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Allometric Equations for Volume, Biomass, and Carbon in Commercial Stems Harvested in a Managed Forest in the Southwestern Amazon: A Case Study

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Abstract: Forests in the southwestern Amazon are rich, diverse, and dense. The region is of high ecological importance, is crucial for conservation and management of natural resources, and contains substantial carbon and biodiversity stocks. Nevertheless, few studies have developed allometric equations for this part of the Amazon, which differs ecologically from the parts of Amazonia where most allometric studies have been done. To fill this gap, we developed allometric equations to estimate the volume, biomass, and carbon in commercial trees with diameter at breast height (DBH) ≥ 50 cm in an area under forest management in the southeastern portion of Brazil's state of Acre. We applied the Smalian formula to data collected from 223 felled trees in 20 species, and compared multiple linear and nonlinear models. The models used diameter (DBH) measured at 1.30 m height (d), length of the commercial stem (l), basic wood density (p), and carbon content (t), as independent variables. For each dependent variable (volume, biomass, or carbon) we compared models using multiple measures of goodness-of-fit, as well as graphically analyzing residuals. The best fit for estimating aboveground volume of individual stems using diameter (d) and length (l) as variables was obtained with the Spurr model (1952; logarithmic) (root mean square error (RMSE) = 1.637, R^2 = 0.833, mean absolute deviation (MAD) = 1.059). The best-fit equation for biomass, considering d , l , and p as the explanatory variables, was the Loetsch et al. (1973; logarithmic) model (RMSE = 1.047, R^2 = 0.855, MAD = 0.609). The best fit equation for carbon was the Loetsch et al. (1973; modified) model, using the explanatory variables d , l , p , and t (RMSE = 0.530, R^2 = 0.85, MAD = 0.304). Existing allometric equations applied to our study trees performed poorly. We showed that the use of linear and nonlinear allometric equations for volume, biomass, and carbon can reduce the errors and improve the estimation of these metrics for the harvested stems of commercial species in the southwestern Amazon.

Keywords: managed forests; carbon sequestration; state Acre; Brazil; tropical forest; rainforest; timber

1. Introduction

Forest management projects in Brazil are required to have estimates of the volume of the stems of commercial trees in the forest that are identified in a “100% survey” of trees > 50 cm diameter at breast height (DBH: measured 1.30 m above the ground or just above any buttresses). The “commercial stem” refers to the portion of the trunk from the point where it is cut when harvested to the first significant branch. Beginning in the second year of forest management activities, the managers must present annual operational plans (POA—Brazilian acronym) [1]. The POAs must include a volumetric equation developed specifically for the forest being managed. The reliability of this information is limited by the paucity of data and by variations in relevant parameters among different parts of the Amazon region. The present paper derives allometric equations for estimating these volumes in the state of Acre in the southwestern portion of Brazil’s Amazon region, which is both one of Amazonia’s most active areas for forest management and the location of forests that differ in important ways from those in other parts of the region. In addition to volume, we also derive equations for biomass and carbon in the commercial stems, although the legal regulations only demand specific equations for volume [1].

While our study is limited to estimating volume, biomass, and carbon in harvested stems (not in whole trees or in the forest as a whole), the information in the study is relevant to efforts to estimate biomass and carbon stocks in products and the respective quantities removed in the stems in the forest management system. Calculations of the role of forest management in climate change (and potentially to climate-change mitigation) also require information on the biomass and carbon removed from the forest in harvested logs and the amounts subsequently incorporated into wood products with different lifetimes. Allometric equations for the harvested logs provide information for the initial step in calculating these carbon stocks and flows. Note, however, that our study does not include data on wood waste (such as stumps and crowns left in the forest), nor on collateral damage, or on trees in non-commercial species and in DBH classes < 50 cm. Besides, the quantification of forest volume, biomass, and carbon also allows the estimation of forest yield in the short- and long-term [2–4].

Allometric models are common tools used to estimate forest volume, biomass, and carbon based on individual or multiple independent variables, such as diameter at breast height, total height, and wood density. Reliable estimates for large trees are especially important both because these are the individuals of commercial interest and because they store a disproportionately large share of the forest’s carbon stock. Lack of sufficient data on large individuals is an important weakness in many existing allometric equations for Amazonian trees.

The literature presents a number of equations for estimating forest volume and the stocks of biomass and carbon for the Amazon region [2,5–14]. However, equations must be generated for the different parts of the Amazon region (each of which has different climatic and environmental conditions) and must respond to forest structural composition and physiognomy [11,15]. Few published studies have developed equations specifically for the southwestern Amazon, and in particular, for the Brazilian state of Acre [16].

The state of Acre has 18 distinct forest types [17], some of which include bamboo [18]. In addition, the state of Acre was the epicenter of the 2005 drought and one of the epicenters of the 2010 drought [19], which contributed to the occurrence of intense forest fires [20]. Droughts and fires in Amazonia change the species composition, structure, and growth of forests [21–23] and reduce forest biomass and carbon stocks [4,24,25]. This is believed to contribute to the low biomass and carbon stocks in this part of Amazonia ($\approx 246 \pm 90 \text{ Mg ha}^{-1}$) [17] compared to other parts of the Amazon ($285\text{--}333.25 \text{ Mg ha}^{-1}$) [7–26]. The distinct nature of forests in southwestern Amazonia means that use of pantropical equations or of equations developed for other parts of the Amazon can lead to erroneous estimates of

forest biomass and carbon stocks [17,27,28]. In addition, many of these equations are based on small numbers of plots with specific species groups and do not include large trees with diameter at breast height > 80 cm [11].

The limitations of equations from other locations reinforce the need for location-specific studies, especially for managed forests, which have their dynamics influenced by many factors. Managed forests in the state of Acre are subject to logging, severe droughts and, in part of the state, the presence of bamboo. Reducing uncertainties in forestry production in Acre therefore requires developing equations specifically for this state [28,29]. In this study we generated allometric equations to estimate the volume, biomass, and carbon stocks in the stems of commercial trees in an area under forest management in the state of Acre. Thus, it is expected to contribute to reducing uncertainties in forest production estimates in the southwestern portion of the Brazilian Amazon. Although the data presented here are limited to commercial stems, this information is also valuable for estimates of whole-forest biomass needed for studies of the forest's role in global climate change.

2. Materials and Methods

2.1. Study Area

The study was conducted in Fazenda Antimari I and II ($9^{\circ}23'43''\text{S}$, $67^{\circ}58'50''\text{W}$), a private property located in the southwestern Amazon in the municipality (county) of Porto Acre, Acre, Brazil (Figure 1). Most of the vegetation in the managed area is classified as “dense forest,” and a small part is classified as “open forest with presence of bamboo” [30].

