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Allometric equations for estimating tree biomass in restored mixed-species Atlantic Forest stands

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Abstract: Restoration of Atlantic Forests is receiving increasing attention because of its role in both biodiversity conservation and carbon sequestration for global climate change mitigation. This study was carried out in an Atlantic Forest restoration project in the south-central region of São Paulo State – Brazil to develop allometric equations to estimate tree biomass of indigenous tree species in mixed plantations. Above and below-ground biomass (AGB and BGB, respectively), stem diameter (DBH: diameter at 1.3 m height), tree height (H: total height) and specific wood density (WD) were measured for 60 trees of 19 species. Different biomass equations (linear and nonlinear-transformed) were adjusted to estimate AGB and BGB as a function of DBH, H and WD. For estimating AGB and BGB, the linear biomass equation models were the least accurate. The transformed nonlinear biomass equation that used $\log DBH^2$, log H and log WD as predictor variables were the most accurate for AGB and the transformed nonlinear biomass equations that used $\log DBH^2*WD$ as predictor variables were the most accurate for BGB. It is concluded that these adjusted equations can be used to estimate the AGB and BGB in areas of the studied project. The adjusted equations can be recommended for use elsewhere in the region for forest stands of similar age, tree size ranges, species composition and site characteristics.
Keywords: Above-ground biomass, Below-ground biomass, Biomass equation, Tree allometry, Atlantic Forest, Restoration.

Resumo: A restauração da Mata Atlântica vem recebendo aumento na atenção por causa do papel na conservação da biodiversidade e sequestro de carbono para a mitigação da mudança global do clima. Este estudo foi conduzido em um projeto de restauração da Mata Atlântica na região centro-sul do Estado de São Paulo – Brasil e buscou desenvolver equações alométricas para estimar a biomassa arbórea de espécies nativas em plantios mistos. Em 60 árvores de 19 espécies foram medidas a biomassa acima e abaixo do solo, o diâmetro do tronco (DAP: diâmetro a 1,3 m de altura), altura (H) e densidade específica da madeira (Ds). Diferentes equações de biomassa (linear e não linear) foram ajustadas para estimar a biomassa acima e abaixo do solo, utilizando DAP, H e Ds como variáveis preditoras. As equações de biomassa lineares foram as menos acuradas para a estimativa da biomassa acima e abaixo do solo. As equações de biomassa não lineares que usaram $\log DAP^2$, log H e log Ds como variáveis preditoras foram mais acuradas para a estimativa da biomassa acima do solo e as não lineares que usaram $\log DBH^2*WD$ como variáveis preditoras foram as mais acuradas para a estimativa da biomassa abaixo do solo. Conclui-se que estas equações ajustadas podem ser usadas na estimativa da biomassa acima e abaixo do solo nas áreas do projeto estudado. Também pode ser considerado o uso destas

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equações ajustadas em outras áreas restauradas da Mata Atlântica com idade do povoamento, classes de tamanho das árvores, composição de espécies e características das áreas similares ao deste estudo, desde que árvores sejam avaliadas para verificar a eficácia da equação a ser usada.

Palavras-chave: *Biomassa acima do solo, Biomassa abaixo do solo, Equação de biomassa, Alometria, Mata Atlântica, Restauração.*

Introduction

The restoration of Brazil's Atlantic Forest on degraded lands and riparian areas is receiving increasing attention in the development of public policies for biodiversity conservation and climate change mitigation purposes, with increasing funds available for this purpose through public and private programs and international cooperation (Rodrigues et al. 2009, Rodrigues et al. 2011, Calmon et al. 2011). An area of particular interest is the capacity of these restored forests to absorb atmospheric carbon dioxide and thereby enhance their role as a carbon sink. Accurate estimates of carbon sequestration in these restored forests require development of equations for accurately estimating tree biomass in mixed native species stands.

Tree biomass is an important characteristic of forest ecosystems, reflecting the accumulation of organic carbon and ecosystem productivity (Dixon et al. 1994, Clark et al. 2001, Masera et al. 2003, Grace 2004, Lal 2005) and it can be an important indicator for monitoring the developmentof restored ecosystems (Naeem et al. 2009). Moreover, accurate tree biomass estimates permit comparisons between restored and reference sites and estimates of nutrient stocks in tree compartments of the ecosystem.

There are several indirect methods for tree biomass estimates, such as allometric equations, most of which use a combination of predictor variables such as tree stem diameter, total height and wood density (Saldarriaga et al. 1988, Brown et al. 1989, Overman et al. 1994, Brown 1997, Nelson et al. 1999, Chave et al. 2005, Cole & Ewel 2006). According to Chave et al. (2005), the most important variables for predicting above-ground biomass are, in decreasing order of importance, tree stem diameter, woody specific density, tree height, and forest type. To select biomass equations models, the Akaike Information Criterion (AIC) provides a simple, effective and direct way to select the variables that will produce the best fitting model (Burnham & Anderson 2010).

