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Development of Allometric Equations for Tree Biomass in Forest Ecosystems in Paraguay

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Abstract

The Atlantic Forest, Humid Chaco, and Dry Chaco are major eco-regions in Paraguay, but information on forest carbon stocks in these forest types remains limited. To establish a system to measure, report and verify forest carbon change under the REDD+ mechanism, we developed new allometric equations to estimate tree biomass in each eco-region. Three models of total and aboveground biomass were developed from destructive sampling data. The models performed well, explaining ≥96% of the variation in aboveground and total biomass, although the best model differed among the eco-regions. The inclusion of height and wood density improved fit in the Atlantic Forest model, but including wood density did not enhance the Humid and Dry Chaco models. Our models will improve the estimation of biomass in Paraguay because they provide better estimates of total and aboveground biomass in each eco-region than pan-tropical generic models.

Discipline: Forestry and forest products
Additional key words: allometric models, Atlantic forests, Chaco forests, living biomass including root, REDD-plus

Introduction

The REDD+ mechanism (Reducing Emissions from Deforestation and forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries) provides financial incentives to help developing countries establish ways to reduce emissions from deforestation and forest degradation. Because the measurement, reporting, and verification (MRV) of forest carbon change are indispensable for REDD implementation, the use of a ground-based inventory with remote sensing is recommended to monitor carbon stocks on a national scale (UNFCCC 2009). For a ground-based inventory, permanent sample plots allow the monitoring of carbon stocks by area (e.g. Fox et al. 2010, Samreth et al. 2012). Estimates of carbon stocks in living biomass can be obtained using allometric equations with measured field variables such as diameter and tree height in the plots (Metzker et al. 2012). However, the main source of uncertainty in biomass estimates lies in the choice of allometric model (Molto et al. 2013).

Although the proportion of forested area has continuously declined during the last 20 years in Paraguay (Huang et al. 2007), information on forest carbon stocks and allometric models remains limited. Generic allometric equations developed by Chave et al. (2005) can be used to estimate forest biomass and carbon stocks across diverse tropical forest types (Gibbs et al. 2007, Asner et al. 2009, Mitchard et al. 2013), including Atlantic Forest (Vieira et al. 2008) and Humid and Dry Chaco (Gasparri et al.

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2008). Besides Chave's generic equations, Burger & Delitti (2008) developed equations for secondary Atlantic Forest in southeastern Brazil. Some species-specific models have also been developed for the Dry Chaco of Argentina (e.g. Conti et al. 2013, Iglesias & Barchuk 2010). Conti et al. (2013) developed multi-species models using crown area and shape instead of diameter at breast height (DBH) in the Chaco of central Argentina, but these equations may not be applicable to inventory data because the crown area of a tree is not essential for monitoring in inventory implementation. Moreover, most allometric equations, including Chave's generic ones, only cover aboveground biomass. Some studies calculated belowground biomass as a proportion of aboveground biomass (e.g. Gasparri et al. 2008).

In this study, we developed allometric equations to estimate biomass, including belowground parts, for the Atlantic Forest, Humid Chaco, and Dry Chaco eco-regions in Paraguay and compared the performance of these models with pan-tropical generic equations developed by Chave et al. (2005).

Material and Methods

1. Study sites

The Paraguay River divides Paraguay into the Paraná (eastern) and Chaco (western) regions (dashed line in Fig. 1), in which floristic composition is clearly separated (Spichiger et al. 2005). Paraguay has five eco-regions: Upper Paraná Atlantic Forest, Humid Chaco, Dry Chaco, Cerrado, and Pantanal. We focused on the first three, which cover >95% of Paraguay (Rodas et al. 2006).

(1) Upper Paraná Atlantic Forest

The Upper Paraná Atlantic Forest is one of 15 eco-regions of the South American Atlantic Forest biome, and extends from southeastern Brazil to eastern Paraguay and northeastern Argentina (Di Bitetti et al. 2003). The predominant vegetation is semi-deciduous subtropical forest with a high frequency of species of the Lauraceae (Di Bitetti et al. 2003, Spichiger et al. 2005). We selected two sites for destructive sampling (Fig. 1). One was the CEDEFO (Centro de Desarrollo Forestal) experimental forest (Fig. 2a), managed by INFONA (Instituto Forestal Nacional), in Pirapo, Itapúa Department, southern Paraguay (26°52'S 55°24'W), where the mean temperature and annual precipitation are 21°C and 1809 mm. The other was a privately owned forest managed by SAGSA (Sociedad Agrícola Golondrina S.A.), Golondrina, northern Caazapá Department (25°32'S 55°28'W). Since 2003, SAGSA has been exporting wood with the Forest Stewardship Council label. The mean temperature and annual precipitation at