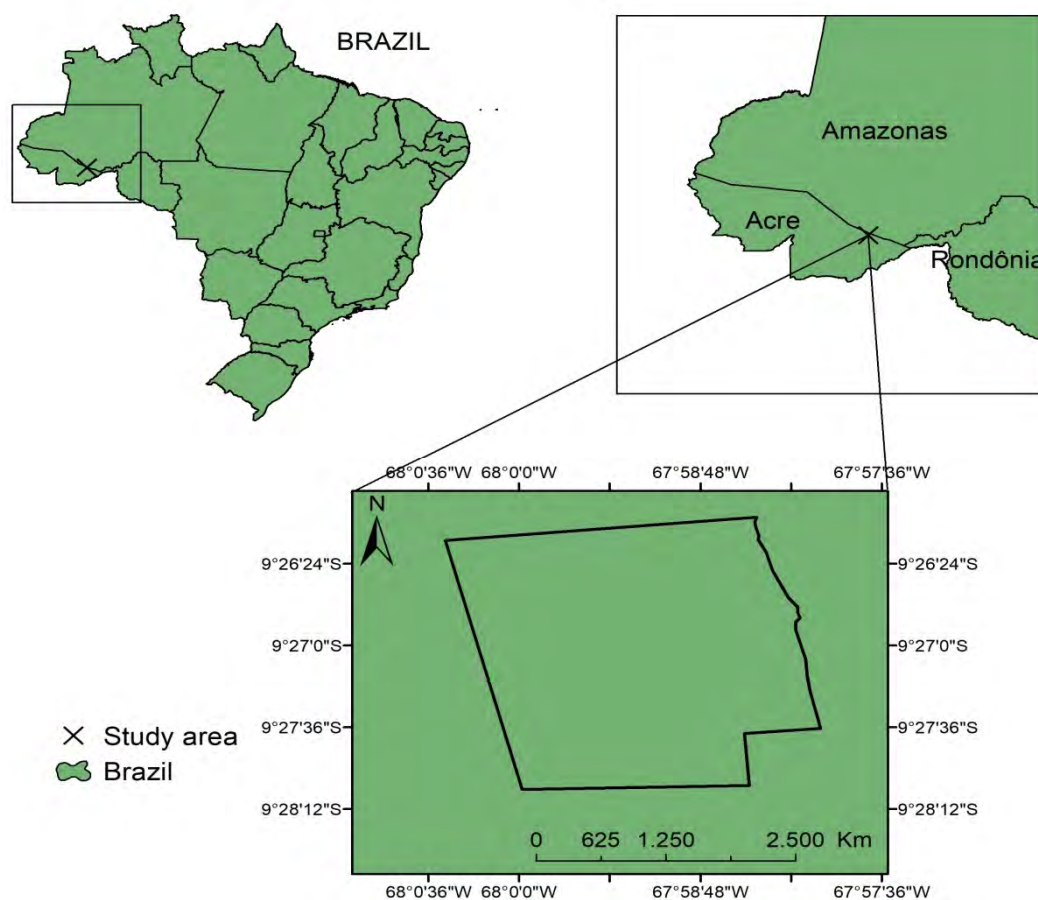


Figure 1. Location of the study area in the southwestern Amazon, in the municipality of Porto Acre, Acre, Brazil.

The climate of the region under the Köppen classification is Am (tropical monsoon) [31]. The average annual temperature is 24.5 °C [32] and annual precipitation ranges from 1750 to 2250 mm. Most of the precipitation falls between October and May, with intense rainfall from January to March. Forest harvest operations take place during the dry season, between June and September [32].

The predominant soils are red argisols (Ultisols) and dystrophic yellow-red latosols (Oxisols) [30,33]. The topography of the region is mostly flat, with slope around 5% [34]. The site has altitudes between 220 and 300 m above mean sea level [33].

The study site was a forest block 1253 ha in area, 386 ha of which was designated for environmental protection and 867 ha for partial harvesting [30]. The forest inventory was carried out by the management company in May 2015 in 100% of the logging area. The company's "sustainable forest management plan" was approved in 2016 by the Acre Environment Institute (IMAC—Brazilian acronym).

2.2. Selection Criteria for Commercial Tree Species

We used stem density and basal area [35] to select tree species for estimation of volume, woody biomass, and wood density. We used data from the forest inventory provided by the company, in which all trees of commercial interest with DBH ≥ 50 cm were measured. All scientific names were checked against the Brazil Flora 2020 database [36].

We selected the 20 species of commercial interest with the highest frequencies of occurrence (stems ha^{-1}) and basal areas ($\text{m}^2 \text{ha}^{-1}$); these species account for 85.9% of the total commercial basal area at the site. The number of individuals sampled per species was proportional to the relative density or frequency of occurrence (stems ha^{-1}) of each species [37]. Within each species we sampled individuals across a range of diameter classes; the number of trees sampled in each class represented the diameter distribution of the trees recorded in the company's forest inventory.

As our sampled trees were drawn from the set of individuals harvested in the commercial logging operation, the forest management company's selection of individuals for harvesting makes the sample differ from the natural forest's total population of individuals in the same diameter classes. Hollow trees are not harvested if detected prior to felling by a check made by penetrating the base of the trunk with a chain saw; in cases where a tree is felled and found to be hollow, the log is discarded. Our sample did not include any hollow logs. In a study of 61 reduced-impact forest management projects in seven tropical countries, Ellis et al. [38] found that hollows represented an average of 0.5% of total felled tree biomass, including non-harvested portions of the trees.

As is the practice throughout the management area we studied, trees in our study were all cut 30 cm above the ground, including those with buttresses. We note that Brazilian regulations allow trees without buttresses to be cut up to 40 cm above the ground (IBAMA Execution Standard n° 1 of 24 April 2007), and there is no height limit for trees with buttresses; many forest-management operations in tropical countries cut the trees at greater heights above the ground. In our study area buttresses were cut from the tree before felling and were left in the forest. Eight of the 18 genera in our sample had buttresses.

2.3. Determination of Volume and Collection of Stem Wood Disks

Volume measurements and collection of wood disks from the stems were performed at the log landings. We estimated stem volume using the Smalian method [39]. First, we measured diameters along the stem at 0.0, 0.30, and 1.0 m from the stump cut. We then measured diameters every 2.0 m until the total length of the commercial log was reached. We calculated the commercial volume using the formula $V = \frac{AS_1 + AS_2}{2} \cdot L$, where AS_1 and AS_2 = stem cross-sectional areas with bark in m^2 , obtained at the two ends of each section, and L = length of each section in m [37,40]. For each section we collected a wood disc from the base of the section to determine the basic density of the wood and the carbon content.

DBH was measured on the standing trees prior to felling. The measurement was made 1.3 m above the ground or above any buttresses. DBH of each tree was also measured in the 100% survey of

commercial trees performed by the forest-management company as a prerequisite for approval of the management plan.

2.4. Determination of Wood Density and Carbon Content of the Stem

Wood disks collected in the field were taken to the laboratory. We cut a wedge from each disk and submerged it in water for 21 days. We then used the immersion method to obtain the saturated volume of the wet wedges. Wedges were then oven dried at 103 ± 2 °C until weight stabilized. We calculated the basic wood density of each sample as the ratio of dry weight (g) to saturated volume (cm^3) [41]. Species-specific basic wood density was calculated as an average of the densities from all samples of each species [11,41]. We estimated stem biomass by multiplying the commercial stem volume by the basic wood density [2,37].

Species carbon content determination was based on a random sample of wedges of each species. These samples were ground, sieved, and completely incinerated at 1200 °C in a universal analyzer (Elemental, model Vario Micro Cube). We obtained the carbon content as the sum of the elements after subtracting the ash content. Species mean carbon content was calculated as an average of the carbon contents of each sampled individual of the species. We multiplied the individual biomass by the species mean carbon content to obtain the carbon stock for each tree stem.

2.5. Models Tested

We tested six models (three linear and three nonlinear) to estimate commercial aboveground volume (V , in m^3). We used DBH (d , in cm) and commercial stem length (l , in m) or a combination of d and l as independent variables (Table 1). Similarly, we tested six models to estimate the aboveground woody biomass (B , in Mg). As independent variables we used diameter (d , in cm), commercial stem length (l , in m), and basic wood density (p , in g cm^{-3}), both individually and combined. To estimate the carbon stock (C , in Mg) we tested five models (Table 1). The independent variables used in these models were diameter (d , in cm), commercial stem length (l , in m), basic wood density (p , in g cm^{-3}), and carbon content (t , in decigrams kg^{-1}).

Table 1. Linear and nonlinear regression models tested to estimate volume, biomass, and carbon of commercial stems.

