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Above-ground biomass models for dominant trees species in cacao agroforestry systems in Talamanca, Costa Rica

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Abstract Tree biomass allometric models are essential to estimate biomass, carbon sequestration and nutrient cycling in cacao agroforestry systems and other land uses with woody perennial species. A total of 34 trees of *Cordia alliodora*, 74 trees of *Theobroma cacao* and 38 trees of eight fruit species (*Inga* spp., *Citrus aurantifolia, C. sinensis, Spondias mombin, Nephelium lappaceum, Persea americana*, *Mammea americana, Mangifera indica* and *Syzigium malaccensis*) were harvested to gravimetrically estimate aboveground biomass (total, stem, branches, and foliage). Additionally, a database with total stem volume of 208 trees of *C. alliodora* was used to estimate above-ground biomass using a biomass expansion factor (BEF) and wood specific gravity estimations from this study. The well-known generic allometric models were fitted to the data using ordinary least squares, and the best ones were selected based on determination coefficient (R^2), adjusted R^2, root of mean square error, Akaike Information Criterion, Bayesian information criterion, and residual analyses. Selected models were compared with published models for the same species or group of species. Tree BEF were estimated for *C. alliodora* and fruit trees. The best fit models explained 93–96% of total aboveground biomass, and 54–95% of biomass by components. BEF differed significantly between timber and fruit trees. These models represent an advance in monitoring of carbon projects.

Keywords Allometric models, biomass expansion factor · *Cordia alliodora* · Fruit trees

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Introduction

Mitigation of climate change through carbon capture in biomass is one the environmental services provided by cacao (*Theobroma cacao* L.) agroforestry systems (CAFS) in indigenous farms in Talamanca, Costa Rica (Andrade et al. 2008; Somarriba et al. 2013) and other tropical regions (Cotta et al. 2006; Smiley and Kroschel 2008; Wade et al. 2010; Somarriba et al. 2013; Marín et al. 2016). CAFS can store up between 7.0 and 138.1 Mg C/ha in biomass worldwide, standing out in Cameroon, Indonesia, Ghana, Mexico and Guatemala with 138.1, 103.4, 101.6, 75.0 and 72.5 t C/ha, respectively (Somarriba et al. 2013; Mohammed et al. 2015; Abou Rajab et al. 2016; Dawoe et al. 2016; Marín et al. 2016;

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N'Gbala et al. 2017; Silatsa et al. 2017; Fernandes et al. 2018; Madountsap et al. 2018; Middendorp et al. 2018; Santhyami et al. 2018; Schneidewind et al. 2019; Salvador-Morales et al. 2020; Sari et al. 2020; Asigbaase et al., 2021; Numbisi et al. 2021).

The estimation of above-ground biomass of woody perennial vegetation is useful to estimate carbon stocks and fluxes, support desertification prevention and control, soil and water conservation, and ecological and economic restoration of landscapes (Wang et al. 2016). Below-ground biomass is another important carbon component, which is frequently estimated as the ratio between total above-ground biomass and subterranean biomass (IPCC 2006). Biomass allometric models are essential for estimating biomass and carbon in land uses (IPCC 2003) to improve bioenergy systems, sustainable forest management (Henry et al. 2011) and studies of nutrient cycling (Fortier et al. 2017; Mahmood et al. 2019). Tree biomass is either estimated directly by harvesting and weighting trees or from stem wood volume assessments combined with both wood density estimates and a biomass expansion factor (BEF) to account for branches and foliage (Brown 1997, IPCC 2006).

Numerous studies (Saj et al. 2013; Abou Rajab et al. 2016; Dawoe et al. 2016; Silatsa et al. 2017; Fernandes et al. 2018; Madountsap et al. 2018; Middendorp et al. 2018; Salvador-Morales et al. 2020; Asigbaase et al. 2021; Numbisi et al. 2021) have estimated carbon stock and fixation rates using general biomass models for tropical forest trees, such as those developed by Chave et al. (2005) and Saldarriaga et al. (1988). However, these general equations can produce large estimation errors (Ngomanda et al. 2014); local biomass models are recommended to increase the accuracy needed in the certification of carbon credits (Lott et al. 2000; Albrecht and Kandji 2003; IPCC, 2003; Segura and Kanninen 2005; Segura et al. 2006). Wartenberg et al. (2019) have used the model for *T. cacao* proposed by Smiley and Kroschel (2008) in Indonesia; whereas, Tiralla et al. (2013) developed allometric models for shade trees such *Aleurites moluccana*, *Cocos nucifera* and *Gliricidia sepium* in Indonesia. However, no models to estimate biomass in cocoa trees have been found for tropical humid in Costa Rica. In this study, allometric models to estimate above-ground biomass (total and by components) of both cacao and the most dominant tree species in the cacao AFS of indigenous farms in Talamanca, Costa Rica were developed. In the same way, BEF for dominant tree species was estimated.

