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Normalization of wood density in biomass estimates of Amazon forests

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Abstract

Wood density is an important variable in estimates of biomass and carbon flux in tropical regions. However, the Amazon region lacks large-scale wood density datasets that employ a sampling methodology adequate for use in estimates of biomass and carbon emissions. Normalization of the available datasets is needed to avoid bias in estimates that combine previous studies of wood density that used wood sampling at diverse positions in the bole or with various methods of density determination. This paper examines the question of whether regressions for radial variation and for variation in wood density along the bole, both developed in dense forest in central Amazonia (CA), are suitable for the open forests in southern Amazonia (SA) that are currently the target of most of Amazonia's deforestation activity. The wood density of the heartwood and density of full disks or slices (bark, sapwood and heartwood) in each tree were measured to assess the radial variation. For variation along the length of the bole, wood density at breast height and at the top of the bole were used. Moisture content of the bole was measured in SA and compared with values reported by studies from CA in similar dense forest. Comparing regressions that predict full-disk density from heartwood density, the pattern of radial variation differs slightly and significantly between the two forest types (ANCOVA $p = 0.006$); the slopes have similar values but the intercepts differ. Variation along the bole in the two forest types does not differ significantly ($p = 0.144$), so the CA model for predicting mean bole density from the density of a slice at breast height gives an unbiased estimate of the mean bole density when applied to SA trees. In SA the mean moisture content of the bole was 0.416 (± 0.068 SD; $n = 223$ trees). Moisture content of the bole had a strong inverse relationship with basic wood density ($r = -0.77$), which explains the lower moisture content in the trees in CA relative to SA. A much weaker inverse relationship was found between moisture content and green wood density ($r = -0.292$). The relationship between wood basic density and green ('fresh') density presented in this study provides an alternative means of obtaining basic wood density directly in the field when oven drying of samples is not possible.

Keywords: Amazon forests, basic wood density, global warming, green wood density, linear regression, moisture content.

Introduction

Wood density has been recognized as an important variable for improving biomass estimates in Amazon forests (Baker et al., 2004; Malhi et al., 2006) and estimates of greenhouse-gas emissions (Nogueira et al., 2005, 2007; Fearnside, 2007). Recent large-scale estimates of wood density across the Amazon have been based on a variety of prior studies (Fearnside, 1997; Baker et al., 2004; Chave et al., 2006). However, many wood-density datasets sampled in Amazonia were intended for technological and commercial uses rather than for biomass estimates (e.g., Brazil, IBDF, 1981, 1983, 1988; Feldalto et al., 1989; Brazil, IBAMA, 1997; de Souza et al., 2002). Studies differ in collection methodology, such as the position of the sampling in the bole and the way that weight and volume are determined, usually tending to overestimate mean density (Fearnside, 1997; Nogueira et al., 2005). For biomass estimates the best measure is basic wood density (fully dry weight divided by green volume) expressed as a mean of the bole, that is, including appropriate corrections for radial variation and variation along the length of the bole of each tree. In order to use the available datasets one therefore needs accurate corrections to avoid bias in wood density means calculated from diverse measures.

Several previously published equations allow normalization to estimate basic density based on data from diverse methods of wood-density measurement, such as those that report density with 12% moisture content (e.g., Brotero, 1956; Sallenave, 1971; Oliveira, 1981 *apud* de Souza et al., 2002; Reyes et al., 1992; Simpson, 1993). Recent large-scale wood density estimates have adopted normalization for moisture content (Baker et al., 2004; Chave et al., 2006), but none have applied corrections for position of sampling in the bole. Complications arise from published wood density values being based on heartwood samples taken near breast height. Regressions developed in central Amazonia are available relating the wood density of a full disk (bark, sapwood and heartwood) to the density of heartwood and for relating the wood density of a full disk at breast height to the mean basic density of the bole (see Table 2 in Nogueira et al., 2005), but these relationships have not been tested in other forest types in the Brazilian Amazon. It is particularly important to have correction equations for wood density to improve biomass estimates in the open forests that occur at the southern fringe of the Amazon region where most deforestation activity and carbon emissions are taking place (Brazil, INPE, 2006). Environmental conditions in this region are different from those in the dense forest of the central Amazon because soils are more fertile, insolation is higher and dry seasons are longer; all of these characteristics affect wood density in some way (Sombroek, 2000; Malhi et al., 2004; ter Steege et al., 2006). Lower wood densities found in open forest with a prolonged dry season in southern Amazonia (Nogueira et al., 2007) suggest a relationship with stem water storage, and hence help explain the phenology and distribution of species (Reich and Borchert, 1984; Schulze et al., 1988; Borchert, 1994).

