Australian Journal of Basic and Applied Sciences

2023 January; 17(1): pages 1-8
https://doi.org/10.22587/ajbas.2023.17.1.1

ORIGINAL ARTICLE AENSI Publications

Alternatives to estimate biomass and carbon in Atlantic Forest fragment in Northeast Brazil

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Received date: 27 November, Accepted date: 29 January 2023

Citation: A. C.dos Santos., M. B. G. dos Santos Freire., A.C. F. da Silva., L. S. M. Mossio., L.C.Marangon., F. José Freire., R.B.de Andrade Lima., L.de Cássia Leôncio Tostes., J. da L. Freitas., G. E. de Melo., C. H. Alves Borges., 2023. Alternatives to estimate biomass and carbon in Atlantic Forest fragment in Northeast Brazil. Australian Journal of Basic and Applied Sciences, 17(1): 1-8. DOI: 10.22587/ajbas.2023.17.1.1.

ABSTRACT: Biomass quantification in the Atlantic Forest is difficult due to a scarcity of destructive tree sampling data for this biome.Many studies have used general pantropical models to quantify their biomass stocks. However, doubts still need to be raised about the ability of these models to accurately estimate the biomass of trees in the Atlantic Forest biome. Thus, the objective of this work was to evaluate and test the performance of allometric equations with different input variables to estimate biomass and accumulated carbon in dominant species in an Atlantic Forest fragment in northeastern Brazil. A recent study in the area, with 1,324 inventoried trees, was used to obtain the phytosociological and dendrometric data needed to analyze forest biomass. We selected five pantropical allometric equations with good reproducibility for humid tropical forests and a local equation (Atlantic Forest) to calculate above-ground biomass (AGB). The input variables used were tree diameter at breast height (DBH), tree height (H), wood density (p), and bioclimatic variables (E) (water stress and rainfall). The findings support the conclusion that there is a significant difference between the six equations tested to estimate biomass and carbon in the forest fragment.Therefore, if H, DBH, and density data are available after the forest inventory of the area, the pantropical equation can be used to quantify the AGB. Otherwise, the local equation is a viable alternative. These results can help elaborate environmental projects targeting the carbon market and enabling the forest for REDD+ projects.

Keywords: Bioclimatic variable, local equation, pantropical equations, rainforest

INTRODUCTION

Accurate forest biomass estimates are essential for determining carbon stocks (C). These estimates have improved substantially for tropical rainforests in recent decades, with new alternatives and developing allometric equations at the local and pantropical levels (Chave et al., 2014).

Generally speaking, there are two methods to determine the biomass of an individual tree or forest: the direct and indirect methods; the first requires felling and rigorous weighing of all trees occurring in a fixed plot (Silveira et al., 2008). The second is done by using allometric models, which consist of correlating the biomass with some easily obtainable variable for application in mathematical equations or using remote sensing (Jucker et al., 2017). Some works have been developed to improve the estimates, mainly in the Brazilian Amazon: Lima et al. (2012) and Oliveira et al. (2012); in Colombia: Alvarez et al. (2012) and in the tropical region of the planet: Feldpausch et al. (2012), Chave et al. (2005) and Chave et al. (2014). In the studies by Chave et al. (2005) and Chave et al. (2014), the authors aimed to build equations that could be used in different regions throughout the tropics. They made equations from a massive database of trees sampled around the tropics.

However, Molto et al. (2013) demonstrated that pantropical models are not very accurate for estimating the biomass of large trees (>40 cm DBH), which generally represent more than 50% of forest C stocks (Bradford & Murphy, 2018; Clark et al., 2019). Also, in this aspect, Singh et al. (2011) concluded that errors in biomass stock estimates result from the absence of allometric equations for higher-diameter classes. According to Feldpausch et al. (2012), reducing uncertainty in pantropical estimates is critical to providing realistic and verifiable carbon data to compose models and policy instruments such as REDD+ and carbon credits. In addition, quantifying C stored in forests is essential in implementing emerging carbon market mechanisms, requiring appropriate allometric models to predict biomass.