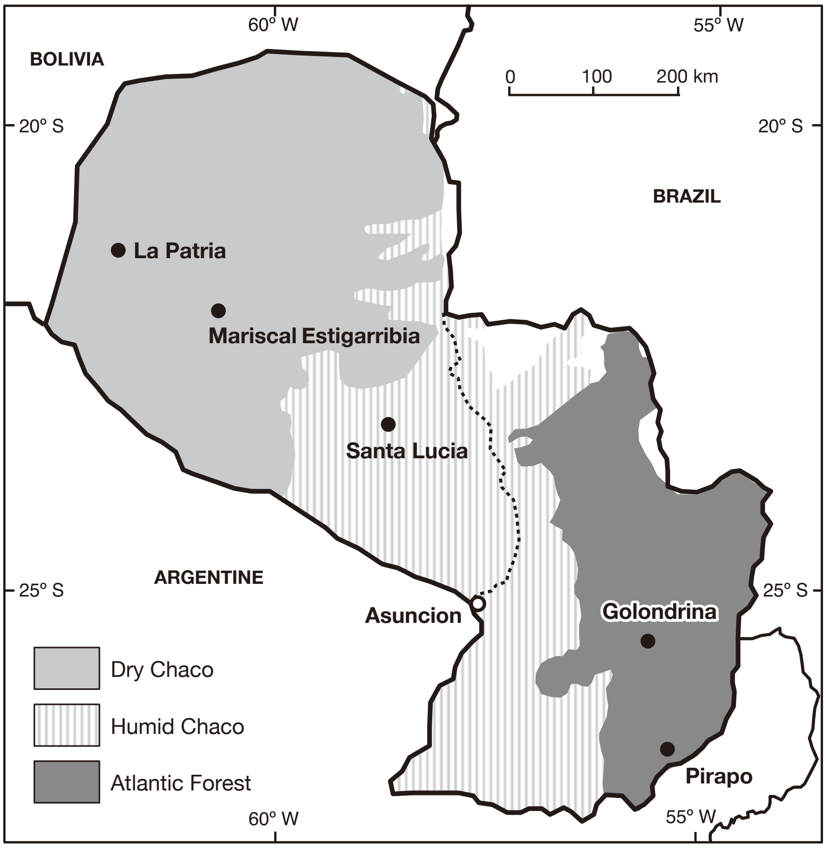

Fig. 1. Map of the study sites in Paraguay. The dashed line marks the Paraguay River.

San Juan Nepomuceno, about 80 km from Golondrina, are 21.5°C and 1720 mm.

(2) Humid Chaco

The Humid Chaco eco-region extends from north-eastern Argentina to central Paraguay. In Paraguay it is a transitional area where many plant species are intermingled: an ecotone between the Paraná and Dry Chaco (Spichiger et al. 1995). Vegetation to the west of the Paraguay River grows on the temporarily waterlogged soils of the flood plains of the Paraguay and Pilcomayo rivers and in the Paraná–Paraguay delta (Spichiger et al. 2005). The "xeromesophyllous" forest here mainly comprises *Schinopsis balansae, Astronium urundeuva*, and *Diplokeleba floribunda*, and mixes with palm savannah (Spichiger et al. 2005, 2006). Destructive sampling was conducted on a ranch at Santa Lucia (23°15'S 58°33'W), in Presidente Hayes Department (Figs. 1 and 2b), about 40 km from Pozo Colorado. The mean temperature and annual precipitation at Pozo Colorado are 23.3°C and 932 mm.

(3) Dry Chaco

The Dry Chaco eco-region extends from northern Argentina to southeastern Bolivia and western Paraguay. Dry Chaco forest is a tropical dry forest associated with typical xeromorphic flora such as *Aspidosperma quebracho-blanco* (Spichiger et al. 1995, 2006). We selected two sites for destructive sampling here, both in Boquerón Department (Fig. 1). At Mariscal Estigarribia, we sampled in an experimental forest managed by Escuela Agrícola de Mariscal Estigarribia, Gobernación de Boquerón (21°59'S 60°37'W). At La Patria, we sampled in an experimental forest of CEMELPA (Centro Modelo Experimental La Patria), an agricultural experimental station, about 120 km from Mariscal Estigarribia (21°23'S 61°29'W; Fig. 2c). The mean temperature and annual precipitation at Mariscal Estigarribia are 24°C and 760 mm.

2. Field sampling

At each site, we selected trees on the basis of species composition in literature (e.g. Spichiger et al. 2006) and in data from permanent sampling plots in the same eco-region (unpublished data of L. Pérez de Molas). The sample numbers and DBH (1.3 m) range at each site are listed in Table 1.