Multi-species biomass equations are usually based on tree data from primary forests, which usually have different tree architectures than those found in planted (restoration) forests, and typically do not estimate root biomass (Brown et al. 1989, Brown 1997, Nelson et al. 1999, Chave et al. 2005). Miranda et al. (2011) developed and fitted allometric models to estimate dry biomass in trees (including both Cerrado and Atlantic forest species) planted in forest restoration areas ranging in age between 5 and 36 years. In their work, the best results were obtained by stepwise procedures with stratification of species by growth rates. However, equations models for estimating tree biomass in multispecies restoration projects are scarce; equations obtained from trees in natural mature forests are usually used for biomass and carbon estimations in restoration projects (Melo e Durigan 2006), in spite of the differences between tree structural patterns in these two different conditions. Here, we aimed at refining allometric equations for estimating biomass of trees planted in an Atlantic Forest restoration project in Brazil, to be used to assess the role of different plantations systems as carbon sinks.

Materials and Methods

The study sites were located at the São Paulo State University (UNESP) Experimental Farm, Botucatu, south-central region of São Paulo State, Brazil (22°52'32''S and 48°26'46''W). According to Köeppen's classification the climate is Cfa. Annual rainfall averages 1,494 mm with the rainy season lasting from October to March. Annual mean temperature is 20.5°C, with the minimum average occurring in July and maximum in February. The natural vegetation is a semi-deciduous tropical moist forest within the Atlantic Forest biome range.

The experiment was undertaken at two sites with Ultisol (22°49'39''S and 48°25'55''W) and Alfisol (22°48'54''S and 48°24'56''W) soils, respectively. At each site an experiment with 5 treatments and three replicates (random blocks design) was established from 1997 to1998, with each plot measuring 50 x 50 m. Treatments ranged from passive restoration (control plots) to a high-diversity native tree species mixture, and included a direct seeding system, an agroforestry system and a commercial species mixture (Engel & Parrotta 2001, Siddique et al. 2008, Nogueira Jr et al. 2011).

In 2009 we sampled 19 of the native tree species (Table 1) included in the experimental treatments (Control, Direct Seeding and High-Diversity Seedling Planting). These species represent more than 95% of the basal area in the restoration plots, based on previous inventories. They included two ecological groups (fast growing pioneer and slower growing secondary species. All selected individuals were located inside the restoration plots at least 10 m from the edge boundaries. Three individuals of each species, representing the range of tree sizes for each species, were sampled in the restoration treatments, by measuring diameter at breast height (DBH) and total height (H). Only for *Psidium guajava* six individuals were sampled, three in understory of Direct Seeding and High-Diversity Seedling Planting treatment and three in open area of Control treatment. For trees with more than one stem, we calculated the equivalent DBH:

$$equivalent\ DBH = \sqrt{dbh1^2 + dbh2^2 + dbh3^2 \ldots dbhn^2}$$

where, dbh = diameter at breast height of each stem

Among the trees sampled, tree heights ranged from 2.7 to 15.8 m and stem diameters ranged from 2 to 33 cm (Table 1). After being measured, each tree was felled and tree biomass was quantified by the direct method. For above-ground biomass (AGB) three compartments were considered: 1) *leaves* - leaves and twigs with diameters up to 1 cm; 2) *twigs/branches* - woody material of crown of the tree up to a minimum diameter of 1 cm; 3) *stem* - the main wooden axis of a tree, located between the base and the crown of the tree. For below-ground biomass (BGB) only roots with diameters >1 cm were considered. Roots were excavated manually for small trees and with the aid of a retro bulldozer for medium and large trees.

The fresh weight of each individual tree and its components was determined in the field using a dynamometer with capacity

Table 1. Diameter at breast height (DBH), height and specific wood density (WD) of each sampled tree (large (L), medium (M) and small (S)), for 19 native tree species (60 harvested trees) assessed by the direct method to quantify biomass.