In this study linear regressions developed in dense forest in central Amazonia (Table 2 in Nogueira et al., 2005) were evaluated for bias when accounting for radial and vertical variation in wood density of trees sampled in the open forests of southern Amazonia. If the linear relationships in the two forest types are not significantly different, a single pooled regression can be developed for the two forests. A pooled regression would also have greater precision. Finally, for the southern Amazon open forests this study also examined the ratio between green mass and dry mass for each sample. This ratio was considered to be equivalent to the moisture content of the bole when obtained from samples at the base and at the top of the bole.

Materials and Methods

Collection sites

The samples used in this study were collected at six sites in primary forests in the central Amazon (CA) and five sites in southern portion of the Brazilian Amazon (SA). The CA sites were located near Manaus, Amazonas state (Nogueira et al., 2005). Four of the SA sites were in the northwestern portion of Mato Grosso state in the counties of Juruena (2 sites), Cotriguaçu (1 site) and Carlinda (1 site). The fifth site was located in the southern portion of the state of Pará in the county of Novo Progresso.

At all CA sites the predominant vegetation is dense forest with a mean altitude of ~100 m above mean sea level (m.s.l.). In SA the vegetation is open rain forest at ~300 m above m.s.l with either vines or palms as subdominant life forms. The soils at the CA sites are yellow latosols (acrisols) that are poor in nutrients (Magnago et al., 1978; Yamazaki et al., 1978). The sites in Mato Grosso state are predominantly on xanthic or orthic ferralsols and ferralic arenosols. At the site in southern Pará the soils are predominantly orthic acrisols and ferralsols on granite shield uplands (FAO, 1988; Sombroek, 2000). At the CA sites the average annual rainfall is about 2300 mm. At the Mato Grosso sites the predominant climate is tropical humid with 2075 mm annual precipitation. Rainfall in CA is below 100 mm/month during three months, from July to September (Marques-Filho et al., 1981). At the Mato Grosso sites there is a six-month dry period from May to September with mean monthly precipitation below 100 mm (Brazil, ANA/SIH, 2006). At the southern Pará site the average annual precipitation is 2280 mm and the dry period extends from June to August (Oliveira et al., 2004; Brazil, ANA/SIH, 2006). In CA the mean monthly temperature is stable throughout the year at around of 26 ^{o}C (Marques-Filho et al., 1981). A similar annual average is found at the other sites (Brazil, INMET, 2006).

Collection of samples for wood density determination

The trees felled in each forest type were always chosen randomly but stratified by size class according to the proportion that each class contributes to basal area in local forest inventories. The research plan was authorized by the Brazilian Institute for Environment and Renewable Natural Resources (IBAMA) and in Mato Grosso state by the Environment Secretariat (SEMA/MT).

For density determination, disks of constant thickness (~3 cm) were taken at breast height (even in the presence of buttresses) or at the top of the stump (Juruena site), and at the top of the commercial bole. For variation in wood density along the length of the bole, samples were taken at breast height and at the top of the bole from 307 trees in CA (identified as 186 species or morpho-species) and 235 trees in SA (130 species or morpho-species). Any radial variation in density was included by obtaining a full slice of even thickness. Basic wood density was determined for this disk or for a wedge obtained from it. When present, samples of the heartwood were taken close to the center of the disks. In 146 trees from the CA sites (dbh 13-106 cm, 112 species or morpho-species), heartwood samples were taken only at breast height, while in 76 trees from the SA sites (dbh = 9-124 cm, 40 species or morpho-species) heartwood samples were also taken at the tops of the stump and bole. The green (or 'fresh') mass and volume were determined on the same day. The green volume was determined by displacing water in a container placed on a battery-operated scale, also used in the mass determination. In this study green mass and volume do not mean that the wood is completely saturated with water (Simpson and TenWolde, 1999), but rather refers to wood newly removed from the tree. In SA trees (n = 223; dbh 5-104 cm, 125 species or morpho-species) the ratio between green mass and mass after oven drying was used as a measure of bole water content (e.g., Borchert, 1994; Schulze et al., 1988). This attribute was obtained both at the base and top of the bole. The green mass was not measured in samples from trees in CA sites. For the dry weight of each sample a vented electric oven was used at 103 ^{o}C (ASTM, 2002) and samples were considered completely dry after three consecutive stable weight readings at 24-hour intervals. For all trees, the mean basic density of the bole (not taper-adjusted) was determined as the arithmetic mean of the density at breast height (or at the top of the stump for the Juruena site) and at the top of the bole. A taper-adjusted mean density was not determined in the SA trees because it did not differ significantly from the arithmetic mean (Nogueira et al., 2005). However, the model developed in dense forest (CA) tested in this study used taper-adjusted mean density of the bole as the dependent variable. In this study it was assumed that mean taper-adjusted and mean non-taper-adjusted measures also did not differ significantly in open forest.