We recorded the species and DBH (*D*) of each sample tree. Before felling, we marked a line at the point where the stem met the soil surface. After felling, we measured the tree height (*H*) with a tape measure, and divided the aboveground biomass (*AGB*) into leaves (with twigs), branches, and stem. The stem was cut into 2-m lengths for weighing. After weighing the other two parts, we

Fig. 2. Views of the study sites. a: Upper Paraná Atlantic Forest at the CEDEFO (Centro de Desarrollo Forestal) experimental forest, Pirapo, Itapúa Department; b: Humid Chaco forest at Santa Lucia, Presidente Hayes Department; c: Dry Chaco forest at La Patria, Boquerón Department.

Table 1. Study site locations, sample numbers, and DBH range in each eco-region of Paraguay

Ecoregion	Locations	Number of samples	DBH range (cm)	Remarks
Atlantic Forest	Pirapo	13	5.4 ~ 63.1	
	Golondrina	3	50.3 ~ 78.6	Aboveground parts only
Humid Chaco	Santa Lucia	10	6.9 ~ 48.8	
Dry Chaco	La Patria	18	3.8 ~ 51.8	
	Mariscal Estigarribia	9	7.0 ~ 28.6	

subsampled about 20% of the leaves, clipped the twigs off, calculated the ratio of leaves to twigs from this subsample and estimated the total fresh weight in each case.

Tree stumps and soil under the tree crown area were excavated with heavy machinery. Stumps, ranging in height from 9 to 65 cm above the soil surface, were separated into *AGB* and belowground biomass (*BGB*), each of which was also weighed. The remaining roots in the pit were collected carefully by hand. At the Dry and Humid Chaco sites, the "mound method" was used to calculate root weight (Monda et al. unpublished): (1) Square or rectangular mounds were made from the excavated soil. (2) The volume of the mound was calculated from measurements. (3) Roots from a subsample block from the mound were collected by hand and weighed. (4) The root weight in the entire mound was calculated from the subsample weight. *BGB* was the summation of coarse roots (separated from the stump) and fine roots (collected from the soil).

At the Dry Chaco sites, some trees had multiple stems (see Appendix), so we measured the *AGB* of each stem separately, computed the weight ratio of each stem to the total stem weight, and assigned the total root weight to each stem proportionally. At Golondrina, we could not cut the stems into 2-m lengths for commercial reasons, so we measured stem volume by applying the Smalian's formula, and then calculated the dry weight from the density of disk samples. Leaves and branches were measured using equivalent procedures to the other sites. We did not measure *BGB* at Golondrina.

After subsampling of each component, samples were then oven-dried at 70°C to constant weight and weighed in the laboratory of La Universidad Nacional de Asunción. Samples were collected in February and July 2012 at Pirapo; in July 2012 at Golondrina; in December 2012 at Santa Lucia; in July 2013 at La Patria; and in October 2013 at Mariscal Estigarribia respectively.

To calculate wood density (WD, g cm^{-3}), we took disk samples from the top stump, middle stem, and top stem sections of each tree, measured the green volume and dry weight of the disks in the laboratory, and computed the wood density of each tree.

3. Data analysis

We developed *D-H* relations for each eco-region using a Weibull function (Feldpausch et al. 2011):

$$H = a \times (1 - \exp(-b \times D^c))$$

where *a, b* and *c* are model coefficients.

We also developed allometric models involving three independent variables: D (cm), H (m), and WD (g cm^{-3}) and applied linear models to log-transformed data. The total biomass (*Total*; kg) and aboveground biomass (*AGB*; kg) by dry weight were dependent variables. We developed the following three models using these parameters to select the best model in each eco-region:

Model 1: $\ln(Total \text{ or } AGB) = a_0 + a_1 \ln(D)$
Model 2: $\ln(Total \text{ or } AGB) = a_0 + a_1 \ln(D^2 H)$
Model 3: $\ln(Total \text{ or } AGB) = a_0 + a_1 \ln(D^2 H\, WD)$

where a_0 and a_1 were model coefficients (derived from least-squares regression). Each model was back-transformed to a power function form. Because the log-transformed data cause bias in biomass estimation (Baskerville 1972), the back-transformed results were multiplied by a correction factor (Sprugel 1983), CF, expressed as:

$$CF = \exp\left(\frac{RSE^2}{2}\right)$$

where RSE was the residual standard error obtained from model regression.

The best-fit model was evaluated by the adjusted coefficient of determination (r^2), RSE, Furnival index (FI), and Akaike's information criterion (AIC). FI (Furnival 1961) can compare models with different dependent variables, and is calculated as:

$$FI = \frac{1}{[f'(Y)]}\sqrt{MSE}$$

where $f'(Y)$ is the derivative of the dependent variable with respect to *Total* and *AGB*, MSE is the mean square error of the fitted model, and [ ] indicates the geometric mean. All models were computed using R software v. 3.0.3 (http://www.r-project.org/).