Botanical Family	Species	DBH			Height			WD		
		L	M	S	L	M	S	L	M	S
			cm			m			g cm^{-3}	
Fab. Mimosoideae	*Piptadenia gonoacantha* J.F. Macbr.	33.3	14.0	4.0	13.6	9.1	5.0	0.54	0.51	0.46
Fab. Faboideae	*Schizolobium parahyba* S.F. Blake	26.1	19.3	13.1	15.8	12.1	11.7	0.29	0.29	0.25
Fab. Mimosoideae	*Parapiptadenia rigida* Brenan	25.8	13.1	7.0	7.1	7.2	5.9	0.60	0.43	0.61
Euphorbiaceae	*Croton floribundus* Spreng.	24.7	19.7	11.0	12.9	9.6	7.0	0.38	0.39	0.35
Anacardiaceae	*Schinus terebinthifolius* Raddi	22.9	17.4	11.5	7.1	7.2	5.9	0.49	0.51	0.47
Verbenaceae	*Citharexylum myrianthum* Cham.	21.7	15.0	11.4	10.7	11.0	8.7	0.40	0.35	0.38
Fab. Mimosoideae	*Enterolobium contorstisiliquum* Morong	19.7	12.8	6.7	10.1	5.2	4.9	0.31	0.28	0.23
Tiliaceae	*Luehea divaricata* Mart.	16.4	11.5	7.2	7.5	6.0	5.8	0.47	0.38	0.42
Boraginaceae	*Cordia superba* Cham.	14.9	9.7	4.9	7.2	6.8	5.5	0.35	0.33	0.29
Cecropiaceae	*Cecropiapachystachia* Trécul	14.4	12.5	9.7	13.0	10.0	8.1	0.41	0.39	0.35
Fab. Faboideae	**Lonchocarpus cultratus* Vell.	13.8	7.1	2.0	8.5	5.8	2.7	0.49	0.42	0.32
Fab. Faboideae	*Machaerium stipitatum* Vogel	11.2	7.3	4.4	9.8	6.9	4.8	0.35	0.36	0.31
Fab. Faboideae	*Centrolobium tomentosum* Guillemin ex Benth	10.9	8.6	6.4	9.9	9.5	9.7	0.54	0.52	0.39
Fab. Faboideae	*Pterogyne nitens* Tul.	9.9	6.9	3.2	8.9	5.9	4.3	0.54	0.52	0.37
Verbenaceae	**Aloysia virgata* Pers.	8.6	7.4	3.9	9.0	8.0	4.7	0.59	0.61	0.61
Fab. Caesalpinoideae	*Hymenea courbaril* Y.T. Lee&Langenh	8.0	5.7	2.6	8.0	5.4	3.3	0.54	0.53	0.54
Apocynaceae	**Peschiera fuchsiaefolia* Miers	6.8	5.0	3.1	7.0	4.6	4.1	0.38	0.39	0.35
Fab. Faboideae	*Dipteryx alata* Vogel	6.8	4.7	4.1	6.3	5.4	4.0	0.55	0.45	0.45
Myrtaceae	**[1]Psidium guajava* L.	6.0	4.7	3.4	7.0	4.6	4.9	0.53	0.50	0.48
Myrtaceae	**[2]Psidium guajava* L.	5.9	5.5	4.5	3.4	4.1	3.0	0.54	0.51	0.46

*Naturally regeneration (not planted) trees.
[1]Understory trees and [2] open area trees (for *P. guajava*).

for 200 kg and precision of 50 g. To determine the dry weight of each tree we first estimated the moisture content of each compartment by taking around 2 kg (fresh weight) of leaves, twigs/branches and roots, and five 3-5 cm thick disks (one near the base and the others at 25, 50, 75 and 95% of the stem height) for each stem. Two wedges were taken from each disk, one for determining the moisture content and the other for specific wood density (WD). In the laboratory the fresh samples of leaves, twigs/branches, stems and roots were weighed, oven-dried at 70°C to constant weight - approximately seven days. The dry weight of individual tree compartments were calculated using fresh weight ratios obtained from these samples. Wood density was analyzed by the Maximum Moisture Content method (Foelkel et al. 1971). The WD for each tree was computed as the arithmetic average of the five discs.

Above and belowground biomass (AGB and BGB) data were subjected to regression analyses, considering as predictor variables the DBH (cm), DBH^2 (cm^2), H (m) and WD (g cm^{-3}). For assessment of goodness of fit of biomass equations four indicators are reported: 1) standard error of parameter estimate of the predictor variables; 2) $P > |t|$, the probability that a t statistic would have a greater absolute value than observed one, given that the true parameter is zero; 3) coefficient of variation, computed percent ratio between the standard deviation of the error term divided by sample mean of the dependent variable; and 4) Akaike Information Criterion (AIC; Burnham & Anderson 2010), based on likelihood and complexity of equation models. Biomass equations having a t value probability > 0.05 for any predictor

variable (DBH, DBH^2, H and WD) or intercept and biomass equations having coefficient of variation > 70% were rejected. The equations models were compared using AIC, choosing the best model the one with smaller AIC. AIC's differences less than 10 indicate similarity among models, and AIC's difference greater than 10 indicate difference among models. Graphical analysis of the error of estimated biomass in relation to the observed biomass was used. The correlation of the predictor variables DBH^2, WD and H with the dependent variables AGB and BGB were assessed. All analysis were conducted using SAS version 9.2 (SAS Institute 2009) except the AIC that was conducted using R (R Development Core Team 2011).