The Atlantic Forest is a highly heterogeneous biome of global ecological significance with high terrestrial carbon stocks (Silveira et al., 2019). However, despite the importance of this biome, there are only two direct samplings of tree biomass, resulting in specific allometric models for these forests (Tiepolo et al., 2002). Furthermore, due to the protection situation of the Atlantic Forest Biome and restrictions on destructive tree sampling, efficient tools are not available to accurately quantify the biomass and carbon stocks these forests store. Therefore, the quantification of carbon needs to be done using generalized equations. (Rutishauser et al., 2013a) Emphasize that choosing an appropriate allometric model reduces uncertainties in the forest biomass stock. Given the above, this work aimed to test allometric equations with different predictor variables to estimate aboveground biomass (AGB) and forest carbon stocks in an Atlantic Forest fragment in the Northeast region of Brazil. As a hypothesis, the DBH and tree height variables equations are expected to present better estimates for evaluating biomass and carbon in the forest community.

MATERIAL AND METHODS

Site description

For this study, we used sampling data from the tree community of a fragment of the Atlantic Forest Domain (8° 33.110' S and 35° 8.857' W), located in Pernambuco, Brazil (Engenho Jaguaré/Usina Trapiche S/A, with 69 hectares), whose vegetation is called Dense Ombrophilous Lowland Forest. The fragment is inserted in a matrix surrounded by sugarcane cultivation (Figure 1). According to Köppen's classification, the region has an Am monsoon climate (Alvares et al., 2013). The average annual temperature is 24.9 ºC, and the average rainfall is 1,687 mm, with a rainy season from January to August and a dry season from September to December. A previous study with 1324 trees was a basis for obtaining phytosociological data from the area (Lima et al., 2019). The study measured DBH and height for all individuals with DBH ≥ 5 cm. We used 40 plots of 10 m x 25 m (250 m^2) for sampling the trees.

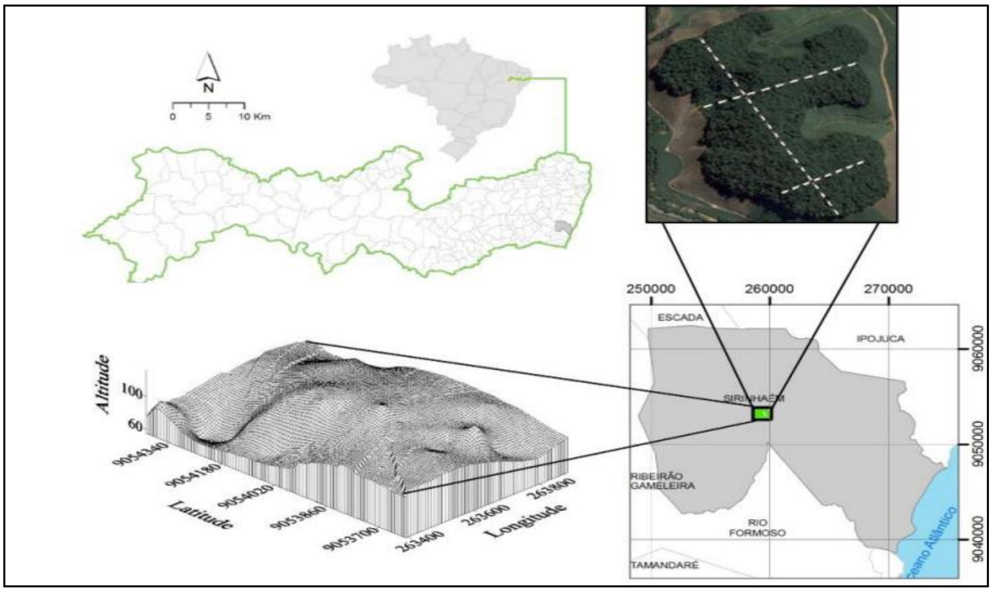

Figure 1: Location of the study area in a tropical rainforest fragment in Northeast Brazil (Source: Walter Lucena), adapted from Lima et al. (2019)

Equations for estimating biomass

Six allometric equations were used to estimate the aboveground biomass of each sampled tree and the forest fragment. To choose the equations, we used the criteria of use and citation in the literature (the most used in studies of forest biomass), generalization of use (specific for tropical forest), a local equation for Atlantic Forest, and equations as an alternative for biomass calculation when not have complete tree height data available. The equations are:

Equation (Bic) – Chave et al. (2014), based on the diameter, wood density, and bioclimatic variable (E) variables:

$$AGB = exp[-1.803 - 0.976 * (E) + 0.976 * ln(p) + 2.673 * ln(DBH) - 0.0299 * (ln(DBH)^2)]$$ Eq. (1)

Where: AGB = aboveground dry biomass (Mg), p = specific density of wood (g cm^{-3}), DBH = diameter measured at breast height (cm), E = bioclimatic variable, based on the geographic coordinate of the area studied, following the guidelines of Chave et al. (2014). In this study, E = 0.1239095.