4. Comparison to general models

We compared the performance of our models by measuring the deviation of the predicted versus measured biomass in each eco-region:

$$\text{Error (\%)} = 100 \times (\text{biomass}_{\text{predicted}} - \text{biomass}_{\text{measured}}) / \text{biomass}_{\text{measured}}$$

We calculated the error of both *Total* and *AGB* models for each sample tree and mean error in each eco-region model and compared our models with the general allometric models of Chave et al. (2005), who developed models for dry, moist, and wet forests, with (model C1) and without tree height (model C2). We used the "Moist forest model" for the Atlantic Forest:

Model C1: $AGB = 0.0509 \times D^2\ H\ WD$

Model C2: $AGB = WD \times \exp(-1.499 + 2.148 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)$

We used the "Dry forest model" for the Dry and Humid Chaco:

Model C1: $AGB = 0.112 \times (D^2\ H\ WD)^{0.916}$

Model C2: $AGB = WD \times \exp(-0.667 + 1.784 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3)$

After estimating *AGB* using the general models, we estimated *BGB* as 28% of *AGB* for Dry Chaco and Humid Chaco (Tropical dry forest) and 24% of *AGB* for Atlantic Forest (Subtropical humid forest) (IPCC 2006, Mokany et al. 2006). Gasparri et al. (2008) used these values to estimate *BGB* in Chaco and Atlantic Forest of northern Argentina.

Results

1. Biomass models

Stand structure differed among the eco-regions. Comparing *D-H* relations using the Weibull-*H* function revealed that the Atlantic Forest stands were taller than the Humid and Dry Chaco stands (Fig. 3).

All models had a high coefficient of determination ($r^2 > 0.96$, $P < 0.0001$; Table 2). The best model differed among the eco-regions and including *H* and *WD* improved the fit in the Atlantic Forest model. AIC showed that *WD* was an important predictor variable in that model. However, including *WD* did not improve the fit in the Humid and Dry Chaco models (Table 2). Models which used only *D* as an independent variable (model 1) were selected as optimal for estimating *Total* and *AGB* in the Humid Chaco, as indicated by high r^2, low AIC, and low FI.

2. Model performance

In all our models, the errors varied among tree sizes and showed large fluctuations in small trees ($D < 20$ cm) and small fluctuations in large trees ($D > 40$ cm) (data not shown).

Fig. 3 compares errors among our models and Chave's generic models. In Atlantic Forest, Chave's model C2, which excludes *H*, was the most biased, and overestimated *AGB* and *Total* (mean error ≈ 40%; Fig. 4). Predicted results for *Cecropia pachystachya* (typical pioneer trees; sample PR17 in Appendix) caused an outlier in models 1 and 2, which exclude *WD*. Conversely, model 3, which includes *WD*, showed no clear differences in error from Chave's model C1 (Fig. 4).

In Humid Chaco, the mean errors in model C1 indicated underestimates, and estimates differed from those of our models. Model C1 also showed wider errors than C2. These tendencies did not occur in the other two eco-regions. Model 3, which includes *WD*, also showed wide errors. Mean errors did not differ significantly between models 1 and 2 (Table 2).

In Dry Chaco, the mean errors in model C1 indicated underestimates, as in Humid Chaco. Although the mean errors did not differ among our three models, model 2 had narrow errors in *AGB* and *Total* (Fig. 4).

As a result, the best models for Atlantic Forest are:

$AGB = 0.0613 \times (D^2HWD)^{0.9801}$

$Total = 0.0632 \times (D^2HWD)^{0.9971}$

The best models for Humid Chaco are:

$AGB = 0.1431 \times (D)^{2.4420}$

$Total = 0.2763 \times (D)^{2.3291}$

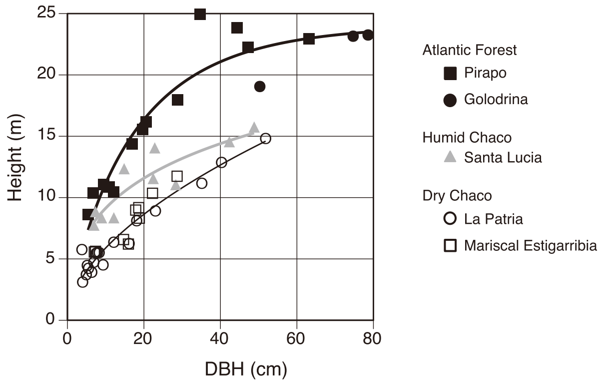

Fig. 3. Comparison of the *D-H* relationship between eco-regions of Paraguay. Curves for the Atlantic Forest (thick line) and Dry Chaco (fine line) were fitted to data from each of the two sites (shown in the key).