Materials and methods

This study was carried out in the Indigenous Reserve of Talamanca (9º00'-9º50' N and 82º35'-83º05' O; 0–300 m of altitude), in South-Eastern Costa Rica. This area is a humid tropical forest, with a rainfall 1900–2740 mm/year with no a dry season and mean monthly temperatures between 22 and 27 °C. Cacao production is the second main land use in this area; plantain (*Musa* AAB) and banana (*Musa* AAA) plantations are the main agricultural land uses, covering 40% of the agricultural area (Orozco et al. 2008).

A total of 84 sample plots, 1000 m^2 each, were established in cacao farms that covers all landscapes and conditions of cacao productive zone in the reserve. The farms were randomly selected from a list of producers database. A maximum of one sampled plot per land use was established in a farm. In the sample plots, all shade trees with diameter at breast height (dbh) $\geq$ 10 cm were identified at the level of species and dbh and two perpendicular measurements of crown diameter measured to estimate crown area assuming a circular form. Relative dominance of cacao and each tree species was calculated as the percentage of the total basal area.

Allometric models were fitted to tree above-ground biomass data of the dominant tree species or group of species in these systems: 1) *Cordia alliodora* (Ruiz & Pav.) Oken, 2) *Theobroma cacao* L., and 3) a mix of the eight most common fruit tree species present in the shade canopy of cocoa plantations, including: *Inga* spp., *Citrus aurantifolia* (Christm.) Swingle, *C. sinensis* (L.) Osbeck, *Spondias mombin* L., *Nephelium lappaceum* L., *Persea americana* Mill., *Mammea americana* L., *Mangifera indica* L. and *Syzigium malaccensis* (L). Merr. & L.M. Perry. These species were selected because they had the highest relative dominance. A total of 34 trees of *C. alliodora*, 74 trees of *T. cacao* and 38 fruit trees were typical of the systems and were selected covering the size (trunk diameter) range observed, measured, and harvested to estimate their above-ground biomass. A database with stem volume of 208 trees of *C. alliodora* (Somarriba and

Table 1 Number and sizes of the sampled trees to develop the allometric models in the most dominant species in agroforestry systems with cacao in Talamanca, Costa Rica

Specie or group of species	Number of sampled trees	Range of size
Theobroma cacao	74	1.3–26.8 cm of d_{30} 1.1–8.3 m of *h*
Cordia alliodora		
Cordia alliodora above-ground biomass	34	3.9–75.7 cm of dbh 5.4–46.3 m of *h*
Cordia alliodora stem volume *	208	14.6–102 cm of dbh
Fruit trees (8 species)	38	1.9–46.5 cm of dbh

(*) Database from Somarriba and Beer (1987) and Ryan et al. (2009). d_{30}: trunk diameter at 30 cm above ground; dbh: trunk diameter at breast height; *h*: total height

Beer 1987; Ryan et al. 2009; Table 1) was also included in this study with stem volumes converted to above-ground biomass using the wood specific gravity (WSG) and the BEF estimates from *C. alliodora* trees harvested in this study.