Chave et al. (2014) reported that an environmental variable defined as $E = 10^{-3} * (0.178 * TS - 0.938 * CWD - 6.61 * PS)$ is an important covariate of tree diameter. In this equation, TS is the temperature seasonality, and CWD is the climatic water deficit (in mm/year). PS is the seasonality of precipitation.

Equation (Ch14) – Chave et al. (2014), based on the diameter, wood density, and total height variables:

$$AGB = [0.0673 * (p * DBH^2 * H)^{0.976}]$$ Eq. (2)

Where: AGB = aboveground dry biomass (Mg), p = specific density of wood (g cm^{-3}), DBH = diameter measured at breast height (cm), H = total tree height (m)

Equation (Ch05) – Chave et al. (2005), based on diameter, density and height of the tree:

$$AGB = exp[-2.977 + ln(p * DBH^2 * H)]$$ Eq. (3)

Where: AGB = aboveground dry biomass (Mg), p = specific density of wood (g cm^{-3}), DBH = diameter measured at breast height (cm), H = total tree height (m)

Equation (Ti) – Tiepolo et al. (2002), based on the variable DBH (cm), adjusted for Atlantic Forest:

$$AGB = 21.297 - (6.953 * DBH) + [0.74 * (DBH^2)]$$ Eq. (4)

Where: AGB = aboveground dry biomass (Mg) and DBH = diameter measured at breast height (cm)

Equation (Fe12) – Feldpausch et al. (2012) based on the variable DBH (cm), total height (H) and wood density, adjusted for humid forests:

$$ln(AGB) = -2.9205 + 0.9894 * ln(DBH^2 pH)$$ Eq. (5)

Where: AGB = aboveground dry biomass (Mg), p = specific density of wood (g cm^{-3}), DBH = diameter measured at breast height (cm), H = total tree height (m)

Equation (Br97) – Brown (1997) based on the variable DBH (cm), adjusted for humid forests:

$$Y = exp[-2.134 + 2.530 * ln(DBH)]$$ Eq. (6)

Where: Y = aboveground dry biomass (Mg) and DBH = diameter measured at breast height (cm)

We used the Global Wood Density Database (GWDD) in Zanne et al. (2009) and the Brazilian database, compiled by the Laboratory of Forest Products of the Brazilian Forest Service, to obtain wood density data.

The AGB calculation was performed only for live trees with DBH ≥ 5 cm, with data from the floristic inventory. The total AGB for each plot was quantified by the sum of the estimated AGBi of the trees for all j trees, according to the expression:

$$B_{plot}(biomass\ Mg\ ha^{-1}) = \frac{\sum_j AGB_i}{1{,}000 * (10{,}000/A)}$$

B_{plot} = total biomass per plot; Σj AGBi = dry mass of all trees in the plot in kg; 1,000 is the factor for converting kg to Mg; 10,000 is the factor for converting meters to hectares; and A is the plot surface (m^2).

Biomass carbon contents vary according to the forest species and rarely exceed 50%. Thus, the carbon stored in the biomass was estimated by multiplying the biomass estimates obtained by the factor of 0.48.

Statistical analysis

The average values of biomass and carbon stocks per hectare using allometric equations were estimated in the 40 sample plots. The normality from data (n=40) was verified using the Kolmogorov-Smirnov test at 5% probability. Data were analyzed using analysis of variance (ANOVA) and subsequently with the Tukey HSD posthoc test using the agricolae package. Statistical analyzes were performed with R software version 3.6.3 (R Development Core Team, 2020).

RESULTS

The total biomass data estimated by the six proposed equations ranged from 116.85 to 228.79 Mg $plot^{-1}$, with an average value of 155.89 Mg $plot^{-1}$. The maximum value assessed by an individual tree was 35.88 Mg, and the minimum was 0.73 Mg (Table 1).