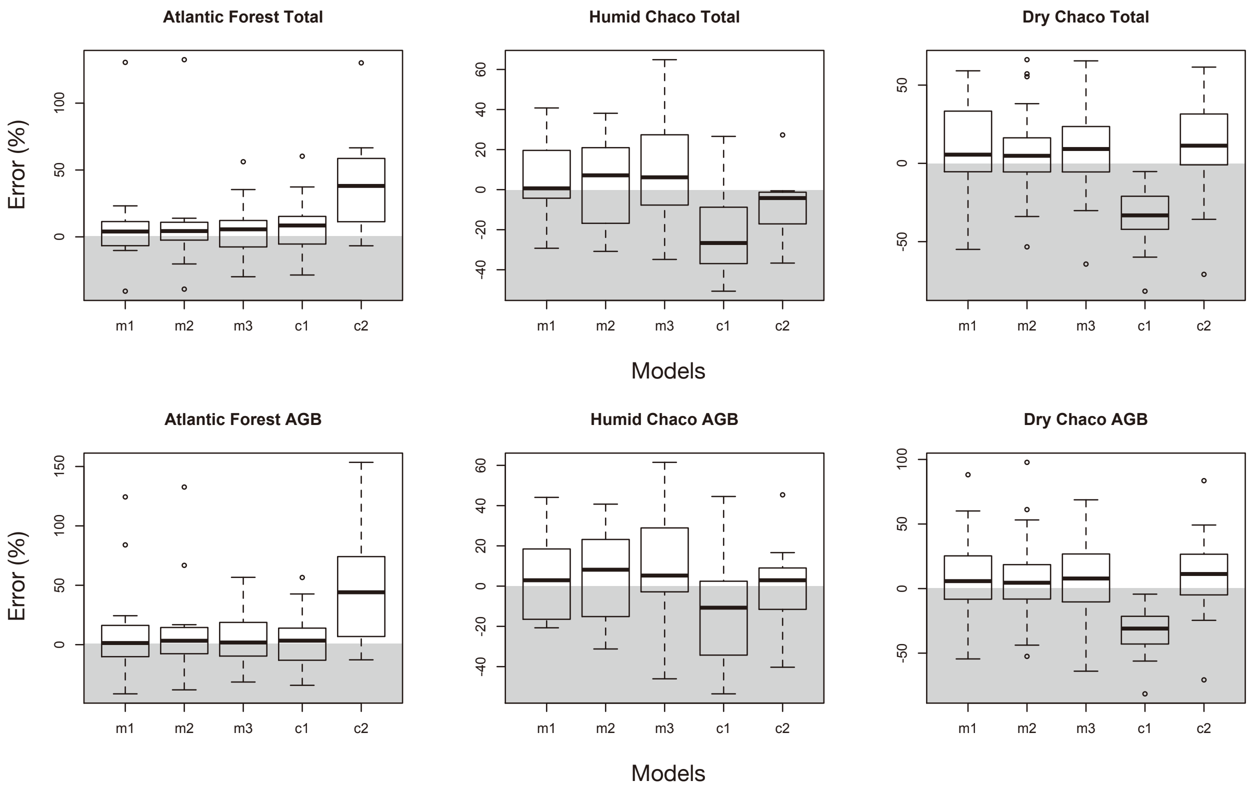

Fig. 4. Comparison of prediction errors between our models (m1, m2, m3) and generic models (C1, C2) in each eco-region of Paraguay. Bold lines show median. Boxes show the interquartile range between the 25th and 75th percentiles. The upper whiskers mark 25th percentile + 1.5 × interquartile range; the lower whiskers mark the 25th quartile – 1.5 × interquartile range. The models are explained in the text.

And the best models for Dry Chaco are:

$AGB = 0.2147 \times (D^2 H)^{0.8391}$

$Total = 0.2733 \times (D^2 H)^{0.8379}$

These equations already include the correction factor (CF).

Discussion

To achieve Tier III estimates of carbon stocks in plant biomass, allometric equations calibrated to national circumstances are required (IPCC 2003, 2006). Although some studies estimated *BGB* from *AGB* or root-to-shoot ratio (e.g. Cairns et al. 1997, Mokany et al. 2006), our models estimate total biomass, including *BGB*, using forest inventory data (*D*, *H*, and *WD* from species records). Our models also performed well, explaining ≥ 96% of the variation in *AGB* and total biomass in three major eco-regions in Paraguay. Because the ratio of *BGB* to *AGB* in both the Dry Chaco and Humid Chaco stands shows relatively high values based on destructive sampling data (see Appendix), our models developed using local data sets could reduce uncertainty in biomass estimation in Paraguay.

The best models for the Humid Chaco use only one parameter, *D*, with limited data. According to discriminant analysis using the geographical distribution of dominant species, the Humid Chaco eco-region is clearly separated into two types, which resemble Dry Chaco and the Atlantic Forest respectively (Spichiger et al. 2006). In Humid Chaco, we only sampled on the western side of the Paraguay River (Santa Lucia), but the stand structure (*D-H* relation; Fig. 3) and species composition on the eastern side may differ. Because models including tree height improve biomass estimation in many tropical forests (Chave et al. 2005, Rutishauser et al. 2013), we propose modified models including *H* for these ecotone conditions:

$AGB = 0.0339 \times (D^2 H)^{1.0401}$

$Total = 0.0690 \times (D^2 H)^{0.9932}$

These models could be used to estimate biomass on both sides of the Paraguay River, because *H* data could incorporate considerable inventory data in the Humid Chaco region.