Linear model statistics from trees in southern Amazon (SA)

Higher adjusted r^2 and lower standard error of the estimate constituted the statistical criteria for selecting the best model to predict full disk density from heartwood density and to predict basic density (dry mass/green volume) from 'green density' (green mass/green volume). The relations between the variables were found to be linear and the residuals were uniformly and normally distributed.

Results

Wood density radial variation

The linear relationships between heartwood density and full-disk density for dense forest (CA) and for open forest (SA) had similar slopes (p = 0.251) but different intercepts (p = 0.006) (Figure 1). Despite not having a statistically significant difference, Figure 1 indicates that the lines are not parallel. The full-disk density values are clearly lower for higher values of heartwood density, but tend to converge for values below approximately 0.5. Therefore, heartwood regressions from dense forest tend to overestimate the mean density of disks in open forest. A separate regression for predicting full-disk density from heartwood is described for the open forest type studied here (Table 1, model 1). The average full-disk density of all SA samples estimated using the SA model is off by only ~0.2%, but is overestimated by 3% using the CA regression. Although the bias when the CA linear regression is applied in SA open forest might appear to be small, this percentage is substantial for carbon balance and can be minimized by use of a region-specific SA regression. In open forest types with intrinsic disturbance a greater difference would be expected between heartwood and full-disk densities than would be the case in dense forest. Open forests dominated by climbing bamboo or by dense tangles of lianas typically have many gaps that favor fast-growing trees with light wood.

[Figure 1 and Table 1 here]

Henceforth, radial variation is denoted “%RV,” meaning the amount by which the heartwood density exceeds the full-disk density, expressed as a percentage of the latter. A tree with negative %RV has lower wood density in the heartwood than in the whole disk, thus decreasing density toward the center, while positive values are found in trees with increasing density toward the center. In open forest, 63% of sampled trees with heartwood had wood density decreasing towards the outside, while in dense forest this was the case for 82% of the trees with heartwood (Nogueira et al., 2005). Percent RV was related to ln(heartwood density) in both forest types ($r^2 = 0.537$ in dense forest and $r^2 = 0.381$ in open forest, both $p = 0.000$). Significant probabilities at the 5% level were also found when the effects of the different factors on %RV were tested simultaneously, with forest type as a factor and density, diameter and height as covariates. Trees with high-density heartwood were lighter toward the outside, while trees with light heartwood tended to increase in density toward the outside (negative values for %RV) (Figure 2). This would seem to be consistent with a tendency for light trees to add denser wood toward the outside as they grow. However, if consider separately the two patterns of radial variation the relationship between %RV and diameter or height do not support this conclusion (Table 2). In SA, trees that *decrease* in density toward the outside do this to a greater degree if they are large, while trees that increase in density toward the outside do not do so to a greater degree if they are large (Table 2, Figure 3A, B).

[Figures 2, 3 and Table 2 here]

Variation in wood density along the bole

Two linear regressions (mean density of the bole × density at breast height) do not differ statistically in paired comparisons between dense (CA) and open forest (SA), ($p = 0.144$; $n = 542$), Figure 4. The linear model developed in CA for estimating taper-adjusted mean wood density of the bole from disks at breast height resulted in accurate estimates of the mean density of the bole: 0.007 ± 0.157 SE difference between measured and estimated mean, or ~1%).

[Figure 4 here]

Moisture content

The mean moisture content of the bole in 223 trees in the southern Amazon was 0.416 (± 0.068 SD; 95% CI 0.407 – 0.425; range 0.246 – 0.595). Moisture content of the bole was inversely related to basic wood density (Pearson correlation = -0.77, $p = 0.000$; $n = 222$) (Figure 5A). There was a much weaker inverse relationship between moisture content and green wood density ($r = -0.292$, $p = 0.000$; $n = 222$) (Figure 5B). These two results are expected if the density of dry wood tissue free of air varies little across all species and if trees with less-dense wood store more water, but not much more air, in the same volume of green wood. The moisture content increased with height along the bole (paired *t*-test, $p = 0.000$; Figure 5C), suggesting more moisture in younger tissues. The percentage moisture content at the base of the bole (top of the stump or at breast height) was 0.399 (± 0.075 SD; n = 223, 95% CI 0.389 – 0.408; range 0.22 – 0.67) while at the top of the bole moisture content was 0.433 (± 0.070 SD; n = 223, 95% CI 0.442 – 0.423; range 0.18 – 0.65). The moisture content of the entire bole was not significantly related to bole diameter at breast height (r = 0.020, p = 0.766, n = 223). Two linear regressions between 'green density' and basic wood density using trees sampled only in open forest (SA) were developed (Table 1, models 2 and 3).