No	Model	Type	Author
Volume			
MV1	$\ln(V) = \beta_0 + \beta_1 \ln(d) + \epsilon$	Linear	Husch (1963; logarithmic) [42]
MV2	$\ln(V) = \beta_0 + \beta_1 \ln(d^2l) + \epsilon$	Linear	Spurr (1952; logarithmic) [43]
MV3	$\ln(V) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(l) + \epsilon$	Linear	Schumacher and Hall (1933; logarithmic) [44]
MV4	$V = \beta_0 d^{\beta_1} + \epsilon$	Linear	Husch (1963) [42]
MV5	$V = \beta_0 (d^2l)^{\beta_1} + \epsilon$	Nonlinear	Spurr (1952) [43]
MV6	$V = \beta_0 d^{\beta_1} l^{\beta_2} + \epsilon$	Nonlinear	Schumacher and Hall (1933) [44]
Biomass			
MB1	$\ln(B) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(p) + \epsilon$	Linear	Chave et al. (2005) [10]
MB2	$\ln(B) = \beta_0 + \beta_1 \ln(d^2l) + \beta_2 \ln(p) + \epsilon$	Linear	Loetsch et al. (1973) [45]
MB3	$\ln(B) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(l) + \beta_3 \ln(p) + \epsilon$	Linear	Schumacher and Hall (1933; logarithmic modified) [44]
MB4	$\ln(B) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(l) + \epsilon$	Linear	Schumacher and Hall (1933; logarithmic) [44]
MB5	$B = \beta_0 d^{\beta_1} l^{\beta_2} + \epsilon$	Nonlinear	Schumacher and Hall (1933) [44]
MB6	$B = \beta_0 d^{\beta_1} l^{\beta_2} p^{\beta_3} + \epsilon$	Nonlinear	Schumacher and Hall (1933; modified) [44]
Carbon			
MC1	$\ln(C) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(l) + \beta_3 \ln(p) + \beta_4 \ln(t) + \epsilon$	Linear	Schumacher and Hall (1933; logarithmic) [44]
MC2	$\ln(C) = \beta_0 + \beta_1 \ln(d^2l) + \beta_2 \ln(p) + \beta_3 \ln(t) + \epsilon$	Linear	Loetsch et al. (1973; modified) [45]
MC3	$\ln(C) = \beta_0 + \beta_1 \ln(d^2l) + \beta_2 \ln(pt) + \epsilon$	Linear	Loetsch et al. (1973; modified) [45]
MC4	$\ln(C) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(l) + \beta_3 \ln(p) + \epsilon$	Linear	Schumacher and Hall (1933; logarithmic modified) [44]
MC5	$\ln(C) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(l) + \epsilon$	Linear	Schumacher and Hall (1933; logarithmic modified) [44]

Where: $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$ are the model parameters (coefficients of the independent variables).

Least-squares regression analysis was used to derive the allometric linear models for estimating volume, biomass, and carbon [46–48]. We back-transformed the estimated values of logarithmic equations to original units to allow comparison with other published equations. We also used a

correction factor [10] to remove the bias associated with logarithmic regression, based on the root mean square error (RMSE): $CF = \exp\left(\frac{RMSE^2}{2}\right)$.

The coefficient of determination (R^2), the root mean square error (RMSE), and mean absolute deviation (MAD) were used as goodness-of-fit criteria to evaluate the estimated linear allometric equations for volume, biomass, and carbon. R^2 is the proportion of variation in the dependent variable explained by the regression equation. RMSE measures the average distance between the observed values and those predicted by the regression equation. MAD is an estimate of average error:

$MAD = \frac{1}{n} \sum_{i=1}^n |x_i - \bar{x}|$, where x represents volume, biomass, or carbon. MAD serves as an accuracy indicator for the estimates of volume, biomass, and carbon generated for the individual trees [2,10,13,48]. We used RMSE and MAD to select the best nonlinear equations. We evaluated residuals graphically to ensure assumptions concerning homoscedasticity and normality were met. The Akaike information criterion (AIC) was also used, providing an additional criterion to select the equation with the best fit [10,49,50]. All statistical analyses were performed in R software, version 3.4.21 [51].

3. Results

Two hundred twenty-three commercial trees had their commercial stems cut into sections and measured. These individuals accounted for 20 species, 18 genera, and 10 families (Table 2). Stem diameter ranged from 50.4 to 150 cm, with mean \pm standard deviation of 79.6 ± 19.8 . Basic wood density and carbon content had average values of 0.56 g cm^{-3} (± 0.16) and 49.0% (± 5.4), respectively.

Table 2. Species used and range of applicability for equations to estimate volume, biomass, and carbon in a forest-management area in Acre state, Brazil.

Family	Scientific Name	N	DBH (cm)		ρ (g cm ⁻³)	
			Range	Mean (\pm SD)	Range	Mean (\pm SD)
Bignoniaceae Juss.	<i>Handroanthus serratifolius</i> (Vahl) S.Grose	8	50.9–78	61.8 \pm 9.5	0.76–0.87	0.82 \pm 0.04
Combretaceae R.Br.	<i>Buchenavia tetraphylla</i> (Aubl.) R.A.Howard	9	50.4–89.1	70.7 \pm 12.9	0.64–0.76	0.69 \pm 0.04
Euphorbiaceae Juss.	<i>Hura crepitans</i> L.	6	74.9–121	96.5 \pm 17.1	0.27–0.43	0.36 \pm 0.05
Fabaceae Lindl.	<i>Albizia niopoides</i> (Spruce ex Benth.) Burkart	7	54.7–79.3	65.8 \pm 8.1	0.61–0.68	0.64 \pm 0.03
	<i>Apuleia leiocarpa</i> (Vogel) J.F.Macbr.	13	64.3–130.5	95.7 \pm 17.6	0.71–0.83	0.77 \pm 0.03
	<i>Barnebydendron riedelii</i> (Tul.) J.H.Kirkbr.	5	66.8–85.9	77 \pm 7.6	0.54–0.62	0.57 \pm 0.03
	<i>Copaifera multijuga</i> Hayne	6	78.9–136.9	97.8 \pm 21.8	0.47–0.60	0.52 \pm 0.05
	<i>Dipteryx odorata</i> (Aubl.) Willd.	11	70–123.5	90.4 \pm 16.2	0.75–0.89	0.80 \pm 0.04
	<i>Hymenaea courbaril</i> L.	8	66.2–121	93.5 \pm 17.6	0.71–0.84	0.76 \pm 0.04
	<i>Parkia paraensis</i> Ducke	20	51.2–149.6	86.9 \pm 27	0.38–0.56	0.46 \pm 0.06
	<i>Schizolobium parahyba</i> var. <i>amazonicum</i> (Huber ex Ducke) Barneby	16	50.9–89.1	62.8 \pm 10.8	0.31–0.65	0.48 \pm 0.08
	<i>Eschweilera grandiflora</i> (Aubl.) Sandwith	13	55.4–111.4	76.4 \pm 16.4	0.69–0.79	0.73 \pm 0.03
Malvaceae Juss.	<i>Ceiba pentandra</i> (L.) Gaertn.	4	99.9–149.9	130.2 \pm 24.4	0.27–0.32	0.29 \pm 0.03
	<i>Ceiba samauma</i> (Mart.) K.Schum.	22	66.5–111.4	78.9 \pm 10.3	0.42–0.65	0.51 \pm 0.06
	<i>Sterculia apetala</i> (Jacq.) H.Karst.	5	70–82.8	75.9 \pm 5.3	0.31–0.47	0.38 \pm 0.06
Meliaceae A.Juss.	<i>Cedrela odorata</i> L.	8	57.3–118.1	70.7 \pm 20.2	0.34–0.47	0.43 \pm 0.044
Moraceae Gaudich.	<i>Castilla ulei</i> Warb.	37	56.7–121	79.7 \pm 15.1	0.34–0.48	0.41 \pm 0.04
	<i>Ficus insipida</i> Willd.	4	74.8–99.9	82.5 \pm 11.8	0.34–0.39	0.35 \pm 0.03
Anacardiaceae R.Br.	<i>Astronium lecointei</i> Ducke	6	52.6–96.4	62.7 \pm 16.7	0.73–0.85	0.82 \pm 0.05
Lecythidaceae A.Rich.	<i>Eschweilera bracteosa</i> (Poepp. ex O.Berg) Miers	15	54.1–95.5	68.1 \pm 10.2	0.54–0.72	0.65 \pm 0.05
Total		223	50.4–149.9	79.6 \pm 19.8	0.27–0.89	0.56 \pm 0.16

Models for Volume, Biomass, and Carbon

We tested six models to estimate stem volume. Goodness-of-fit criteria were computed for all models and are given in Table 3. All of the parameters in the tested models were significant at the 1% probability level. Linear models MV2 and MV3 had the best fits, both with the highest value of R^2 (0.83) and lowest value of MAD (1.059). Model MV2 was the best-fit linear model, since it had the lowest values of RMSE (1.637) and AIC (856.53). Among the nonlinear models (Models MV4, MV5, and MV6), Model MV6 had the best fit, with the lowest values of RMSE (1.634) and MAD (1.066) and the second-lowest value of AIC (856.76; Table 3).