Each individual tree was measured standing (dbh for shade trees, stem diameter at 30 cm aboveground -d_{30}- and diameter of first branch -dfb- for cacao and crown diameters for all species), harvested and its total height (h) measured after felling. Above-ground biomass was separated into four components (stump, stem, branches, and foliage), weighted in fresh (portable balance: 99 kg × 50 g), and two sub-samples (plate portable balance: 300 kg × 0.1 g) by component oven-dried at 60 °C until constant weight to estimate biomass. The volume of stumps, stems and large branches (diameter > 15 cm) were estimated with Huber´s equation (Loetch et al. 1973), and transformed to biomass using WSG estimated from 347 samples of 12 species collected in the same study area from the stem at different heights (0.40 to 1.30 m) and large branches, including: *C. alliodora*, *T. cacao* and fruit tree species (*P. americana*, *Inga* spp., *S. mombin*, *N. lappaceum*, *S. malacensis*, *C. aurantifolia, C. sinensis and M. indica*). WSG was estimated by water displacement (Segura and Kanninen 2005; Segura et al. 2006). The BEF of *C. alliodora* and fruit tree species was estimated as the ratio between total above-ground biomass and stem biomass.

All measured and calculated variables (total above-ground biomass, by components, dbh, d_{30}, h, Ca for each species or group of species) were examined for normality and homogeneity of variances. The Pearson correlation coefficient (r) between biomass and allometric variables (diameter, height and crown area) was estimated.

The commonly used generic allometric models were fitted to the data (Loetch et al. 1973) using the ordinary least squares method. The best fit models were selected based on: a) the highest R^2 and adjusted R^2 (adj R^2) b) the lowest root of mean square error, Akaike Information Criterion and Bayesian Information Criterion, c) models and parameters with statistical significance and d) residual analyses (estimated vs observed values) with no systematic bias were used to assess the range of tree sizes where models work adequately (Correia et al. 2018; Sanquetta et al. 2018). All statistical analyses were carried out with Infostat.

Selected models were used to estimate extremes and projected beyond the range of observed values to explore the consistency of their biological behavior (Clutter et al. 1983; Segura and Andrade 2008; Picard et al. 2012; Sileshi 2014; Correia et al. 2018; Sanquetta et al. 2018). The performance of the best-fit models was compared with models for the same species using the mean relative error (Van Breugel et al. 2011). The model for *T. cacao* was compared with that proposed by Smiley and Kroschel (2008) (Eq. 1), using a linear model to estimate d_{50} values based on d_{30}. The model for *C. alliodora* was compared with that developed by Segura et al. (2006) (Eq. 2) and the multispecies model developed from Cole and Ewel (2006) for small trees ($1.4 \leq dbh \leq 28.7$ cm) (Eq. 3). The model for fruit trees was compared to those developed by Goodman et al. (2014) (Eq. 4), that for *Psidium guajava* by Rathore et al. (2018) (Eq. 5) and that for *M. indica* by Saha et al. (2021) (Eq. 6).

$$B = 0.202 * d_{50}^{2.112} \quad (1)$$

$$Log(B) = -0.755 + 2.072 * Log(dbh) \quad (2)$$

$$B = 0.525 + 0.015 * dbh^2 * h \quad (3)$$

$$Ln(B) = -2.6512 + 2.0212 * Ln(dbh) + 0.9302 * Ln(h) + 1.3257 * Ln(g) \quad (4)$$

$$B = 0.069 * cd^{2.456} \quad (5)$$

$$Ln(B) = -0.227 + 1.802 * Ln(dbh) \quad (6)$$

where; B: Above-ground biomass (kg/tree), d_{50}: Trunk diameter at 50 cm above ground, dbh: Diameter of breast height (cm), h: Total height (m), g: Wood specific gravity (g/cm^3), cd: Collar diameter (cm).

Results

Dominance, wood specific gravity and biomass

The shade canopy of cacao plantations was dominated by timber and fruit tree species with a total basal area of 10.3 m^2/ha. *C. alliodora* was the most dominant species of the shade strata (46% of basal area), and eight fruit tree species (*Inga* spp., *C. aurantifolia, C. sinensis*, *S. mombin, N. lappaceum, P. americana, M. americana, M. indica* and *S. malaccensis*) were responsible for 19% of basal area. WSG of the tree species varied between 0.35 and 0.83 g/cm^3, where stems had greater values than branches (0.57 vs 0.46 g/cm^3, respectively) (Table 2). *N. lappaceum* had the highest WSG in stems (0.83 g/cm^3).