[Figure 5 here]

Discussion

Wood density normalization for biomass estimates

Sampling of wood density for use in biomass estimates must consider that different patterns of radial variation in wood density and of variation along the bole have been found in tropical trees. Generally, density declines from the heartwood outwards in mature forest or in late-successional species, with the inverse occurring in typical colonizing species, and a decline in density with increasing height of the sample position in the bole has been found in all species groups (Wiemann and Williamson, 1988; 1989; Suzuki, 1999; Woodcock and Shier, 2002, 2003; Nogueira et al., 2005, 2007; Wittmann et al., 2006). The radial density variation, as shown by the %RV values in Table 2 and Figures 3 A,B, suggests that SA trees reinforce the strength of their central cores as they grow larger, rather than adding a series of successively denser nested cylinders of wood.

Theoretically there are four possible strategies as trees grow larger: (1) species with uniformly low density over the course of their development, (2) uniform high density, (3) species that invest in an increasingly dense heartwood core as they grow and (4) species that initially have lower density overall and invest in higher density wood toward the outside of the bole as they grow. Only the first three patterns were detected in this study (if inferred at the 5% level probability). Nonetheless, in CA trees Figure 3 shows a trend to higher in wood density toward the outside, although at the 5% level the probability is not significant. Studies with pioneer and early successional species have found dramatic radial increases from pith to bark (Wiemann and Williamson, 1988, 1989; Woodcock and Shier, 2002, 2003).

The relationships reported in this paper make it possible to correct previously published datasets for almost all bias from radial variation and from variation along the bole. For example, a heartwood dataset or a dataset of full-disk densities at breast height sampled in dense and open forest can be converted to values representing basic density of the whole bole that are suitable for biomass estimates. However, there are still no calibration equations for estimating density of the full disk using non-tapered core samples. These relationships are important because core sampling is a practical and non-destructive method and because several recent studies have used increment borers (Woodcock, 2000; Woodcock and Shier, 2003; Muller-Landau, 2004; DeWalt and Chave, 2004; King et al., 2006).

Bias from variation along the bole has not been corrected in recent large-scale wood-density estimates and can result in substantial overestimation. The results (Figure 4) show that the pattern of variation along the bole is similar between dense and open forest and that a single regression developed in dense forest or simple percentage corrections can also be used in open forest (about 4.3% on average, see Nogueira et al., 2005, 2007).

Radial and along-the-bole variation of wood density

Bias in wood density datasets for Amazonian forest is predominantly related to radial variation because most of the available wood density measurements have been confined to heartwood (Brazil, IBDF, 1981, 1983, 1988; Brazil, IBAMA, 1997; Baker et al., 2004, Table A1). Although the calibration equations given in this study contribute to improving biomass estimates, it is important to consider that the patterns of radial density shown are not representative at the community level because they are based exclusively on trees with heartwood and therefore do not apply to all species. The occurrence of trees with dense heartwood is expected to differ between dense and open forest types because species with light (< 0.50 g cm^{-3}) and medium (0.50-0.72 g cm^{-3}) density wood are more abundant in open forest (91%) than in dense forest (67%), (Nogueira et al., 2005, 2007). Therefore, in open forest the use of datasets based only on heartwood can overestimate density because light species without heartwood will be under-represented, in contrast to dense forest, which is predominantly composed of species with medium or dense wood. Tropical species with light wood density usually do not have heartwood, and in species with lower central density there is a tendency for wood density to be higher toward the outside, as shown in Figure 2. Families such as Malvaceae, Caricaceae and certain genera of Leguminosae generally have light wood or lack heartwood. Chave et al. (2006) suggest that western Amazonian forests are also dominated by families with low mean wood density. In addition, ter Steege et al. (2006) and Baker et al. (2004) emphasise the importance of generic-level patterns in composition. The fast-growing species that are common in liana-dominated and in bamboo-dominated open forests also may not have heartwood.

Although prior studies suggest that substantial radial variation is predominant in species with low wood density (Wiemann and Williamson, 1988, 1989), this study shows that the difference between heartwood and full-disk density is also high for species with high heartwood density (Figure 2). Despite heartwood and full-disk density being strongly correlated (Figure 1), Figure 2 indicates that when heartwood is very dense, the sapwood and bark have a lower relative density.