Table 3. Volume: estimated regression parameters (* = $p < 0.001$), root mean square error (RMSE), coefficient of determination (R^2), Akaike information criterion (AIC), mean absolute deviation (MAD), and correction factor (CF) for the six tested models for volume.

Model	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	RMSE	R^2	AIC	MAD	CF
MV1	−6.51250 *	1.88558 *		2.318	0.67	1011.70	1.621	1.0527
MV2	−8.23500 *	0.8734 *		1.637	0.83	856.53	1.059	1.0242
MV3	−8.23250 *	1.74399 *	0.87702 *	1.641	0.83	858.71	1.059	1.0243
MV4	0.0014095 *	1.909563 *		2.317	−	1011.52	1.615	−
MV5	0.000322 *	0.859100 *		1.635	−	856.16	1.068	−
MV6	0.000313 *	1.7610 *	0.80000 *	1.634	−	856.76	1.066	−

Where: $\hat{\beta}_0$, $\hat{\beta}_1$, $\hat{\beta}_2$ are the intercept and the estimated regression parameters (coefficients of the variables in the order they appear in each equation).

We tested six regression models to estimate biomass. Models MB2 and MB3 had the highest R^2 values (0.86), but Model MB2 had the smallest RMSE (1.047), MAD (0.609), and AIC (658.12) values. Therefore, Model MB2 was selected as the best-fit linear model for biomass estimation (Table 4). Model MB6 was selected as the better of the two nonlinear models (Models MB5 and MB6) in terms of the goodness-of-fit criteria (Table 4).

Table 4. Biomass: estimated regression parameters (* = $p < 0.001$), root mean square error (RMSE), coefficient of determination (R^2), Akaike information criterion (AIC), mean absolute deviation (MAD), and correction factor (CF) for the six tested models for biomass.

Model	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	RMSE	R^2	AIC	MAD	CF
MB1	−6.51456 *	1.93113 *	1.317114 *		1.296	0.78	753.60	0.857	1.048296
MB2	−8.26306 *	0.87461 *	0.97690 *		1.047	0.86	658.12	0.609	1.024296
MB3	−8.26077 *	1.73728 *	0.89154 *	0.96957 *	1.052	0.86	661.39	0.611	1.024398
MB4	−9.16151 *	1.52337 *	1.35403 *		1.696	0.62	873.64	1.027	1.059213
MB5	0.0002996 *	1.367517 *	1.254061 *		1.679	−	869.06	1.049	−
MB6	0.0003331 *	1.821004 *	0.712642 *	1.15938 *	1.025	−	649.79	0.615	−

Where: $\hat{\beta}_0$, $\hat{\beta}_1$, $\hat{\beta}_2$, $\hat{\beta}_3$ are the intercept and the estimated regression parameters (coefficients of the variables in the order they appear in each equation).

We tested five linear-regression models to estimate carbon stock. Models MC2 and MC3 had the highest R^2 values (0.87) and the smallest RMSE, MAD, and AIC values. Model MC3 was selected as the best-fit model due to its simplicity and statistical significance (Table 5). For each equation a plot of the distribution of residuals and of predicted versus observed values, and a histogram of the residuals, is provided in the Supplementary Material (Annexes 1–4).

Table 5. Carbon stock: estimated regression parameters (* = $p < 0.001$), root mean square error (RMSE), coefficient of determination (R^2), Akaike information criterion (AIC), mean absolute deviation (MAD), and correction factor (CF) for the five models of carbon stock tested.

Model	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	RMSE	R^2	AIC	MAD	CF
MC1	−6.59205 *	1.73329 *	0.90503 *	0.91298 *	3.45897 *	0.503	0.87	333.95	0.294	1.023900
MC2	−6.62824 *	0.87661 *	0.92627 *	3.411260 *		0.500	0.87	330.55	0.293	1.023819
MC3	−8.26837 *	0.87431 *	0.98260 *			0.530	0.85	355.15	0.304	1.024306
MC4	−8.93939 *	1.73890 *	0.88605 *	0.99259 *		0.551	0.84	373.57	0.310	1.212228
MC5	−9.86152 *	1.51991 *	1.35952 *			0.883	0.59	582.37	0.526	1.061534

Where: $\hat{\beta}_0$, $\hat{\beta}_1$, $\hat{\beta}_2$, $\hat{\beta}_3$, $\hat{\beta}_4$ are the intercept and the estimated regression parameters (coefficients of the variables in the order they appear in each equation).

4. Discussion

In this study we fit allometric equations for volume, biomass, and carbon stock of the commercial stems of individuals with DBH ≥ 50 cm in 20 commercial tree species in a managed forest in the southwestern Amazon. Model MV2, which includes commercial stem length and DBH as independent variables, provided the best fit to estimate volume of commercial stems in our study area (Tables 1 and 3). Of course, commercial stem volume, biomass, and carbon should not be confused with these parameters for whole trees or for the entire forest. Nevertheless, these properties of stems represent one of the factors for which information is needed for estimating the corresponding parameter values in studies for use in quantifying the role of Amazonian forests and forest management in global greenhouse-gas emissions.

The commercial stem length plus the stump height represents the commercial height, which is, in practice, difficult to measure accurately for standing trees in tropical forests. Many authors support the inclusion of height in volumetric models to guarantee biologically realistic models [2,5,11,52–55]. Trees in Acre are shorter than those in central Amazonia both because the forests in Acre have more individuals of species with lower stature and because individuals of any given diameter of the same species are shorter in Acre [55].

In estimating aboveground biomass, it is important to include in the model all structural variables that affect biomass, including those that vary geographically [11,15,56–58], such as total height (reflected in commercial stem length) and basic wood density [2,10]. This was observed in the present study: Models MB2 and MB6, which included basic wood density as an explanatory variable, had the best fits for biomass estimation (Table 4). Basic wood density has been shown to be an important variable for estimating biomass [59–61], but it is often not used due to the difficulty of field collection and dependence on further laboratory analysis. Instead of directly determining this variable, many studies rely on databases such as GlobAllomeTree and the Global wood density database [62,63]. This facilitates inclusion of basic wood density as an explanatory variable in biomass models, which can reduce model uncertainties [2,10,56,61].

The 0.56 g cm^{-3} mean basic density of the wood in the stems we studied is very close to the value of 0.54 g cm^{-3} found by Nogueira et al. [60] for trees from Acre. Trees in the Manaus area in central Amazonia are much denser, averaging 0.67 g cm^{-3} [53]. As most of the available data on Amazonian wood density has been from studies in locations such as Manaus, Santarém, and Belém, means for Amazonia based on all available data, such as the 0.69 g cm^{-3} value derived by Fearnside [64], result in substantial overestimation of biomass if applied to southwest Amazonia.

In our study, Model MB2: Loetsch et al. (logarithmic) [45] (Tables 1 and 4) provided the best fit for estimating biomass utilizing site-specific basic wood density. Our best equation (MB2) underestimated commercial stem biomass by 2.97% (Table 6). This deviation from the observed value is small when compared to other equations that have been generated for the Brazilian Amazon. In order to make valid comparisons of our equation with equations that have been developed for the aboveground biomass of Amazonian trees, one first must calculate the amount of the aboveground biomass that is in the commercial stems. In these cases an approximation can be made of the commercial stem biomass by

applying each equation to our sampled trees and subtracting the stump biomass from our study and the crown biomass calculated as a proportion of aboveground biomass as estimated in the Peruvian portion of southwest Amazonia by Goodman et al. [11], where the crown represented 44% of the aboveground biomass. Comparisons were made with studies that have generated equations in Brazilian Amazonia: Higuchi et al. [65] (central Amazonia), Nogueira et al. [14] (southern Amazonia), and Chave et al. [2] (a pantropical equation that includes the Nogueira et al. [14] dataset from Amazonia). The study by Nogueira et al. [14], which has an equation for biomass of the commercial stem plus the stump, can be compared to our study by subtracting the estimated stump biomass calculated in our study.

Table 6. Comparison of biomass equations when applied to the 223 trees > 50 cm diameter at breast height (DBH) in our dataset.