The mean total above-ground biomass of *T. cacao* was 32.1 kg/tree with 69% in stem and large branches and 22% and 9% in small branches and foliage, respectively. *C. alliodora* had a mean total above-ground biomass of 878.7 kg/tree, where stem was the main component followed by large branches, small branches, and foliage (79, 16, 3 and 2%, respectively). BEF for *C. alliodora* was 1.25 ± 0.15, with no statistical differences ($p > 0.05$) between tree sizes. Individual fruit trees weighted 256.2 kg/tree with 48% in stems, 46% in branches, and 6% in foliage. BEF for fruit trees was 2.4 ± 1.6.

Table 2 Basal area and wood specific gravity of the dominant tree species in cacao agroforestry systems in Talamanca, Costa Rica

Species	Basal area		Wood specific gravity (g/cm^3)	
	m^2/ha	%	Stem	Large branches
Theobroma cacao	10.20	44.7	0.51 ± 0.05	n/a
Cordia alliodora	5.78	25.3	0.47 ± 0.08	0.43 ± 0.07
Inga spp.	0.94	4.1	0.48 ± 0.13	0.48 ± 0.15
Citrus spp.	0.39	1.7	n/a	n/a
Spondias mombin	0.33	1.4	0.44 ± 0.11	0.41 ± 0.04
Nephelium lappaceum	0.23	1.0	0.83 ± 0.08	n/a
Persea americana	0.22	1.0	0.48 ± 0.09	0.35 ± n/a
Mammea americana	0.14	0.6	n/a	n/a
Mangifera indica	0.06	0.3	n/a	n/a
Syzigium malaccensis	0.04	0.2	0.60 ± 0.04	0.63 ± n/a
Other fruit tree species*	4.48	19.6	0.76 ± 0.09	n/a
Total*	22.81	100.0		

Values of wood specific gravity correspond to mean ± standard deviation. n/a = not available. *: includes *Licania operculipetala* and *Psidium guajava*

Correlation between biomass and tree allometric variables

A high linear correlation between above-ground biomass and tree dimensions was detected ($0.58 < r < 0.94$); stem diameter was a better explanatory variable than canopy area and total height, with a mean Pearson correlation coefficient of 0.93, 0.82 and 0.71, respectively; outliers were detected for fruit trees (Fig. 1). This analysis points out which allometric variables should be considered for the development of the models.

Above-ground biomass models

The best-fit models for total above-ground biomass or by component were those based on diameter (dbh or d_{30}) (Figs. 1, 2). In all cases, the best-fit models included logarithmic transformations of the variables (Fig. 2 and Table 3). These models had the best statistical performance (in terms of R^2, adjR^2, RSME, AIC and BIC) (Table 2). Between 93 and 96% of the variability found in the total above-ground biomass was