In dense forest, species with denser heartwood are more abundant (Figure 2), while in open forest there are many species with light heartwood. Also, because of this the stand-level wood density tends to be lower in disturbed forest or in forests the initial stages of development because of the prevalence of colonizing species (Suzuki, 1999). Thus, wood density is an indicator of the changes in primary vegetation in Amazonian forests and is important for studies of biomass loss in standing forests (Laurance et al., 2006). This could be important in assessing changes in biomass of Amazonian forest caused by global warming because the methods used so far are only able to assess increments in diameter over a period of years, but not intrinsic changes in biomass stock, such as those caused by changes in wood density and other wood properties (Bräker, 2001).

Moisture content

Moisture content of the bole depends directly on wood properties because when specific gravity is high, lumen volume is low and maximum moisture content is restricted (Simpson, 1993; Simpson and TenWolde, 1999). Species with lower wood density have more parenchyma tissues and hence higher water-storage capacity than denser species (Figure 5A) (Borchert and Pockman, 2005; Borchert, 1994; Schulze et al., 1988; Suzuki, 1999). Because of this a higher moisture content is expected in the boles of trees in open forest because there are more light-density species than in dense forest (Nogueira et al., 2005, 2007), a difference with important implications for estimates of biomass in Amazonian forests. In dense forest the moisture content used by Chambers et al. (2001) for converting fresh biomass to dry mass in central Amazonia was 0.38 (± 0.08 SD; $n = 50$ trees) for all above-ground tree components (bole, branches, leaves), similar to the value of 0.39 (bole only) adopted by Higuchi et al. (1998) based on 38 trees and to the value of 0.388 found by da Silva (2007) based in 128 trees. The moisture content of boles in open forest found in this study (0.416) differs significantly from the value found by Higuchi et al. (1998) and by da Silva (2007) in dense forest in the central Amazon ($t = 5.641$, df = 222, p value < 0.0005) and from the value of 0.38 reported by Chambers et al. (2001) ($t = 7.847$, p value < 0.0005). This suggests that allometric equations developed in dense forest that estimate fresh mass from diameter only (such as the equations of Chambers et al., 2001 and Higuchi et al., 1998) will lead to three kinds of overestimate when applied to open forest. In addition to overestimates of biomass resulting from the lower wood density and shorter trees of open forests (Nogueira et al., 2008), an additional 3-4% overestimate will occur if fresh mass is converted to dry mass using moisture contents typical of dense forest. Two examples are the estimates of Cummings et al. (2002) and the estimates in Brazil's National Communication under the United Nations Framework Convention on Climate Change (Brazil, MCT, 2004), both of which applied the Higuchi et al. (1998) model to forests the "arc of deforestation" in southern Amazonia. The increase in the percentage moisture content with height of the bole (e.g., Figure 5) indicates that measurements are needed of moisture content along the length of the bole in order to obtain dry mass from tree biomass measures (Nelson et al., 1999).

Previous studies have developed equations for determining wood density as a function of moisture content (e.g. Simpson, 1993). The two new equations presented in Table 1 are useful for estimating moisture content in the boles of trees and for converting green (fresh) density to basic density from samples taken at breast height or representative of the whole bole (mean of the bole). These equations can be useful in remote parts of the Amazon forest, since the equations allow basic wood density to be obtained directly in the field without requiring the use of a vented electric oven.

Conclusions

In spite of the importance of corrections to the heartwood density dataset for improved biomass and carbon-flux estimates, linear regressions developed in dense forest of central Amazonia do not adequately describe radial variation in trees in the open forest of southern Amazonia. Heartwood regressions from dense forest tend to overestimate the mean density of disks or the mean of the bole in open forest. However, for corrections of variation along the bole in open forest, the regression from dense forest provides an accurate correction of the wood-density mean. Two new regressions described in this study allow basic wood density to be obtained from the green-density mean of the bole (either from samples taken at breast height or from the mean of the bole). The equations can also be useful in studies of water storage in trees. In open forests in southern Amazonia, moisture content of the bole is significantly higher than in dense forest in central Amazonia. For normalization of wood densities from a variety of datasets an equation is needed that directly relates values from cores taken with increment borers to the wood density of disks (heartwood, sapwood and bark).

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Figure Legends

Figure 1. The relationship between basic density of the full disk and basic density of the heartwood in dense forest in central Amazonia (n = 146 trees) and in open forest in southern Amazonia (n = 38 trees).