Author	Equation (a)	CBB	DEV	PDO	SAE
This study	$\ln(\text{CBB}) = -8.26306 + 0.87461 \ln(d^2l) + 0.97690 \ln(p)$	784.51	−24.04	−2.97	
Higuchi et al., 1998 [65]	$\text{FAGB} = 0.0009 \times d^{1.585} \times h^{2.651}$	229.0	−579.5	−71.7	
Chave et al., 2014 [2]	$\text{AGB} = 0.0673 \times (pd^2h)^{0.976}$	384.42	−424.13	−52.46	
Nogueira et al., 2008 [14]	$\ln(\text{TBB}) = -1.929 + 2.335 \times \ln(d)$	956.89	+148.34	+18.35	
Nogueira et al., 2008 [14]	$\ln(\text{AGB}) = -1.716 + 2.413 \times \ln(d)$	1045.10	+236.55	+29.26	d'Oliveira et al., 2012 [27]
S. Brown et al., 1989 [66]	$\text{AGB} = 34.4703 - 8.0671 \times d + 0.6589 \times d^2$	181.90	−626.65	−77.50	I.F. Brown et al., 2009 [67]
S. Brown, 1997 [68]	$\text{AGB} = 42.69 - 12.800 \times d + 1.242 \times d^2$	973.70	+165.15	+20.43	Salimon et al., 2011 [17]

CBB = commercial stem biomass (total for 223 trees) estimated, as appropriate, using crown percentage of AGB = 44% from Goodman et al. [11] and stump to 30 cm as percentage of CBB = 2.34% from this study (Mg); DEV = deviation from observed value ($D - 808.55$) (Mg); PDO = percent deviation from observed value ($E/808.55 \times 100$) (%); SAE = studies in Acre that used this equation. CBB = commercial stem biomass (Mg); AGB = aboveground biomass (kg); FAGB = fresh aboveground biomass (conversion to dry weight AGB and CBB based on 43% water content of forest near Manaus measured by da Silva [69]); TBB = total stem biomass (including stump) (kg); d = diameter (cm); l = commercial stem length (m); h = total height (m) (note: values from the management company's 100% inventory); p = basic wood density (g cm^{-3}).

The equation developed by Higuchi et al. [65] for fresh aboveground biomass based on 315 trees ≥ 5 cm DBH (of which 71 were ≥ 20 cm DBH) in the central Amazon, which includes DBH and total height, underestimated biomass of the commercial stems of individual trees measured in the present study by 71.7% (Table 6) on average. When applied to trees in southern and southwestern Amazonia, the Higuchi et al. [65] equation has been found to underestimate the biomass of trees >66 cm DBH and to overestimate the biomass of smaller ones (Figure 2 in [14]). The Higuchi et al. [65] equation is the one that has been used for calculating CO₂ emissions from deforestation in Brazil's national communications to the UNFCCC (e.g., [70]).

The Nogueira et al. [14] equation, which includes only DBH, for calculating total stem (including stump) biomass in the “arc of deforestation” in the southern part of Brazilian Amazonia, overestimated the biomass of individual commercial stems in our dataset by 18.4% after adjustment for the stump (Table 6). The Higuchi et al. [65] and Nogueira et al. [14] datasets include very few individuals with DBH > 60 cm and none with DBH > 131 cm. Note that our dataset is for trees with DBH > 50 cm, and that the equations from other studies may perform better for smaller trees.

Nogueira et al. [14] developed their equation for aboveground biomass in southern Amazonia based on a total of 263 trees that were felled and weighed in Mato Grosso and Pará states. Mean basic density of stems in the Nogueira et al. [14] study was 0.593 g cm^{-3} , or 5.89% greater than the 0.56 g cm^{-3} mean for the stems in the present study in Acre. Both studies determined basic wood density from disks cut from the trunks (thus accounting for radial variation in density) and accounted for density differences along the lengths of the trunks. The Nogueira et al. [14] equation for “bole” (here termed “stem”) biomass includes the stump, while our equation does not. In the Nogueira et al. [14] study the stumps were small because the trees were cut “as close as possible” to the ground. Mean stump height for the trees used for the Nogueira et al. [14] stem biomass equation was 11 cm (range 3–44 cm), and the biomass of the stumps represented only 1.02% of the biomass of the remainder of the stem. The comparable percentage for the stumps of trees in the present study (cut at 30 cm above the ground) was 2.34%, and the stumps would therefore only account for a higher calculated commercial stem

biomass by this percentage as a result of applying the Nogueira et al. [14] biomass equation to our sample trees.

Trees in open forest with presence of bamboo in southwestern Amazonia are significantly shorter than trees of the same diameter in southern Amazonia, where bamboo is not present. The effect on aboveground biomass from shorter total height of trees in southwest Amazonian forests with presence of bamboo (including both the effect of bamboo and other differences between regions) makes a tree with 50 cm DBH have approximately 6% less aboveground biomass than a tree of the same diameter in southern Amazonia, while a 100-cm DBH tree has 4.5% less aboveground biomass (Figure 2 in [54]). If trees of all diameters ≥ 5 cm DBH are considered, this effect represents a reduction of forest biomass by 7.5% [14]. In our study the effect of bamboo is modest because only 15 (6.7%) of our 223 sampled trees were in open forest with presence of bamboo, while the remaining 208 trees (93.3%) were in dense forest. Note that Nogueira et al. [54] referred to the effect as being for forest with “dominant” bamboo, but the location of the plots for the trees used for the southwest Amazonia portion of that study [70] is currently classified as with “presence” of bamboo [33], making it the same as the portion of our study area with bamboo. Considering the percentage of trees in open forest with presence of bamboo in our study, the expected biomass-reducing effect from height in the forest with bamboo presence from applying the Nogueira et al. [14] equation to our sample would be 0.4%. For the dense forest in Acre (without bamboo), the effect on height for a 50-cm DBH tree would be 2%, and for a 100-cm DBH tree the effect would be 1% (Figure 2 in [54]).

The combined effect of stump inclusion and higher wood density in the Nogueira et al. [14] study would account for 2.8% higher biomass. The additional effects on tree height of each forest type (“dense forest” and “forest with presence of bamboo”), assuming 50-cm DBH trees and weighting by the proportions of each forest type in our sample, would increase the total adjustment to 5.1%. This leaves 13.3% to be explained by other differences between the structure of forests in southwest versus southern Amazonia, as well as the effect of smaller diameter trees in the dataset used for the Nogueira et al. [14] equation. Schewhart and Wilks [48] note that the effect of tree height is greatest for small-diameter trees.

On the other hand, the pantropical equation by Chave et al. [2] for aboveground biomass has the variables DBH, total height, and basic wood density, and the study’s equation includes individuals with DBH from 5 to 212 cm, but it underestimates individual stem biomass of our sampled trees by 52.5% on average (Table 6). Although our Model MB2 and the model by Chave et al. [2] have the same variables, the combination of variables differs between the models. The difference in results is also explained by the fact that our model does not include smaller diameters.

Caution is needed in making direct comparisons between the different equations due to differing criteria, measurement methods, and independent variables included in the models in each study. Differences can include the way that the mass of the stem is determined (direct weighing versus converting volume to mass based on wood density), the temperature used to dry samples for density determination, and the determination of basic density based on rehydration). Inclusion of large trees is necessary in generating equations for volume, biomass, and carbon in order to reduce underestimation. In addition, diameter ranges should often be rethought in generating allometric equations for a given class in order to reduce underestimation or overestimation of biomass for individual trees and, consequently, of forest biomass. As the datasets for most allometric equations have large numbers of small-diameter trees and few large individuals, the estimates for larger trees could be biased by trends present in the full datasets that reflect patterns among the smaller trees, in addition to the high uncertainty in the upper diameter ranges due to limited data. With an adequate number of data points for large trees, it should be possible to develop equations specific to different diameter ranges and thereby reduce overall uncertainty.

One potential source of bias is the fact that our study only considered commercial tree species, while other equations consider all species. As commercial species are likely to have higher wood density than non-commercial species, one would expect estimates based on equations developed for all

species to underestimate the biomass of our sampled trees by an amount that reflects the difference in mean wood density between our sampled trees and the mean for all species in forests in Acre. However, the mean wood density of our trees (0.56 g cm^{-3}) is only 4% higher than the mean of 0.54 g cm^{-3} for trees of all species considered in the study in Acre by Nogueira et al. [59]. This percentage difference is 5–19 times less than the differences between the values predicted by existing equations and the observed biomasses of our sampled trees (Table 5).