Results

The partitioning of dry biomass between the compartments of the 19 tree species evaluated was highly variable, did not show any pattern among species (Figure 1), and was probably due simply to different sizes of the trees (Table 1). From the aggregate data from the 60 trees measured, twigs/branches represented 38%, stems 33%, roots 20% and leaves only 8% of total tree biomass (4,260 kg). The average biomass per tree was 71 Kg (twigs/branches 27 Kg, stem 24 Kg, roots 14 Kg and leaves 6 Kg).

The correlation of the predictor variables DBH^2, WD and H with the dependent variables AGB and BGB (Figure 2) were higher in the logarithmic models (Figure 2g, 2h, 2i, 2j, 2k and 2l) than in the arithmetic ones (Figure 2a, 2b, 2c, 2d, 2e and 2f).
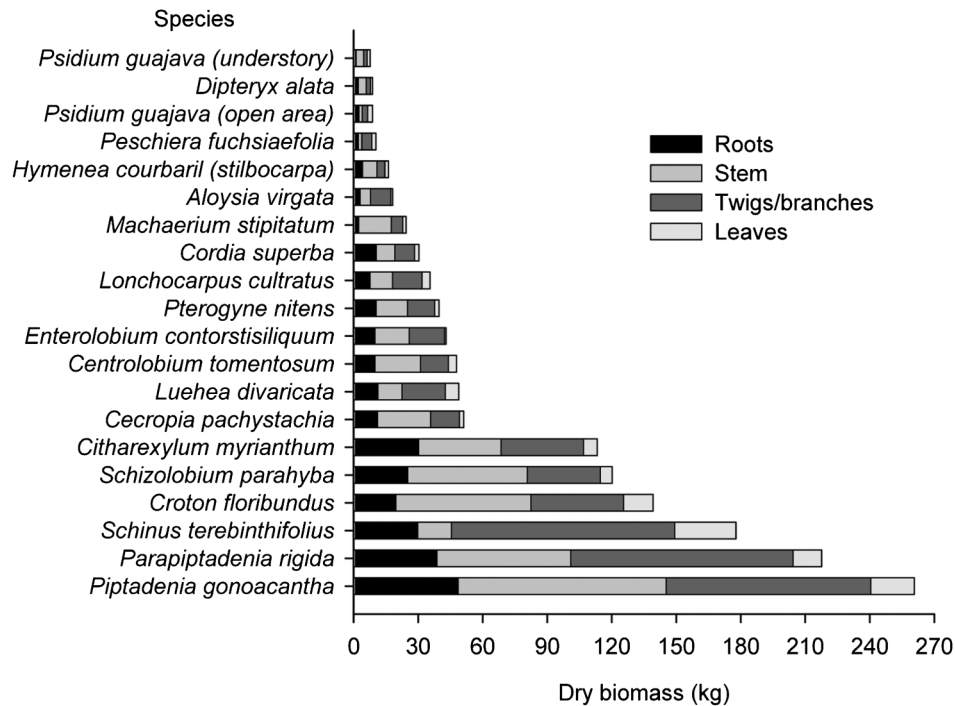
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Figure 1. Average tree biomass (n = 3) by compartment in 19 species from an experimental area of Atlantic Forest restoration project.

Among the predictor variables (DBH^2, H and WD) the DBH^2 had the highest correlation with biomass (AGB and BGB). However, biomass equations using only DBH did not meet the required conditions to be accepted, regarding the arbitrated values of indicators.

For aboveground biomass (AGB) estimates, eight equations models (Table 2) were selected. Equations 4, 5 and 7 were the best fitted, with lower coefficient of variation and AIC. Equations 1 and 2 showed the lowest goodness of fit, with residues not uniformly distributed along the x-axis (Figure 3), mainly for trees < 10 cm DBH. However, log-transformed equations showed a higher goodness of fit and lower error of estimated biomass. By AIC the best models to AGB were the models 5, 7 and 4, respectively.

For belowground biomass (BGB) estimates, six equation models were selected (Table 2). The log-transformed equations 11 and 13 were the best fitted regarding their lower coefficient of variation, lower error of estimated biomass and lower AIC. Similar to AGB, the untransformed equation (equation 9) led to the lowest goodness of fit, with higher coefficient of variation and AIC value (Table 2). By AIC the best models to BGB were the models 13 and 11, respectively.