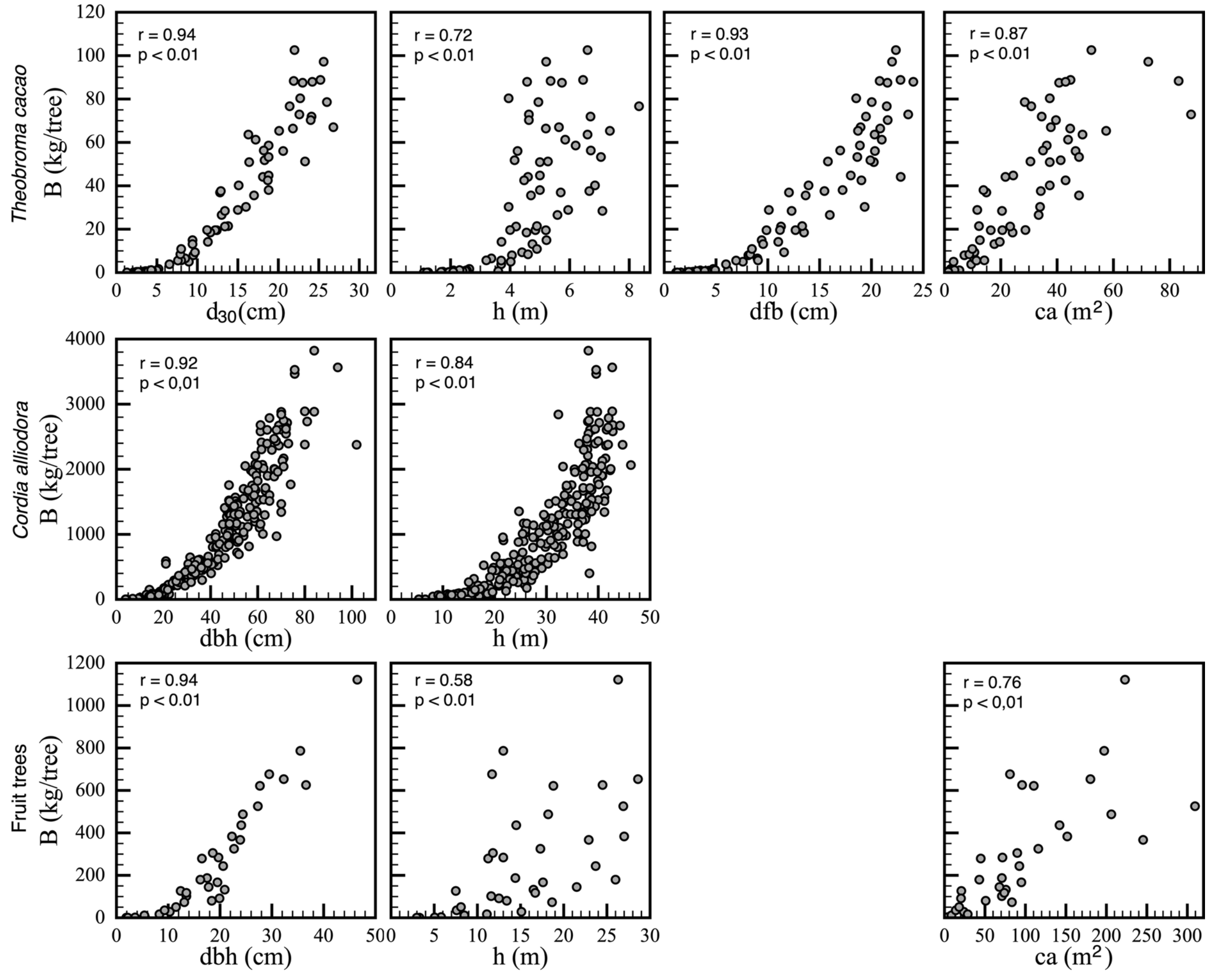

Fig. 1 Correlation between total above-ground biomass and tree size variables of the most dominant tree species in the cacao agroforestry systems in Talamanca, Costa Rica. B: above-ground biomass; d_{30}: trunk diameter at 30 cm height; dbh: trunk diameter at breast height; h: total height; dfb; diameter of first branch; ca: crown area; r: Pearson correlation coefficient with its respective p value

explained by trunk diameter. The analysis of residuals showed important bias (overestimation) in large trees (Fig. 2). For this reason, the model for *T. cacao* is recommended for a $d_{30} < 23$ cm whereas the models for *C. alliodora* and fruit trees must be used for trees with a maximum dbh of 70 and 32 cm, respectively (Fig. 2). The best-fit allometric models to estimate some components of biomass had high adjR^2 (>0.82), except in the case of small branches of fruit tree (adjR^2 = 0.54) (Table 2).

Best-fit models showed a higher accuracy than others published for the same species. In *T. cacao*, the model developed in this study has a MRE of 22%, much lower than the 140% by Smiley and Kroschel (2008) model which overestimated aboveground biomass in all sizes (Fig. 3). The MRE of this model for *C. alliodora* was lower than those from estimates with Segura et al. (2006) and Cole and Ewel (2006) models (37 vs 41 vs 62%, respectively). These two last models underestimated aboveground biomass in small tree sizes (Fig. 3). In the case of fruit trees, the MRE in this study was lower than Rathore et al. (2018), Saha et al. (2021), and Goodman et al. (2014) models (35 vs 46 vs 87 vs 274%, respectively). Rathore et al. (2018) and Saha et al. (2021) models overestimate whereas Goodman et al. (2014) model underestimated total aboveground biomass (Fig. 3).