Allometric equations for carbon stock are structurally similar to aboveground biomass equations, using diameter, height, and basic wood density as explanatory variables. Nonetheless, inclusion of carbon content as an additional explanatory variable can provide greater specificity in carbon-stock estimates as compared to estimates that use a single constant value for all species [71,72]. The default value used by the Intergovernmental Panel on Climate Change (IPCC) for the carbon content of the total dry aboveground biomass (wood, bark, twig, leaves) is 47% [71], and in this study the average carbon content of commercial stems was 49%. The inclusion of carbon content follows the physical and biological principles of allometric theory [72–74] and is important for understanding global climate change and its impacts. In this study, the best fit for estimating carbon stock was provided by Model MC3, which included both the square of DBH and height, as well as basic wood density and carbon content (modified from Loetsch et al. [45]; Tables 1 and 5). In this equation, an increase of 1% in $\text{DBH} \times \text{commercial stem length}$ produces an increase of 0.87% in carbon stock, keeping p and t constant. On the other hand, an increase of 1% in $p \times t$ results in an increase of 0.98% in carbon stock, keeping DBH and commercial stem length constant.

Studies in Acre by I.F. Brown [67], d'Oliveira et al. [27], and Salimon et al. [17] estimated aboveground biomass stock (Mg ha^{-1}) by applying the allometric equations developed by S. Brown et al. [65], Nogueira et al. [14], and S. Brown [68], respectively. The biomass equation generated in the present study (MB2) underestimated large-tree commercial stem biomass by only 2.97%, while the three equations that have been applied in Acre deviated by much larger amounts: the S. Brown et al. [65] equation underestimated by 77.5%, the Nogueira et al. [14] equation for aboveground biomass overestimated by 29.3%, and the S. Brown [68] equation overestimated by 20.4% (Table 6). Although the three equations are based on the same independent variable (DBH), they are different polynomial models with discrepant coefficients between models [50,75], which can produce different results even among similar studies. The lack of consensus among researchers on standard methodologies and models leads to a range of widely differing results [75]. The paucity of measurements for large trees in the datasets underlying these studies results in high uncertainty.

Southwestern Amazonia is particularly threatened by climate change because of an expected rapid increase of severe droughts of type experienced in 2005 and 2010 [76,77]. The forests in southwest Amazonia have composition and structure quite different from the areas where most of Amazonia's forest allometry studies have been conducted. As compared to central and northern Amazonia, forests on the southern and southwestern edges of the region are more dynamic, that is, they have faster turnover of trees with higher rates both of mortality and recruitment [78], which would lead to trees of shorter stature, to a greater proportion of gaps in the forest, and to a greater frequency of early-successional species. The lower wood density in Acre's forests is also critical. It is therefore essential to have allometric equations developed specifically for this region for use by forest managers. Region-specific allometric equations for stems of commercial trees represent just one part of the set of information needed for use in evaluating the contribution of managed forests to the global carbon cycle [72,79], and to support the implementation of payments for ecosystem services [80].

5. Conclusions

The allometric equations presented in this study allow accurate volume, biomass, and carbon estimates for the commercial stems of large trees using diameter (d), commercial stem length (l), basic wood density (p), and carbon content (t) as explanatory variables. These equations respect physical, geometric, and biological principles for forests and provide consistent parsimonious estimates.

Allometric equations specific to southwestern Amazonia produce results different from those developed for other parts of the Amazon or for tropical forests in general. Equations developed in southwestern Amazonia are therefore needed to accurately quantify the volume, biomass, and carbon stock in managed forests in this part of the Amazon.

Supplementary Materials: The following are available online at <http://www.mdpi.com/1999-4907/11/8/874/s1>, Figure S1. Volume models MV1–MV3 compared with other studies: percent deviation, observed versus estimated values, and regression residuals; Figure S2. Volume models MV4–MV6 compared with other studies: percent deviation, observed versus estimated values, and regression residuals; Figure S3. Biomass models MB1–MB4 compared with other studies: percent deviation, observed versus estimated values, and regression residuals; Figure S3. Biomass models MB5–MB6 compared with other studies: percent deviation, observed versus estimated values, and regression residuals; Figure S5. Carbon-stock models MC1–MC5 compared with other studies: percent deviation, observed versus estimated values, and regression residuals.

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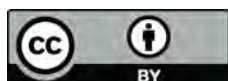
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Supplementary Material

Allometric equations for volume, biomass and carbon in commercial boles harvested in a managed forest in the southwestern Amazon

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Figure S1. Volume models MV1-MV3 compared with other studies: Percent deviation, Observed versus estimated values and regression residuals.	2
Figure S2. Volume models MV4-MV6 compared with other studies: Percent deviation, observed versus estimated values and regression residuals.	3
Figure S3. Biomass models MB1-MB4 compared with other studies: Percent deviation, observed versus estimated values and regression residuals.	4
Figure S3. Biomass models MB5-MB6 compared with other studies: Percent deviation, observed versus estimated values and regression residuals.	5
Figure S5. Carbon-stock models MC1-MC5 compared with other studies: Percent deviation, observed versus estimated values and regression residuals.	6
References.	7

Figure S1. Volume models MV1-MV3 compared with other studies: Percent deviation, Observed versus estimated values and regression residuals

Linear models for estimating bole volume for twenty tree species sampled in a managed forest area in Acre state, Brazil.

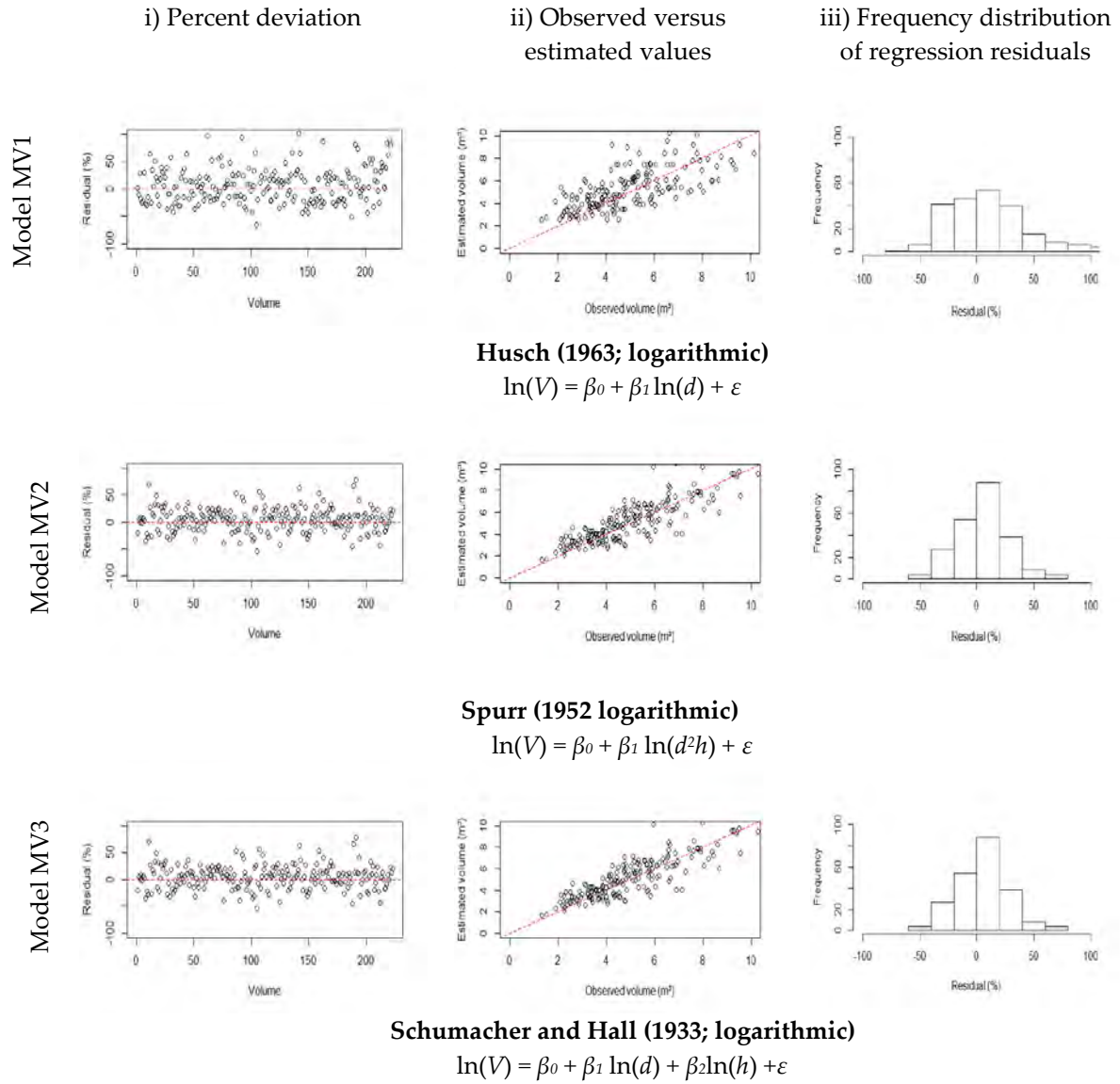


Figure S2. Volume models MV4-MV6 compared with other studies: Percent deviation, Observed versus estimated values and regression residuals.