Table 1: Aboveground biomass (Mg) per plot (250 m^2) estimated by the six proposed equations

	Allometric equations*					
Descriptive statistics	Bic	Br97	Ch05	Ch14	Fe12	Ti
Total	186.50	228.79	121.34	129.56	116.85	152.28
Average	4.66	5.72	3.03	3.24	2.92	3.81
Minimum	1.25	1.32	0.74	0.83	0.73	0.91
Maximum	28.96	35.88	15.19	15.05	14.15	15.76
Standard deviation	±4.24	±5.33	±2.20	±2.18	±2.05	±2.38
Sample variance	18.01	28.43	4.86	4.74	4.21	5.68
Coefficient of variation (%)	91.01	93.22	72.69	67.21	70.22	62.59

*Bic = equation with bioclimatic variables (Chave et al., 2014), Br97 = equation by Brown (1997), Ch05 = equation by Chave et al. (2005), Ch14 = equation of Chave et al. (2014), Fe12 = equation of Feldpausch et al. (2012) and Ti = equation of Tiepolo et al. (2002)

Table 2 presents the average aboveground biomass stocks by area (Mg ha^{-1}). The highest stocks obtained with the Br97 equation were ~50% higher than the values obtained by the Fe12 equation, which presented the lowest values for the AGB.

Table 2: Average aboveground biomass stocks estimated in an Atlantic Forest fragment

	Allometric equations					
	Bic	Ch14	Ti	Fe12	Br97	Ch05
	--------------------------------- (Mg ha^{-1}) -------------------------------					
Average	186.50	129.56	152.28	116.85	228.79	121.34
Standard error	26.84±	13.77±	15.07±	12.97±	33.72±	13.95±
Coefficient of variation CV%	91.01	67.21	62.59	70.22	93.22	72.69

Estimates of aboveground biomass stocks (Mg ha^{-1}), by the six equations (general and local), were statistically different by analysis of variance (F = 4.403, p-value < 0.001) at 5% probability (Figure 2).

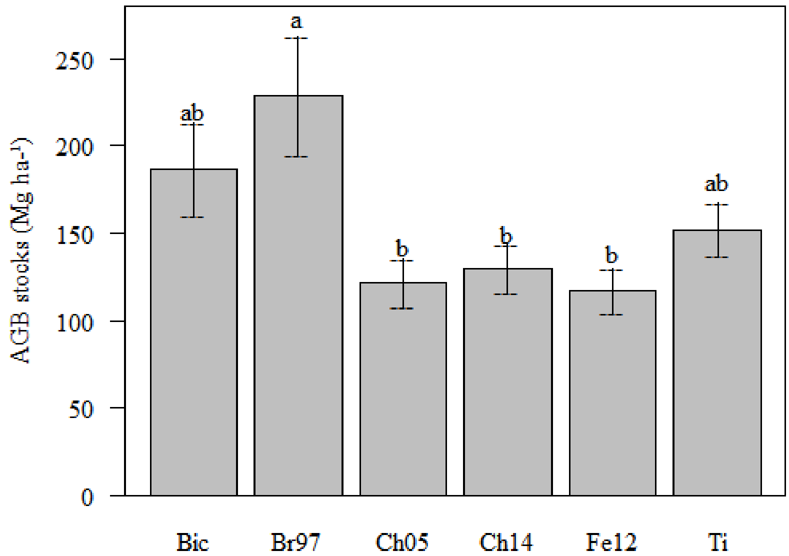

Figure 2: Aboveground biomass stocks in the Atlantic Forest. Different letters indicate statistically significant differences by the Tukey HSD test at 0.05 significance.

As for aboveground biomass carbon stocks estimates, the mean values ranged from 56.09 ± 6.23 Mg ha^{-1} to 109.82 ±16.19 Mg ha^{-1} (Figure 3). The highest values for C stocks were obtained by the Br97 equation, while the Fe12 equation obtained the lowest stocks.