Figure 2. Percentage difference between basic density of heartwood and of the full disk (%RV) in dense and open forest plotted against heartwood density.

Figure 3. Relationships between diameter (at breast height or above buttresses) and total height of trees with %RV (meaning the percentage difference between basic density of heartwood and that of the full disk) in open forest in southern Amazonia and in dense forest in central Amazonia (**A** and **B**). Positive values of %RV mean that density decreases towards the outside and negative %RV values mean density increases towards the outside.

Figure 4. Relationships between the mean basic wood density of the bole and wood density at breast height (full disk) in dense forest in central Amazonia (n = 307) and in open forest in southern Amazonia (n = 235).

Figure 5. Relationships between moisture content (%) and mean basic wood density of the bole (**A**) and between moisture content (%) and mean ‘green density’ of the bole (**B**). Variation in moisture content (%) along the length of the bole is also presented **(C)**.

Table 1. New linear regressions developed in open forest in southern Amazonia (SA) proposed in this study.

Model	*Model description*	*Regression statistics*
1	[Wood density of the full disk] = 0.161 (±0.035) + 0.713 (±0.054) × [Heartwood basic density]	Coefficients ± Std Error; Adjusted r^2 = 0.831, Std error of estimate (SEE) = 0.050, F = 176, n = 38
2	[Mean basic density of the bole] = -0.143 (±0.034) + 0.728 (±0.033) × [Mean green wood density of the bole]	Adjusted r^2 = 0.680, SEE = 0.064, F = 474, n = 224.
3	[Mean basic density of the bole] = -0.076 (±0.036) + 0.654 (±0.035) × [Green wood density at breast height]	Adjusted r^2 = 0.665, SEE = 0.065, F = 359, n = 181 trees.

Table 2. Correlation between pattern of radial variation in density (%RV) with diameter and total height in trees from two forest types: Dense forest, central Amazonia and Open forest, southern Amazonia.

% RV in trees from Dense and Open forest		Diameter	Total height
		Pearson correlation and (p value)*	
Density DECREASING towards the outside	Dense (n =120)	0.000 (0.997)	0.061 (0.505)
	Open (n = 24)	**0.431 (0.035)**	**0.459 (0.024)**
Density INCREASING towards the outside	Dense (n = 26)	0.377 (0.057)	0.278 (0.169)
	Open (n = 14)	0.041 (0.890)	0.210 (0.470)

* Numbers in bold type are significantly different at the 5% level.

Figure 1.

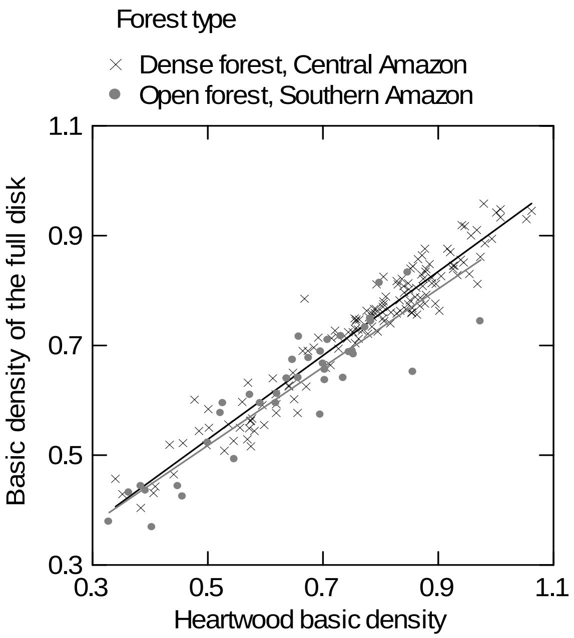

Forest type
× Dense forest, Central Amazon
● Open forest, Southern Amazon
1.1
0.9
0.7
0.5
0.3
Basic density of the full disk
0.3
0.5
0.7
0.9
1.1
Heartwood basic density

Figure 2.