Non-linear models for estimating bole volume for twenty tree species sampled in a managed forest area in Acre state, Brazil.

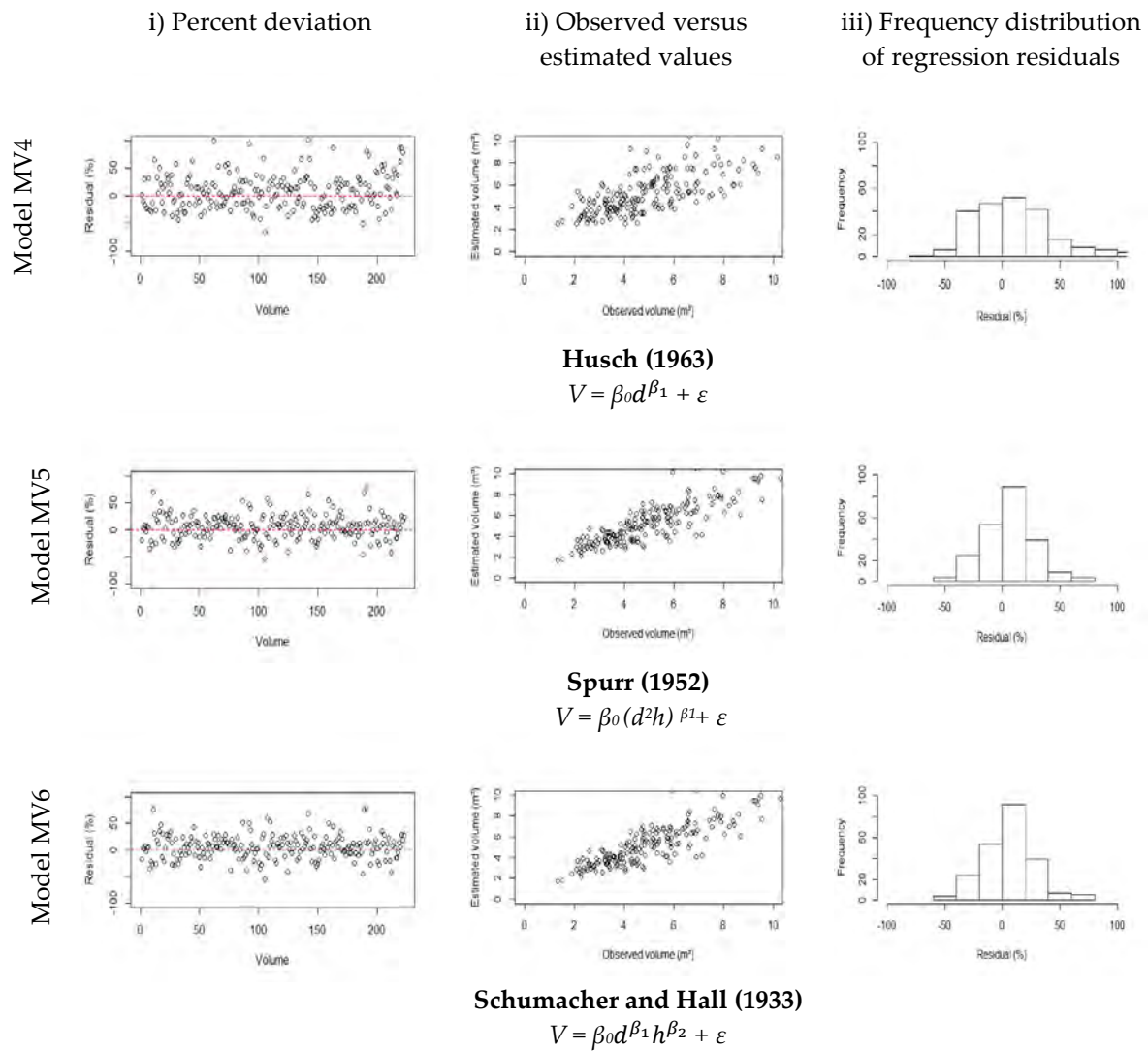


Figure S3. Biomass models MB1-MB4 compared with other studies: Percent deviation, observed versus estimated values and regression residuals

Linear models for estimating bole biomass for twenty tree species sampled in a managed forest area in Acre state, Brazil.

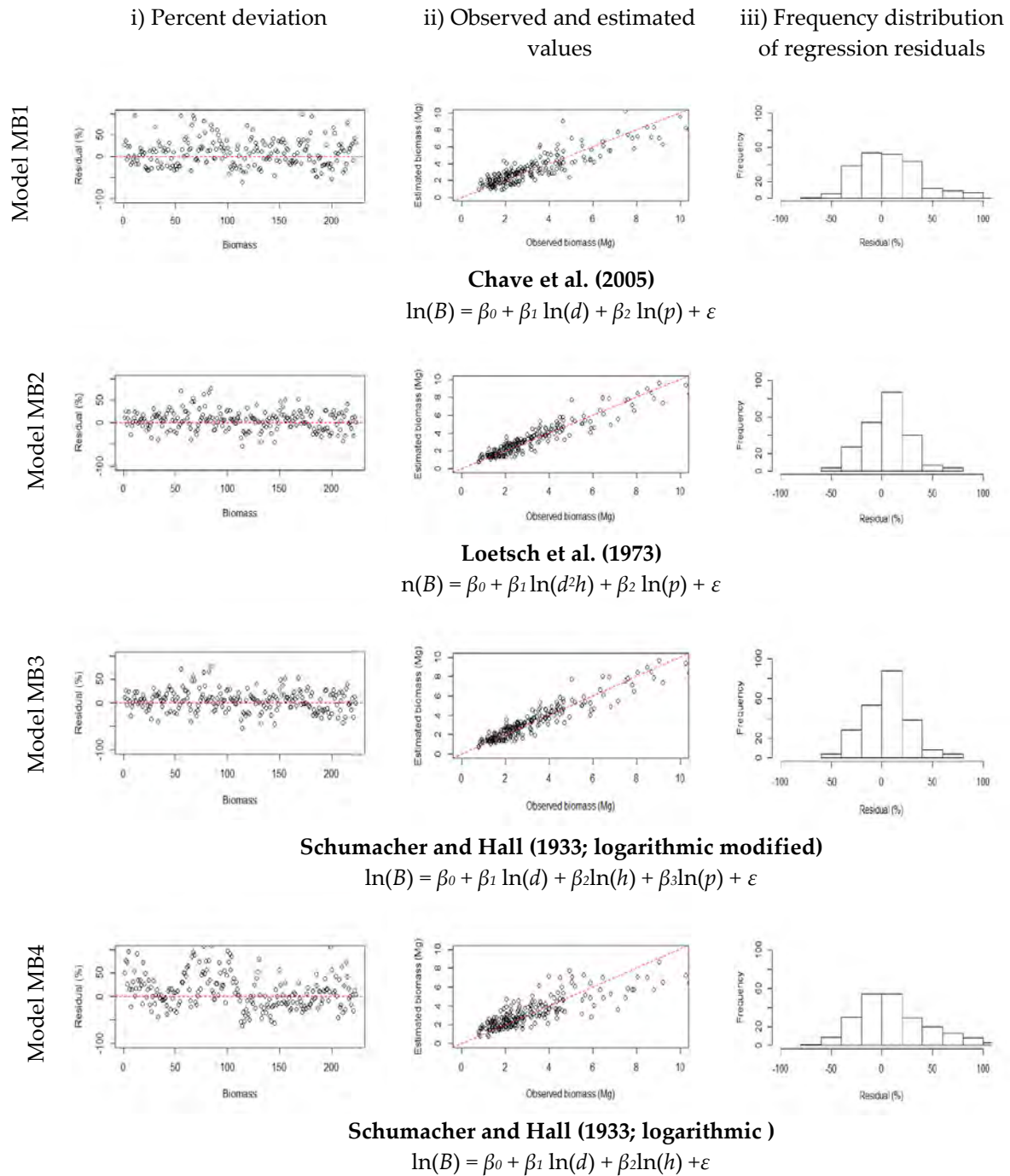


Figure S4. Biomass models MB5-MB6 compared with other studies: Percent deviation, observed versus estimated values and regression residuals