Discussion

In general, most trees had a higher proportion of twigs/branch biomass than stem biomass, when compared to other studies undertaken in natural forests that involved a wider range of tree sizes (Chave et al. 2005). Only few species (*M. stipitatum, C. tomentosum, C. pachystachia, S. parahyba, C. floribundus, H. courbaril* and *D. alata*) had a higher proportion of biomass in stem than in other aboveground biomass components. In this experiment, trees were still young, around 11-12 years old, and therefore their architectural development was not completed yet, with poor stem development. Stem

biomass will probably increase over time, when the tree individuals increase their DBH as well as WD. Furthermore, since the stands not yet completely stocked, higher availability of light stimulates greater branch development, in contrast to what occurs in more dense natural forests, where stronger light competition reduces branch formation and a higher investment in stem growth. This can be observed by the contrasting biomass allocation of *Psidum guajava* where trees growing in the understory had a higher proportion of stem than tress growing in full sunlight.

Since average root biomass was 20%, the BGB compartment represents an important component of total stand biomass. Fonseca et al. (2012) found a percentage of 22% of coarse roots in total tree biomass of native forest plantations in the humid tropical lowlands of Costa Rica. In a New Zealand beech (*Nothofagus*) forest ecosystem, roots represented 22% of total live tree biomass (Hart et al.2003). Root biomass or BGB is often expressed as a proportion to AGB, such as a root-shoot ratio (R/S ratio). The R/S ratio was 0.25, similar to forests in tropical zones (0.24, Cairns et al. 1997), montane moist forests (0.22, Sanford & Cuevas 1996) and New Zealand beech forest ecosystems (0.28, Hart et al. 2003). This indicates that studies focusing only in above ground biomass will be considerably underestimating the capacity of forest to stock carbon in projects that aim at climate change mitigation.

Tree height is well-known as an important indicator of site quality (Teshomea & Petty 2000) and together with DBH defines the main structural pattern of forest systems. While inclusion of both DBH and H in regression equations for biomass estimation is usually recommended (Silveira et al. 2008), in our analysis the use of only DBH^2 and H in equations 6 and 12 led to low goodness of fit, except when WD was included (in equations 5, 8 and 14), reducing the error of estimated biomass. However, the equations 6 and 12 that only use DBH^2 and H as predictor variables is not recommended to

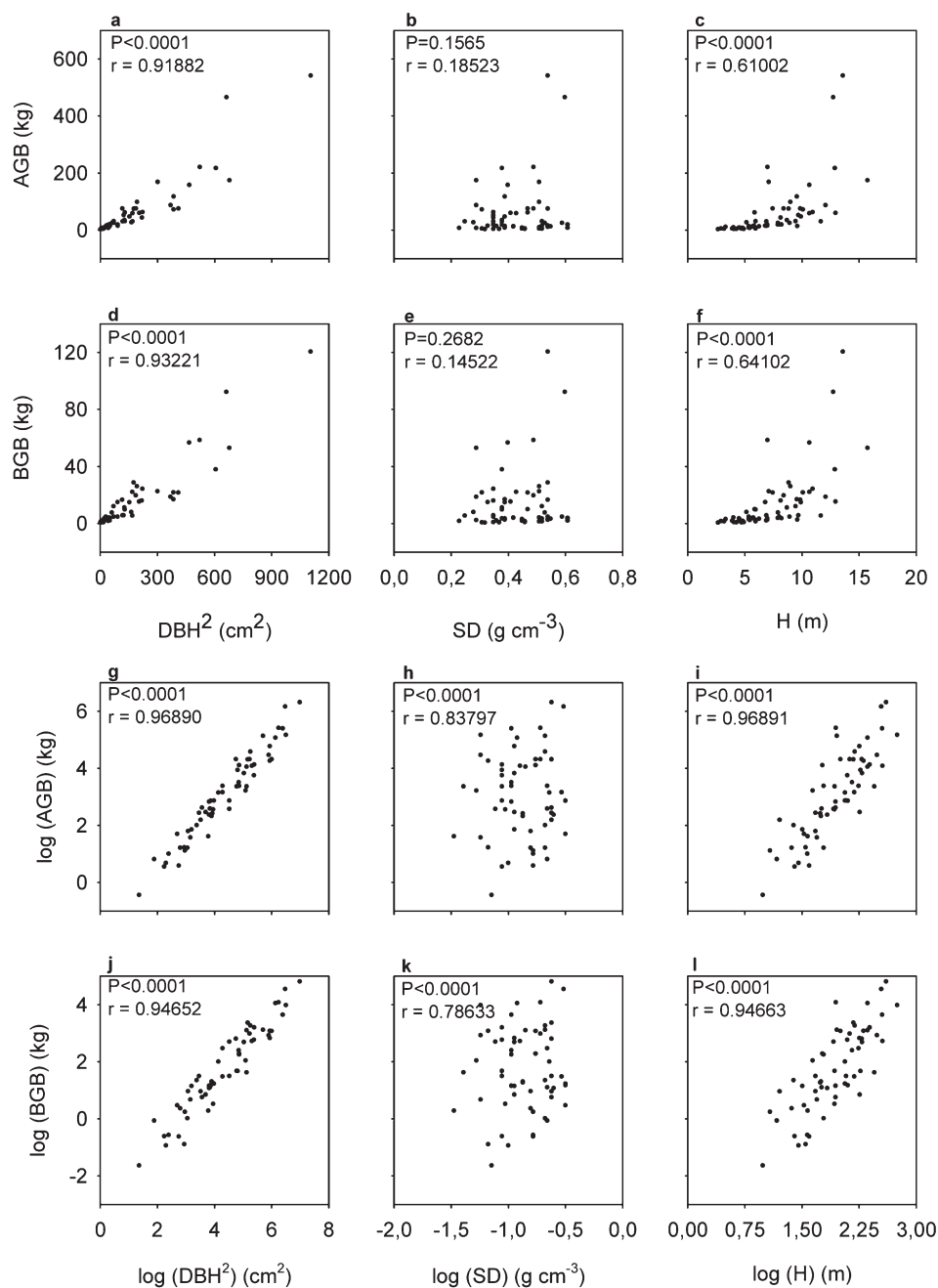Allometric equations for Atlantic Forest stands