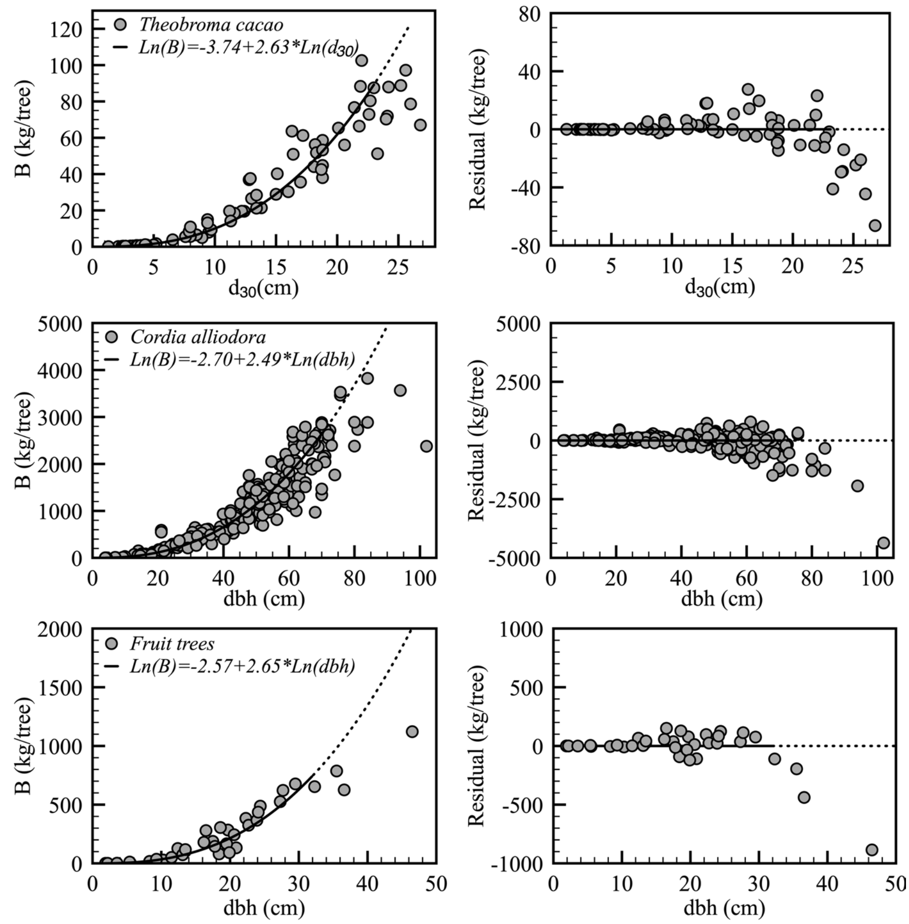

Fig. 2 Best-fit allometric models, and its corresponding residual plots, to estimate total above-ground biomass of the most dominant tree species in cacao agroforestry systems in Talamanca, Costa Rica. B: above-ground biomass (kg/tree); d_{30}: trunk diameter at 30 cm height (cm); dbh: trunk diameter at breast height (cm)

Discussion

WSG varied widely between tree species. In the case of *C. alliodora* average WSG was 0.47 g/cm^3, in agreement with reports by Segura et al. (2006) in Nicaragua, and Carpio (1992) in Costa Rica. In contrast, *Inga* in this study had a lower WSG than the one reported by Segura et al. (2006) in coffee plantations in Nicaragua (0.48 vs 0.57 g/cm^3, respectively). WSG of fruit trees (0.48–0.83 g/cm^3) agreed with values reported by Nagar et al. (2021) (0.48 to 0.63 g/cm^3). This variable is used for application of some biomass models (Zanne et al. 2009; Wu et al. 2017; Khan et al. 2020) and is critical for a precise estimation of biomass and carbon through Tier III (Nagar et al. 2021).

The BEF for *C. alliodora* averaged 1.25 with no variation between tree sizes, which disagree with Brown et al. (1989) and Segura and Kanninen (2005) in forests, and Segura et al. (2006) in coffee agroforestry systems who found a decrease in BEF with an increase in size. Trunk diameter had the best correlation with total above-ground biomass in all allometric models. Total height was not a good predictor of total above-ground biomass of neither shade trees nor *T. cacao* trees, due mainly to modifications of canopy architecture by pruning for crop management (Niether et al. 2018; Schneidewind et al. 2019) and shade regulation (Tscharntke et al. 2011; Riedel et al. 2019). Crown area, which showed a low correlation with above-ground biomass, is an easy but inaccurate variable to measure (Wang et al. 2016).