In Atlantic Forest, *Cecropia pachystachya* is a typical pioneer tree species (Holz et al. 2009), with low *WD* (Wittmann et al. 2008). In addition to *H*, *WD* is another important predictor that can improve biomass estimation (Chave et al. 2006). Models with different coefficient values would

Table 2. Regression analysis results for total and aboveground biomass in each eco-region of Paraguay

Forest type	Model	a_0	a_1	r^2	CF	RSE	AIC	Furnival Index	Error (%)
Total biomass									
Atlantic Forest									
Model 1	$\ln(Total) = a_0 + a_1 \ln(D)$	-1.7296	2.3527	0.9721	1.0491	0.3096	10.23	0.00174	9.96
Model 2	$\ln(Total) = a_0 + a_1 \ln(D^2H)$	-3.0325	0.9564	0.9725	1.0483	0.3073	10.04	0.00172	9.83
Model 3	$\ln(Total) = a_0 + a_1 \ln(D^2HWD)$	-2.7901	0.9971	0.9832	1.0292	0.2399	3.61	0.00135	5.77
Humid Chaco									
Model 1	$\ln(Total) = a_0 + a_1 \ln(D)$	-1.3094	2.3291	0.9831	1.0232	0.2143	1.34	0.00104	4.21
Model 2	$\ln(Total) = a_0 + a_1 \ln(D^2H)$	-2.7017	0.9932	0.9799	1.0277	0.2339	3.09	0.00113	4.99
Model 3	$\ln(Total) = a_0 + a_1 \ln(D^2HWD)$	-1.8688	0.9416	0.9708	1.0443	0.2944	7.27	0.00143	8.00
Dry Chaco									
Model 1	$\ln(Total) = a_0 + a_1 \ln(D)$	-0.8627	2.1169	0.9631	1.0463	0.3009	15.69	0.00375	8.91
Model 2	$\ln(Total) = a_0 + a_1 \ln(D^2H)$	-1.3360	0.8379	0.9683	1.0397	0.2789	11.59	0.00347	7.67
Model 3	$\ln(Total) = a_0 + a_1 \ln(D^2HWD)$	-0.9973	0.8360	0.9642	1.0448	0.2962	14.84	0.00369	8.29
Aboveground biomass(*AGB*)									
Atlantic Forest									
Model 1	$\ln(AGB) = a_0 + a_1 \ln(D)$	-1.8023	2.3218	0.9745	1.0543	0.3251	13.32	0.00124	11.06
Model 2	$\ln(AGB) = a_0 + a_1 \ln(D^2H)$	-3.2590	0.9668	0.9750	1.0530	0.3214	12.95	0.00122	10.77
Model 3	$\ln(AGB) = a_0 + a_1 \ln(D^2HWD)$	-2.8223	0.9801	0.9850	1.0315	0.2491	4.79	0.00095	6.28
Humid Chaco									
Model 1	$\ln(AGB) = a_0 + a_1 \ln(D)$	-1.9656	2.4420	0.9856	1.0218	0.2075	0.70	0.00141	4.00
Model 2	$\ln(AGB) = a_0 + a_1 \ln(D^2H)$	-3.4156	1.0401	0.9797	1.0307	0.2458	4.08	0.00166	5.51
Model 3	$\ln(AGB) = a_0 + a_1 \ln(D^2HWD)$	-2.5269	0.9840	0.9653	1.0581	0.3360	9.65	0.00227	10.21
Dry Chaco									
Model 1	$\ln(AGB) = a_0 + a_1 \ln(D)$	-1.1185	2.1238	0.9621	1.0479	0.3059	16.58	0.00484	9.33
Model 2	$\ln(AGB) = a_0 + a_1 \ln(D^2H)$	-1.5833	0.8391	0.9638	1.0457	0.2989	15.34	0.00471	8.95
Model 3	$\ln(AGB) = a_0 + a_1 \ln(D^2HWD)$	-1.2531	0.8387	0.9631	1.0466	0.3019	15.87	0.00476	8.72

CF: correction factor, RSE: residual standard error, AIC: Akaike information criterion.

have different sensitivities to *WD* bias (Molto et al. 2013). *WD* is an important variable with which to reduce error in estimating secondary forest biomass, including *Cecropia* spp. (Nelson et al. 1999). This means that our models using all three parameters would provide good estimates of living biomass in Paraguay's Atlantic Forest, whether from secondary or primary species. Our sampling in the Dry and Humid Chaco did not involve tree species with low *WD* except *Ceiba chodatii*, but because the trunk of *C. chodatii* is bottle-shaped, we excluded it from our calculations. A unique model is needed for *Ceiba* spp. (Sato et al. 2015).