Figure 2. Pearson correlation between predictor variables (DBH, WD and H) and dry biomass (aboveground biomass – AGB and belowground biomass – BGB) for 60 trees of 19 Atlantic Forest species.

biomass estimate because of low goodness of fit.

Only WD correlated [?] with DBH^2 (equations 4 and 7 for AGB and equations 11 and 13 for BGB) provided good predictions of biomass. This may be attributed to the influence of WD in the variation of dry biomass between species and individuals of different sizes. For example, if only DBH^2 and H are used as predictor variables an underestimation of biomass for small trees having high WD such as *A virgata* and *P. guajava* and an overestimation of the biomass for large trees having low WD like *S. parahyba* are expected.

Estimates of forest biomass using different equations have led to very contrasting results. In the Brazilian Atlantic Forest, different models produced considerably different biomass

estimates (Vieira et al. 2008, Lindner & Sattler 2012). However, for Vieira et al. 2008 pantropical models of biomass equations (c.f. Chave et al. 2005), using DBH^2, H and WD as predictor variables may be used to estimate above-ground tree biomass in the Atlantic Forest. Nevertheless, in the present study Chave et al. (2005)'s equation underestimated tree AGB, with an estimation of 1,885 Kg. This may be due to the fact that our study included trees with different DBH and H ranges (and different tree architectures), with many small individuals in these young forest stands in the early stage of reforestation (low average WD). It should be noted that equations used to estimate biomass, here or anywhere, first need to be based on the appropriate range of tree sizes, and secondarily to the range

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Table 2. Regression analyses (N = 60) and Akaike Information Criterion (AIC) for equations models of above- and belowground biomass (AGB and BGB, respectively) of 19 native tree species used in the Atlantic Forest restoration project.

Biomass equation models	Parameter Estimate		Standard error	P > |t|	Coefficient of variation	AIC
	Symbol	Value				
AGB						
1) $AGB = \alpha + \beta(DBH^2)$	α	-13.127	6.4131	0.0452	68.76	614.3
	β	0.428	0.0242	<0.0001		
2) $AGB = \alpha + \beta_1(DBH^2) + \beta_2(WD)$	α	-100.353	20.1404	<0.0001	59.56	598.0
	β_1	0.430	0.0209	<0.0001		
	β_2	200.402	44.4777	<0.0001		
3) $\log(AGB) = \alpha + \beta\log(DBH^2)$	α	-1.890	0.1718	<0.0001	12.41	419.9
	β	1.127	0.0378	<0.0001		
4) $\log(AGB) = \alpha + \beta_1\log(DBH^2) + \beta_2\log(WD)$	α	-1.027	0.1710	<0.0001	8.97	382.4
	β_1	1.144	0.0274	<0.0001		
	β_2	1.085	0.1477	<0.0001		
5) $\log(AGB) = \alpha + \beta_1\log(DBH^2) + \beta_2\log(H) + \beta_3\log(WD)$	α	-1.305	0.2067	<0.0001	8.67	379.4
	β_1	1.055	0.0479	<0.0001		
	β_2	0.340	0.1519	0.0292		
	β_3	1.077	0.1428	<0.0001		
6) $\log(AGB) = \alpha + \beta\log(DBH^2*H)$	α	-2.541	0.1987	<0.0001	12.76	422.9
	β	0.883	0.0305	<0.0001		
7) $\log(AGB) = \alpha + \beta\log(DBH^2*WD)$	α	-0.970	0.1015	<0.0001	8.96	380.6
	β	1.142	0.0272	<0.0001		
8) $\log(AGB) = \alpha + \beta\log(DBH^2*H * WD)$	α	-1.853	0.1312	<0.0001	9.66	389.5
	β	0.896	0.0231	<0.0001		
BGB						
9) $BGB = \alpha + \beta_1(DBH^2) + \beta_2\log(WD)$	α	-17.381	4.2857	0.0002	51.18	412.3
	β_1	0.097	0.0045	<0.0001		
	β_2	35.903	9.4645	0.0004		
10) $\log(BGB) = \alpha + \beta\log(DBH^2)$	α	-2.960	0.2177	<0.0001	27.78	290.9
	β	1.072	0.0479	<0.0001		
11) $\log(BGB) = \alpha + \beta_1\log(DBH^2) + \beta_2\log(WD)$	α	-2.134	0.2570	<0.0001	23.83	273.6
	β_1	1.088	0.0412	<0.0001		
	β_2	1.038	0.2221	<0.0001		
12) $\log(BGB) = \alpha + \beta\log(DBH^2*H)$	α	-3.535	0.2655	<0.0001	30.12	300.5
	β	0.832	0.0408	<0.0001		
13) $\log(BGB) = \alpha + \beta\log(DBH^2*WD)$	α	-2.086	0.1518	<0.0001	23.68	271.7
	β	1.086	0.0407	<0.0001		
14) $\log(BGB) = \alpha + \beta\log(DBH^2*H * WD)$	α	-2.887	0.2051	<0.0001	26.65	285.9
	β	0.845	0.0361	<0.0001		