The best-fit models included logarithmic transformations that may correct heterocesdacity of the variance (Segura and Kanninen 2005; Segura et al. 2006; Andrade et al. 2018). The best models in this study are simple and based only on trunk diameter (d_{30} or dbh) such as those developed by Segura and Kanninen (2005) and Andrade et al. (2018). Local,

Table 3 Best-fit allometric models to estimate biomass (total above-ground and by components) of the most dominant tree species in cacao agroforestry systems in Talamanca, Costa Rica

Species/components	Model	R^2	$AdjR^2$	RMSE	AIC	BIC
Theobroma cacao						
Total above-ground	$Ln(B) = -3.74 + 2.63*Ln(d_{30})$	0.98	0.98	0.29	30.7	37.6
Stem and large branches	$Ln(B) = -8.12 + 4.02*Ln(d_{30})$	0.95	0.95	0.71	165.0	172.0
Small branches	$Ln(B) = -3.61 + 2.04*Ln(d_{30})$	0.92	0.92	0.48	107.0	114.0
Foliage	$Ln(B) = -4.31 + 1.93*Ln(d_{30})$	0.88	0.87	0.59	138.0	145.0
Cordia alliodora						
Total above-ground	$Ln(B) = -2.70 + 2.49*Ln(dbh)$	0.93	0.93	291	302.0	0.409
Stem	$Ln(B) = -3.35 + 2.60*Ln(dbh)$	0.92	0.92	371	381.0	0.473
Canopy	$Ln(B) = -3.78 + 2.34*Ln(dbh)$	0.93	0.93	242	252.0	0.374
Fruit tree species						
Total above-ground	$Ln(B) = -2.57 + 2.65*Ln(dbh)$	0.96	0.96	44	48.7	0.41
Stem and large branches	$Ln(B) = -3.21 + 2.79*Ln(dbh)$	0.96	0.96	46.3	51.0	0.42
Small branches	$Ln(B) = -2.58 + 0.379*dbh - 0.0057*dbh^2$	0.54	0.51	118	124.0	1.22
Foliage	$Ln(B) = -3.06 + 1.84*Ln(dbh)$	0.82	0.82	74.5	79.2	0.63

B: total above-ground biomass (kg/tree); d_{30}: trunk diameter at 30 cm height (cm); dbh: trunk diameter at breast height (cm); R^2: determination coefficient; $AdjR^2$: adjusted R^2; RMSE: root mean square error; AIC: Akaike Information Criterion; BIC: Bayesian Information Criterion

species-specific allometric models developed in this study give more accurate estimations of tree biomass than models developed from other regions (IPCC, 2003; Segura et al. 2006; Andrade et al. 2018). MRE for local models varied between 22–37% and 41–274% in models from other regions. Several authors argued the importance of developing local biomass models to reduce errors in biomass and carbon estimations (Andrade et al. 2018; Ubuy et al. 2018; Vorster et al. 2020). Allometric models in this study are developed for species that cover 80% of the total basal area of these agroforestry systems, underlining their importance for the accurate estimation of tree above-ground biomass and carbon in the region.

The number of trees sampled per species in another indicator of the model prediction uncertainty. According to Vorster et al. (2020), a model developed with a low number of trees could not represent true variability in tree growth forms. In this research, allometric biomass models tend to overestimate above-ground in large trees ($d_{30} > 23$ cm in *T. cacao*, dbh > 70 cm in *C. alliodora* and dbh > 32 cm in fruit trees), for this reason they are recommended for a specific range of sizes. The models herein developed had a good fit, except for the multispecies fruit tree models (Segura and Kanninen 2005; Fayolle et al. 2013; Flade et al. 2020).

Conclusions

The biomass of both cocoa and shade trees in cocoa agroforestry systems in Talamanca can be accurately estimated with models developed in this study. These local models can reduce the uncertainties to levels acceptable to Tier III (the highest level of accuracy) carbon monitoring requirements. The models in this study estimate above-ground biomass of species that cover 80% of the total basal area in these agroforestry systems.