Alves et al. (2010) minimized uncertainties in biomass estimation caused by regional floristic and canopy height differences among sites by including average *WD* values and an estimate of *H* in allometric equations. Our models provide better estimates of total and aboveground biomass in each eco-region than Chave's generic models. However, our sample numbers were limited, particularly in the Humid Chaco. Further sampling will extend the range of the data set and reduce uncertainty in the estimation of living biomass in Paraguay's forest ecosystems.

Our models represent a first attempt to develop allometric equations for regional biomass estimation in Paraguay. Around Paraguay, in Brazil and Argentina, estimates of forest carbon stocks in living biomass include palms, tree ferns, and lianas (Frangi & Lugo 1985, Gerwing & Farias 2000, Gehring et al. 2004, Gasparri et al. 2008, Alves et al. 2010). In Paraguay, the *Copernicia alba* palm is a characteristic species of the seasonally flooded plains of the Chaco (Gauto et al. 2011). Although palm and liana are minor fractions in living biomass carbon stocks (e.g. < 5%; Alves et al. 2010), seasonally flooded areas are spread throughout western Paraguay, and their carbon stocks in biomass may be crucial to accurate estimation on a national scale. Further studies are necessary to evaluate the published allometric models or develop original models to estimate the living biomass for plants other than trees. We also need to establish permanent sampling plots in which to monitor forest carbon stocks in various forest types, including palm forests, in Paraguay.

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Appendix. Size and dry mass of each component of the sample trees.

a) Atlantic Forest

Location	Sample ID	Species	DBH (cm)	H (m)	Leaf (kg)	Branch (kg)	Stem (kg)	Root (kg)	Wood density (g cm^{-3})	BGB/AGB ratio	Remarks
Pirapo	PR1	*Chrysophyllum gonocarpum*	20.5	16.1	15.9	156.4	157.3	52.4	0.643	0.16	
	PR2	*Balfourodendron riedelianum*	28.7	17.9	1.6	8.3	362.4	78.5	0.774	0.21	
	PR5	*Cordia trichotoma*	34.7	24.9	27.6	138.1	602.4	103.2	0.500	0.13	
	PR6	*Sorocea bonplandii*	12.0	10.4	8.2	22.1	30.5	8.6	0.522	0.14	
	PR7	*Nectandra cff. Megapotamica*	47.2	22.2	36.8	332.2	969.6	260.5	0.563	0.19	
	PR8	*Diatenopteryx sorbifolia Radlk.*	44.2	23.8	1.1	329.1	961.0	155.2	0.567	0.12	
	PR9	*Ocotea dyospirifolia*	63.1	22.9	24.4	846.6	1655.7	350.1	0.473	0.14	
	PR10	*Campomanesia xanthocarpa*	5.4	8.6	0.3	1.0	6.0	2.1	0.817	0.28	
	PR15	*Nectandra angustifolia*	16.9	14.3	10.4	35.9	65.8	14.1	0.468	0.13	
	PR16	*Sorocea bonplandii*	9.4	11.0	1.3	6.9	23.0	3.8	0.535	0.12	
	PR17	*Cecropia pachystachya*	19.6	15.5	2.3	20.5	54.8	11.0	0.248	0.14	
	PR18	*Parapiptademia rigida*	10.9	10.8	1.2	9.3	25.2	5.8	0.654	0.16	
	PR19	*Balfourodendron riedelianum*	6.6	10.3	0.6	2.0	12.9	2.0	0.699	0.13	
Golondrina	GL1	*Cordia americana*	78.6	23.2	16.8	2739.5	2787.8		0.824		Aboveground parts only
	GL2	*Alchornea triplinervia*	74.7	23.1	41.0	1141.0	933.7		0.460		Aboveground parts only
	GL3	*Chysophyllum gonocarpum*	50.3	19.0	54.4	959.4	524.5		0.647		Aboveground parts only