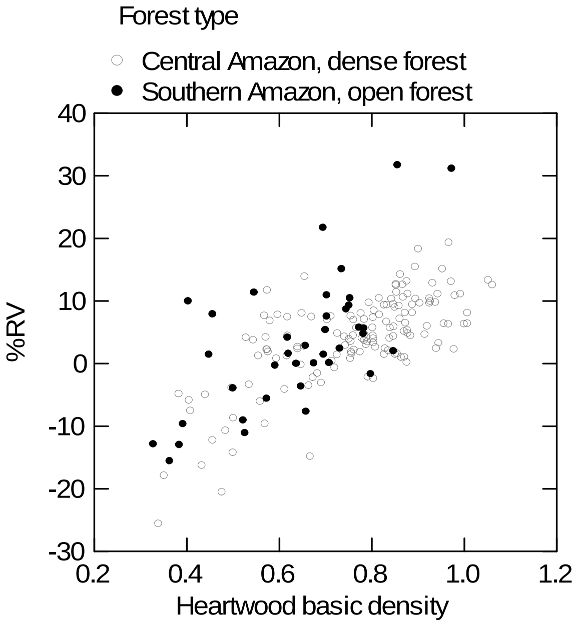

Forest type
○ Central Amazon, dense forest
● Southern Amazon, open forest
40
30
20
10
0
-10
-20
-30
%RV
0.2
0.4
0.6
0.8
1.0
1.2
Heartwood basic density

Figure 3.

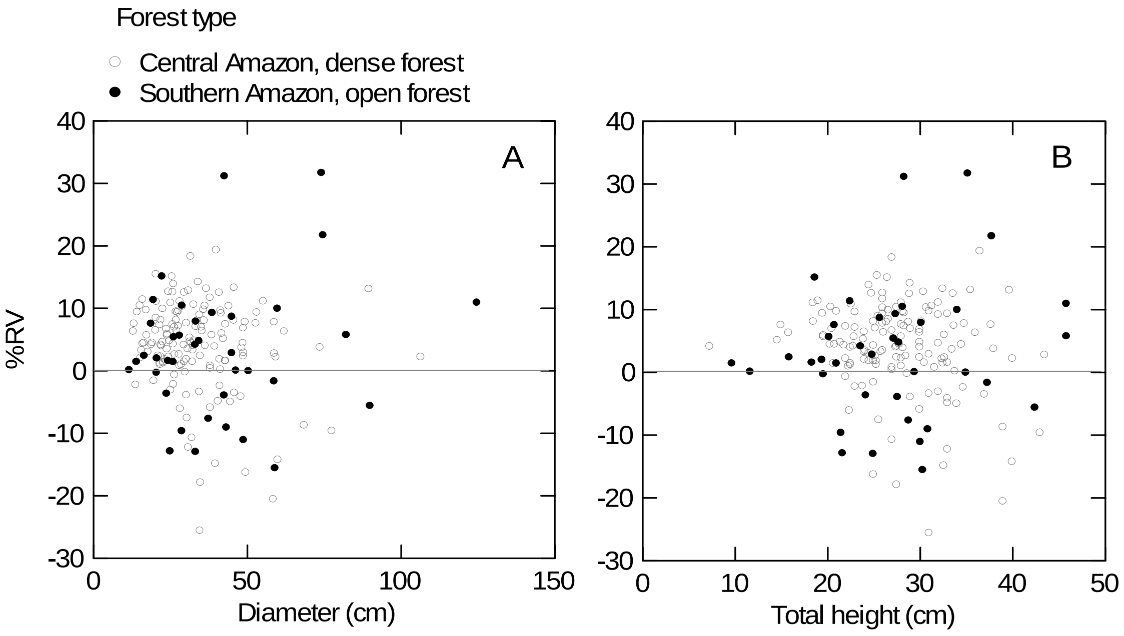

Forest type
○ Central Amazon, dense forest
● Southern Amazon, open forest
A
B
%RV
40
30
20
10
0
-10
-20
-30
0
50
100
150
Diameter (cm)
0
10
20
30
40
50
Total height (cm)

Figure 4.