Non-linear models for estimating bole biomass for twenty tree species sampled in a managed forest area in Acre state, Brazil.

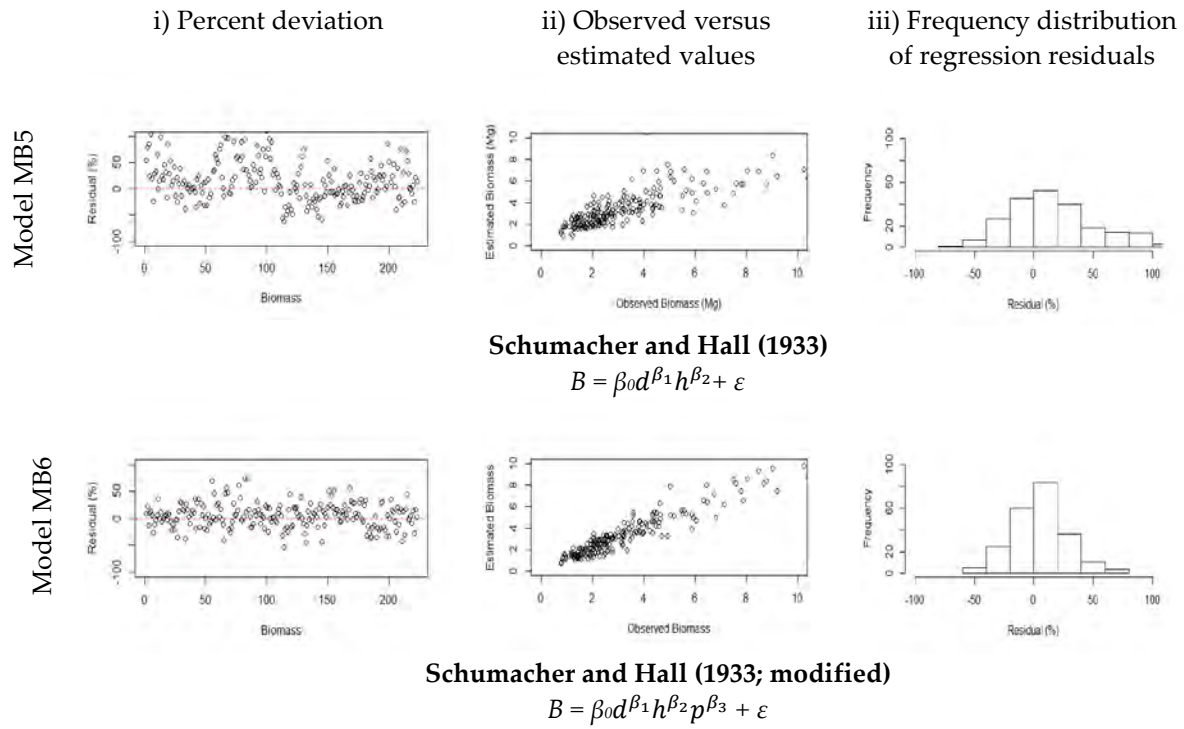
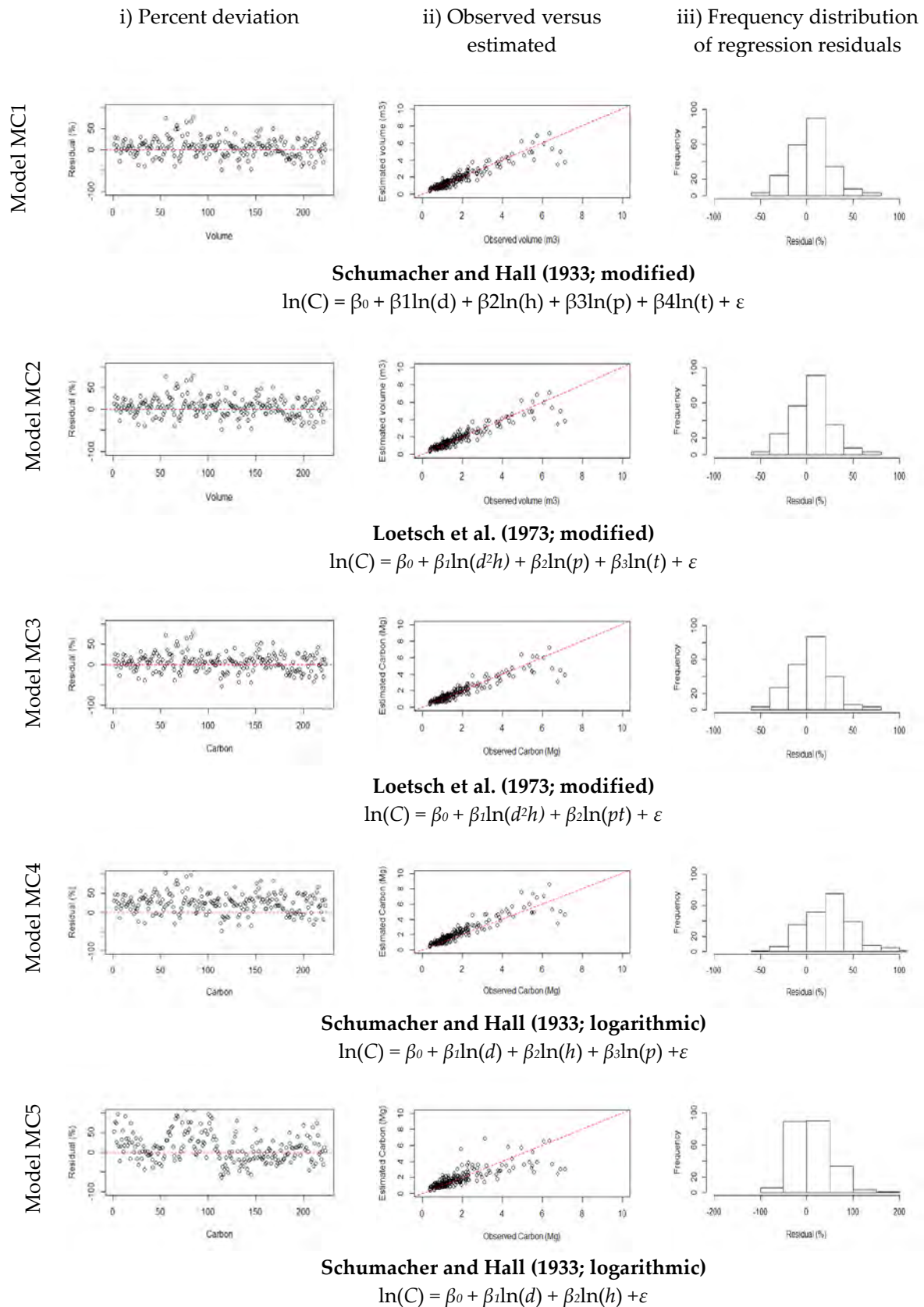


Figure S5. Carbon-stock models MC1-MC5 compared with other studies: Percent deviation, observed versus estimated values and regression residuals

Linear models for estimating bole carbon for twenty tree species sampled in a managed forest area in Acre state, Brazil.



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