b) Humid Chaco

Location	Sample ID	Species	DBH (cm)	H (m)	Leaf (kg)	Branch (kg)	Stem (kg)	Root (kg)	Wood density (g cm^{-3})	BGB/AGB ratio	Remarks
Santa Lucia	SL1	*Diplokeleba floribunda*	8.9	8.3	0.5	20.6	5.1	11.4	0.562	0.43	
	SL2	*Astronium urundeuva*	22.4	11.5	8.3	156.6	94.1	125.7	0.637	0.49	
	SL3	*Cordia americana*	22.8	14.0	3.6	189.6	57.0	125.6	0.670	0.50	
	SL4	*Schinopsis balansae*	42.3	14.5	23.7	734.1	704.9	214.7	0.759	0.15	
	SL5	*Tabebuia nodosa*	28.3	11.0	3.6	213.6	131.5	123.6		0.35	Not available for wood density
	SL6	*Astronium urundeuva*	7.3	8.8	0.4	12.4	2.5	7.1	0.686	0.46	
	SL7	*Astronium urundeuva*	14.8	12.3	2.9	77.2	27.1	41.8	0.684	0.39	
	SL8	*Schinopsis balansae*	48.8	15.7	32.1	1081.2	1162.3	623.0	0.812	0.27	
	SL9	*Caesalpinia paraguariensis*	6.9	7.7	0.4	9.2	9.6	15.9	0.663	0.83	
	SL10	*Erythroxylon cf. patentisimum*	12.1	8.3	5.0	28.5	46.1	16.4	0.462	0.21	

c) Dry Chaco

Location	Sample ID	Sub-ID	Species	DBH (cm)	H (m)	Leaf (kg)	Branch (kg)	Stem (kg)	Root (kg)	Wood density (g cm^{-3})	BGB/AGB ratio	Remarks
La Patria	PA1	1	*Salta triflora*	12.1	6.3	0.4	42.3	25.2	12.8	0.944	0.19	PA1 had two stems
		2	*Salta triflora*	4.0	3.1	0.0	2.8	2.5	1.0	0.747	0.19	
	PA2	1	*Acacia praecox*	7.9	5.5	1.4	18.0	14.7	17.6	0.678	0.51	PA2 had three stems
		2	*Acacia praecox*	7.5	5.4	0.7	7.6	4.9	6.6	0.499	0.50	
		3	*Acacia praecox*	3.8	5.7	0.5	4.8	2.0	3.6	0.738	0.49	
	PA4		*Cercidium praecox*	18.1	8.1	2.0	102.7	53.4	20.7	0.748	0.13	
	PA5	1	*Cynophalla retusa*	9.3	4.5	0.8	16.5	9.6	7.8	0.708	0.29	PA5 had three stems
		2	*Cynophalla retusa*	5.5	4.2	0.6	7.4	4.9	3.7	0.719	0.29	
		3	*Cynophalla retusa*	5.2	4.4	1.0	20.2	3.6	7.2	0.486	0.29	
	PA6		*Caesalpinia paraguariensis*	8.3	5.5	0.7	18.6	14.5	7.2	0.816	0.21	
	PA7		*Aspidosperma quebracho-blanco*	23.0	8.9	19.6	162.7	100.0	64.8	0.602	0.23	
	PA8		*Anisocapparis speciosa*	16.1	6.2	4.4	42.1	32.1	35.7	0.726	0.45	
	PA9	1	*Sarcotoxicum salicifolium*	6.9	4.7	1.2	23.4	11.0	2.7	1.076	0.08	PA9 had three stems
		2	*Sarcotoxicum salicifolium*	6.4	3.9	0.6	9.6	4.9	1.2	0.714	0.08	
		3	*Sarcotoxicum salicifolium*	4.9	3.7	0.3	4.3	3.3	0.6	0.476	0.08	
	PA10		*Schinopsis lorentzii*	40.3	12.8	28.2	679.0	382.9	319.8	0.620	0.29	
	PA11		*Aspidosperma quebracho-blanco*	35.1	11.1	29.4	302.7	271.8	158.9	0.622	0.26	
	PA12		*Aspidosperma quebracho-blanco*	51.8	14.8	90.0	892.4	705.3	372.2	0.613	0.22	
Mariscal Estigarribia	ME1		*Aspidosperma quebracho-blanco*	28.6	11.7	19.3	197.1	243.2	109.4	0.664	0.24	
	ME2	1	*Aspidosperma quebracho-blanco*	18.6	9.1	6.1	57.0	77.6	34.1	0.641	0.24	ME2 had two stems
		2	*Aspidosperma quebracho-blanco*	17.8	8.9	3.6	49.3	57.6	26.8	0.598	0.24	
	ME3		*Ziziphus mistol*	15.9	6.2	1.1	87.8	26.7	31.3	0.704	0.27	
	ME4		*Aspidosperma quebracho-blanco*	7.3	5.6	0.6	5.8	9.5	4.7	0.714	0.30	
	ME9		*Schinopsis lorentzii*	22.2	10.3	0.5	137.1	125.8	66.3	0.820	0.25	
	ME10		*Ziziphus mistol*	18.8	8.3	0.5	82.4	77.8	47.1	0.705	0.29	
	ME11	1	*Prosopis nigra*	14.6	6.5	4.0	52.6	32.9	35.3	0.621	0.39	ME11 had two stems
		2	*Prosopis nigra*	7.0	5.5	2.8	7.7	5.0	6.4	0.578	0.42	

AGB: Leaf + Branch + Stem
BGB: Root