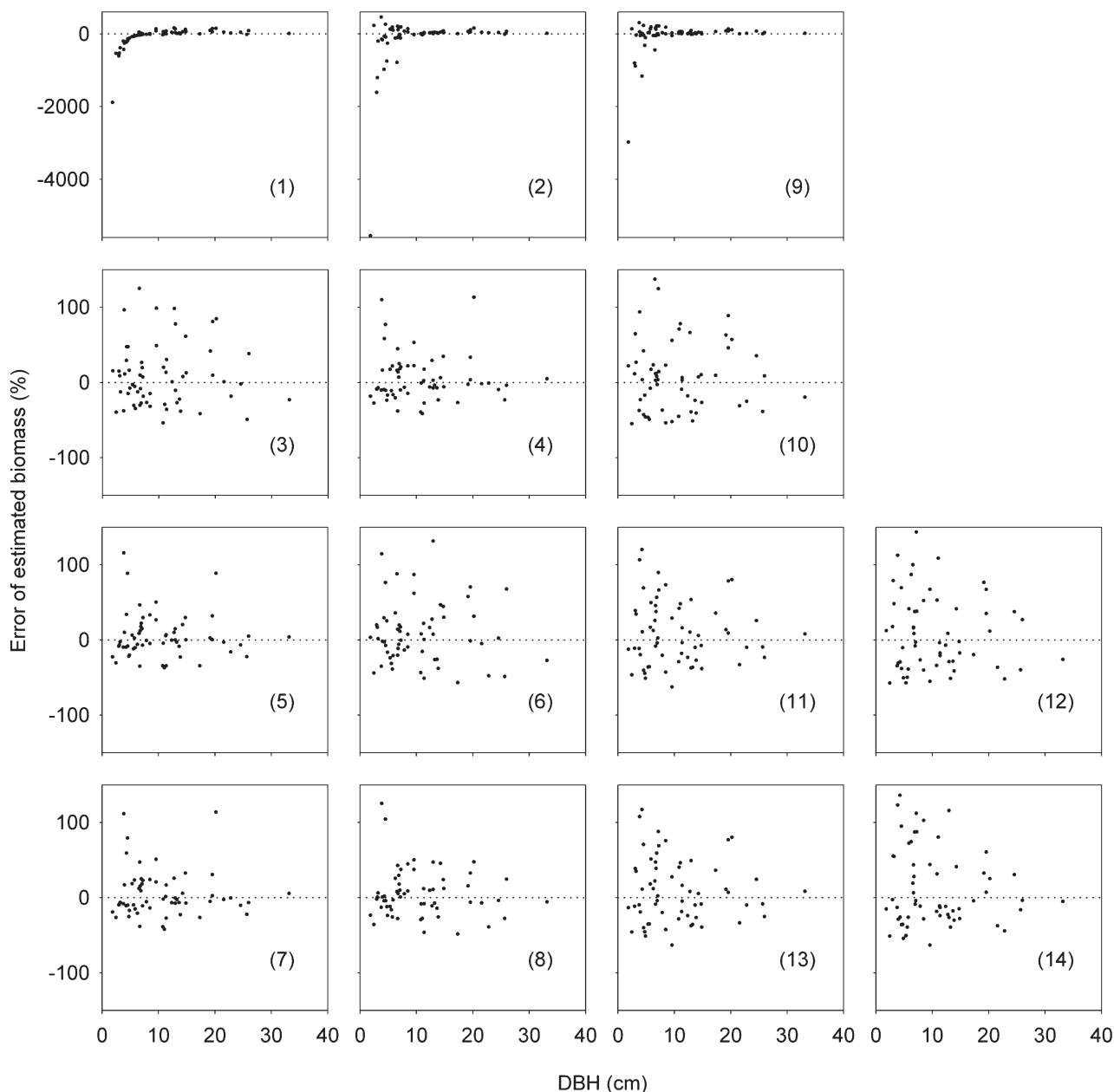DBH = diameter at breast height (1.3 m) height; H = total height; WD = specific wood density.