Stem diameter in all species was the best predictor of total above-ground biomass, explaining 93–96% of total above-ground biomass, and 54–95% of biomass by component. Neither total height nor crown area were good predictors of above-ground biomass due to pruning and other management practices. Biomass models based exclusively on trunk diameter (d_{30} and dbh) are simple to use.

The biomass expansion factor (BEF) for *C. alliodora* estimated can be used to assess total above-ground biomass based on previous inventories or estimation of stem volume of this popular and widespread (in Latin America) timber species. This study also shows that BEF from timber species cannot be used to estimate above-ground biomass of fruit trees.

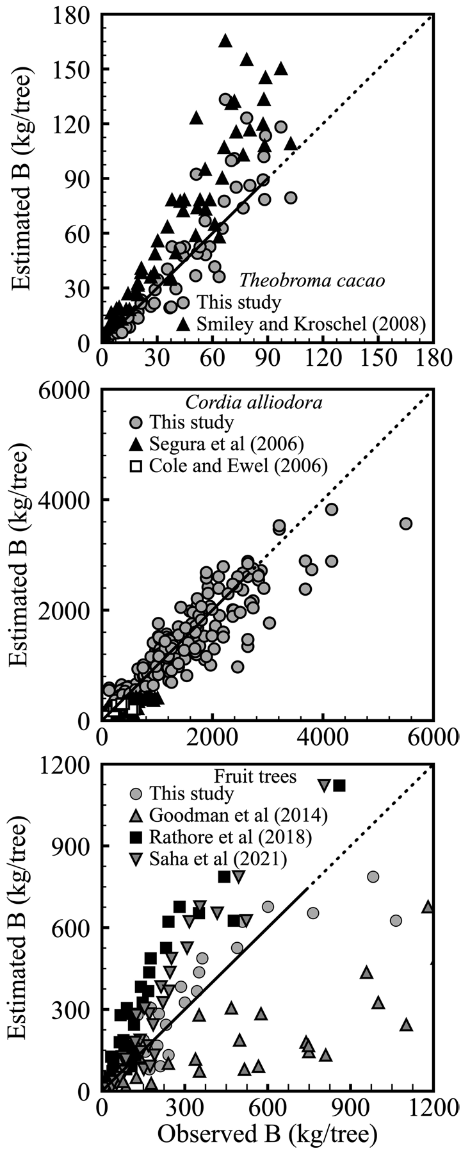

Fig. 3 Comparison between the best-fit models developed for the most dominant tree species in cacao agroforestry systems in Talamanca, Costa Rica and models developed by other authors. $Ln(B) = -3.741 + 2.626*Ln(d_{30})$ by this study and $B = 0.202*d_{50}^{2.112}$ by Smiley and Kroschel (2008) for *Theobroma cacao*. $Ln(B) = -2.70 + 2.49*Ln(dbh)$ by this study, $Log(B) = -0.755 + 2.072*Log(dbh)$ by Segura et al. (2006) and $B = 0.525 + 0.0015*dbh^2*h$ by Cole and Ewel (2006) for *Cordia alliodora*. $Ln(B) = -2.57 + 2.65*Ln(dbh)$ by this study, $Ln(B) = -2.6512 + 2.0212*Ln(dbh) + 0.9302*Ln(h) + 1.3257*Ln(g)$ by Goodman et al. (2014), $B = 0.069*cd^{2.456}$ by Rathore et al. (2018) and $Ln(B) = -0.227 + 1.802*Ln(dbh)$ by Saha et al. (2021) for fruit trees. B: total above-ground biomass (kg/tree); d_{30}: trunk diameter at 30 cm height (cm); dbh: trunk diameter at breast height (cm); h: total height (m); g: specific gravity (g/cm^3); cd: collar diameter (cm)

The allometric models developed in this study will be useful in the formulation of carbon projects in Talamanca (Costa Rica) and, with validation, in other humid tropical regions. The role of cacao agroforestry systems in climate change mitigation is increasingly promoted. Carbon credits for cacao agroforestry systems can be produced in Clean Development Mechanism (CDM), Reducing Emissions from Deforestation and forest Degradation (REDD+) programs, and in Voluntary Carbon Markets (VCM).

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