0.07	0.06	1.23
20	Branch	−2.149	2.840	0.82	0.05	0.22	0.46	2.05
21	Branch + foliage	−1.648	2.614	0.90	0.02	0.15	0.20	1.73
22	Stem	−1.799	2.877	0.94	0.01	0.12	0.18	1.63
23	Total	−1.417	2.755	0.97	0.01	0.08	0.05	1.44
Cordia alliodora								
24	Branch	−1.620	2.257	0.79	0.09	0.30	1.07	2.84
25	Branch + foliage	−1.121	1.932	0.71	0.10	0.32	1.19	3.26
26	Stem	−0.942	2.062	0.89	0.03	0.18	0.41	2.30
27	Total	−0.755	2.072	0.95	0.01	0.12	0.15	1.80

models are proposed for this purpose; however, few of these satisfy the statistical requirements and considerations of precision and practical utility (Saldarriaga et al. 1994).

With the logarithmic transformations, the equation parameters may be estimated using procedures of minimal squares (Parresol 1999; Eamus et al. 2000), and the problem of heteroscedasticity of the variance may be corrected (Causton 1985; Saldarriaga et al. 1994; Eamus et al. 2000). Many authors (Bartelink 1996; Clough and Scott 1989; Kanninen and Pérez 2002; Segura and Kanninen 2005) have developed models using dbh as a predictor of total aboveground biomass in other species in different forest ecosystems.

The best allometric models found in this study for shade trees provide consistent estimations and logical relationships between dbh and total aboveground biomass for all the species studied in agroforestry conditions. More than 93% of the variability found in the total aboveground biomass is explained by dbh. Moreover, these models are practical because dbh can be easily measured accurately. However, the use of these models in different agro-ecological conditions and with a wide range of dbh values should be validated with local data.

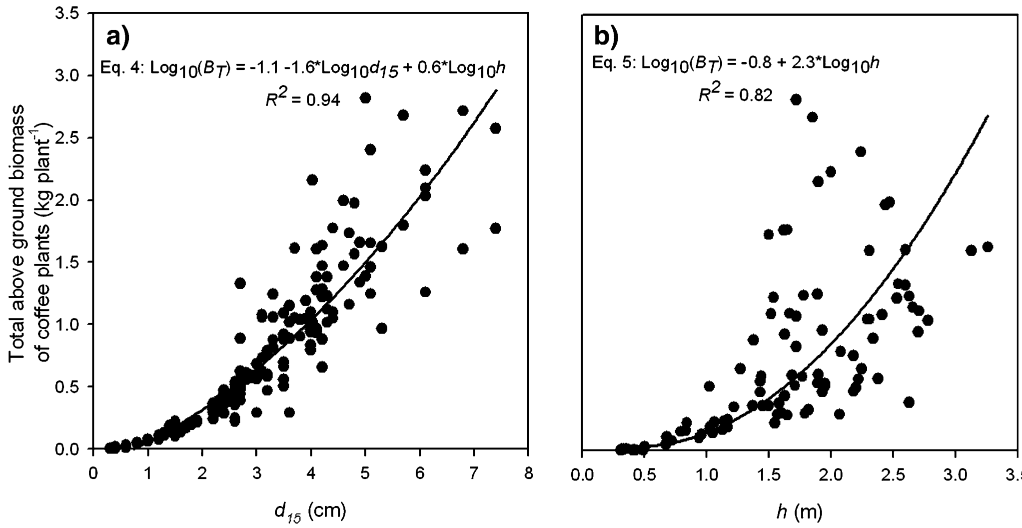

Fig. 3 Relationship between total aboveground biomass and (a) d_{15} and (b) h in coffee plants (*Coffea arabica*) in agroforestry systems

Table 3 The best models for estimation total aboveground biomass (B_T) (kg/plant) in coffee plants (*Coffea arabica*) in agroforestry systems. Symbols used are: coefficient of adjusted determination (R^2), mean square error (MSE), root mean square error (RMSE); predicted residual (PRESS), Furnival index (FI)

Equation	Model	Parameter			R^2	MSE	RMSE	PRESS	FI
		a	b	c					
Independent variables: d_{15} (cm)									
2	B_T = a + b * d_{15}	−0.357	0.371		0.70	0.13	0.36	13.13	0.36
3	$Log_{10}(B_T)$ = a + b * $Log_{10}(d_{15})$	−1.181	1.991		0.93	0.03	0.16	2.58	0.98
Independent variables: d_{15} (cm) and h (m)									
4	$Log_{10}(B_T)$ = a + b * $Log_{10}(d_{15})$ + c*Log_{10}(h)	−1.113	1.578	0.581	0.94	0.02	0.15	2.21	0.98
Independent variables: h (m)									
5	$Log_{10}(B_T)$ = a + b * Log_{10}(h)	−0.779	2.338		0.82	0.07	0.27	6.89	0.97

Models for total aboveground biomass in coffee plants

The inclusion of both d_{15} and h, as independent variables, increased the fit of the models. Usually, the highest precision is obtained when more variables are introduced to the model. However, the inclusion of more than one independent variable may cause problems of collinearity (Saldarriaga et al. 1994). The results found in this study indicate low correlation between d_{15} and h, which can be explained by the pruning of coffee plants. Usually, the coffee plants (>3 years) are pruned for renovating the plantation, thus increasing the variability of allometric data.

For practical purposes, the best option might be a simple model with one independent variable, thus requiring less effort in field measurements (Eq. 3, Table 3). The best-fit model for coffee plants (Eq. 4, Table 3) provides consistent estimations and logical relationships of d_{15} and h with the total aboveground biomass. This model is also very practical, because d_{15} and h are easily measurable in the field. However, its application in plants with different characteristics and architecture should be validated with local data.

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