Figure 3. Residual analysis (error plots of estimated biomass (%) by the observed biomass) for14 equation models trees of 19 Atlantic Forest species. Biomass equation models for above- and belowground biomass (AGB and BGB):(1) $AGB = \alpha + \beta(DBH^2)$; (2) $AGB = \alpha + \beta_1(DBH^2) + \beta_2(WD)$; (3) $\log(AGB) = \alpha + \beta\log(DBH^2)$; (4) $\log(AGB) = \alpha + \beta_1\log(DBH^2) + \beta_2\log(WD)$; (5) $\log(AGB) = \alpha + \beta_1\log(DBH^2) + \beta_2\log(H) + \beta_3\log(WD)$; (6) $\log(AGB) = \alpha + \beta\log(DBH^2*H)$; (7) $\log(AGB) = \alpha + \beta\log(DBH^2*WD)$; (8) $\log(AGB) = \alpha + \beta\log(DBH^2*H*WD)$;(9) $BGB = \alpha + \beta_1(DBH^2) + \beta_2(WD)$; (10) $\log(BGB) = \alpha + \beta\log(DBH^2)$; (11) $\log(BGB) = \alpha + \beta_1\log(DBH^2) + \beta_2\log(WD)$; (12) $\log(BGB) = \alpha + \beta\log(DBH^2*H)$; (13) $\log(BGB) = \alpha + \beta\log(DBH^2*WD)$; (14) $\log(BGB) = \alpha + \beta\log(DBH^2*H*WD)$.

of tree architectural types found in the forest where such equations will be applied.

The sampling error in forest inventory estimates has two main components (Parresol 1999). The first is the component related to random selection of sample units and the second component is associated with the error of the regression model itself. In the present study, the 19 tree species sampled represent more than 95% of the restoration plots basal area, be in the Control, Direct Seeding and High-Diversity Seedling Plantings. The three harvested individuals of each species represent the range of sizes which were found in the planting sites. Regarding the regression errors they were high for equations 1, 2 (for

aboveground biomass) and 9 (for belowground biomass), suggesting that the use of untransformed log equations is inadequate to estimate tree biomass in forest plantations.

To reduce the error of estimated biomass the use of log-transformed biomass equations was more appropriated, such as the equation 5 for AGB and the equation 13 to BGB which had a better goodness of fit. Finally, we concluded that in decrease order the better equations for above- and belowground biomass estimate in restored areas are:

$$\log(AGB) = -1.305 + 1.055\log(DBH^2)$$
$$+ 0.34\log(H) + 1.077\log(WD)$$

$$\log(AGB) = -0.970 + 1.1421 \log(DBH^2 * WD)$$

$$\log(AGB) = -1.027 + 1.144 \log(DBH^2) + 1.085 \log(WD)$$

and

$$\log(BGB) = -2.086 + 1.086 \log(DBH^2 * WD)$$

$$\log(BGB) = -2.134 + 1.088 \log(DBH^2) + 1.038 \log(WD)$$

However, log-transformed biomass equations may be only applicable to mixed plantations with tree DBH, H and WD ranges similar to the ones showed in Table 1. Provided that there are similarities in species composition, the biomass equations presented here may be useful for application on a local and regional scale. Although these biomass equations may be applied in the context of the Atlantic Forest restoration, for projects focusing on environmental services like carbon sequestration, it is suggested that some tree individuals be evaluated by direct (destructive) method to verify whether the equation to be used overestimates or underestimates tree biomass (Brown 1997).

Conclusions

The logarithmically-transformed equation that use diameter at breast height, total height and specific wood density as predictor variables are the most accurate equation for estimating above-ground biomass. Furthermore, the logarithmically-transformed equations that use diameter at breast height and specific wood density as predictor variables showed good accuracy for estimating above- and below-ground biomass. These biomass equations may be recommended for estimating tree biomass in Atlantic Forest restoration projects, providing some similarity in species composition, age or structural development, and site characteristics.

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