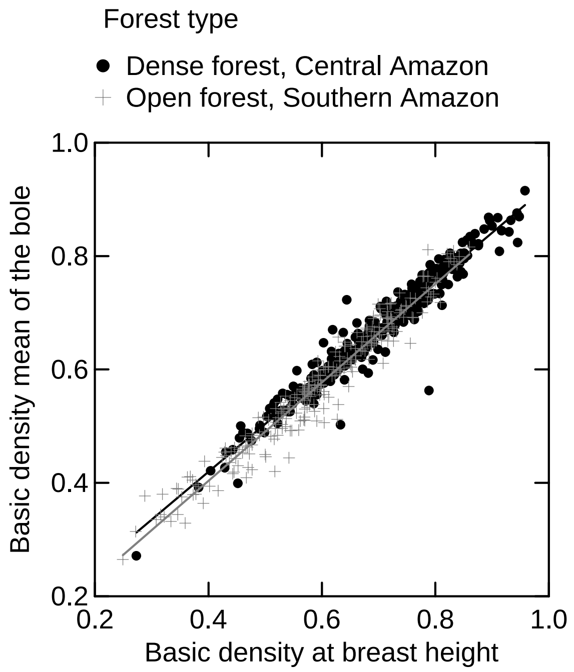
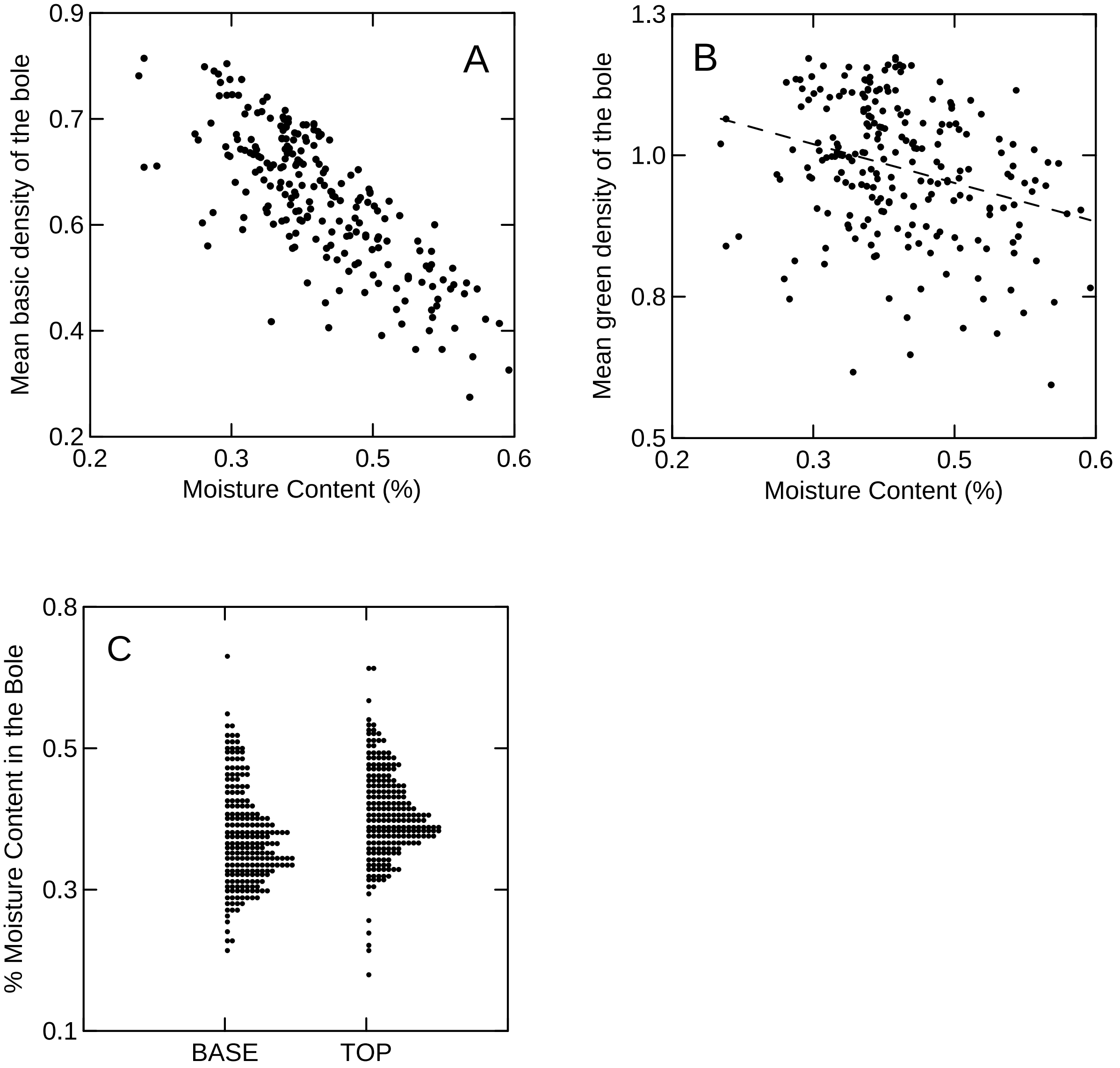

Forest type
● Dense forest, Central Amazon
+ Open forest, Southern Amazon
1.0
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1.0
Basic density mean of the bole
Basic density at breast height

Figure 5.


A
Mean basic density of the bole
0.9
0.7
0.6
0.4
0.2
0.2
0.3
0.5
0.6
Moisture Content (%)
B
Mean green density of the bole
1.3
1.0
0.8
0.5
0.2
0.3
0.5
0.6
Moisture Content (%)
C
% Moisture Content in the Bole
0.8
0.5
0.3
0.1
BASE
TOP