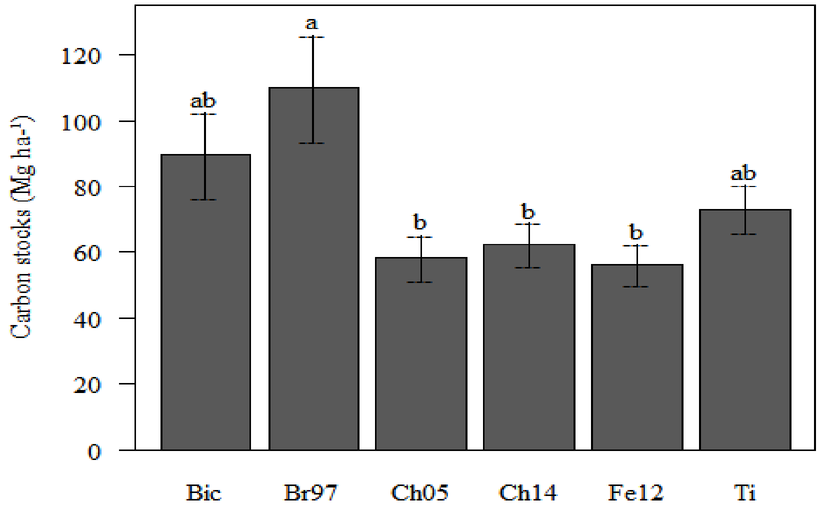

Figure 3: The arboreal component carbon stocks (Mg C ha^{-1}) in an Atlantic Forest fragment, Brazil. Bars represent the standard error of the mean (± SEM)

The primary information on adjustments, precision, references, forest typologies, and applicability, referring to the six regression equations used in this study, are presented in Table 3.

Table 3: Summary data from the fits of the equations used to estimate biomass in the Atlantic Forest in Northeast Brazil

Code	Author	DBH (cm)	Variables	Equation	R^2	Applicability
Bic	Chave *et al.* 2014	5–212	DBH, *p* e E	B = exp(-1.803 - 0.976E + 0.976ln (*p*) + 2.673 ln(DBH) - 0.0299 (ln(DBH))^2)	0.98	Rainforest
Ch14	Chave *et al.* 2014	5–212	DBH, *p* e H	$B = 0.0673 \times (p\text{DBH}^2\text{H})^{0.976}$	0.99	Rainforest, dry and flooded forests
Ch05	Chave *et al.* 2005	5–222	DBH, *p* e H	$B = 0.0509 \times \rho\text{DBH}^2\text{H}$	0.99	Rainforest
Br97	Brown, 1997	5–148	DBH	Y = exp (-2.134 + 2.530* ln(D))	0.97	Rainforest
Ti	Tiepolo et al. (2002)	4–116	DBH	$B = 21.297 - 6.953\text{DBH} + 0.74.\text{DBH}^2$	0.91	Atlantic Forest
Fe12	Feldpausch *et al.* (2012)	2–180	DBH, *p* e H	$\ln(\text{AGB}) = -2.9205 + 0.9894 \ln(\text{DBH}^2 p\text{H})$	0.97	Rainforest

DISCUSSION

The highest AGB value observed in this study refers to an individual with DBH=143.24 cm (Fabaceae family). The lowest estimated value is related to an individual with 5.33 cm in diameter (Lecythidaceae family). The lowest coefficient of variation value for estimating aboveground biomass was obtained by the equation of Tiepolo et al. (2002), with ~62%, while the most significant variation in the estimates was observed in the equation proposed by Brown (1997), with ~93%. The average values of biomass estimate by area obtained by the equations used in this study are consistent with others developed in tropical rainforests in the Atlantic Forest Biome, for example, by Diniz et al. (2015) in Atlantic Forest formations ~115.6 Mg ha^{-1}. Colmanetti et al. (2018), using the equation of Chave et al. (2014), obtained an average of ~158 Mg ha^{-1} in Serra da Cantareira; Ribeiro et al. (2009) reported biomass estimates of ~166.67 Mg ha^{-1} in an area of mature Atlantic Forest in Viçosa (MG).

Estimates calculated by the Br97 and Bic equations showed higher values (Figure 2), with a tendency to overestimate the biomass, especially for thicker trees in the forest community (DBH>100 cm). On the other hand, the equations Ch05, Ch14, Fe12, and Ti presented similar estimates. It is noteworthy that equation Br97 uses DBH as the only independent variable while Bic uses DBH, wood density, and variable (E). Furthermore, equations Ch05 and Ch14 use all available variables: DBH, H, and p; finally, in the Ti equation, only the DAP is used to estimate the biomass. Wood-specific density (*p*) is an essential predictor of AGB, especially considering a wide range of vegetation types. Besides, Fayolle et al. (2013) demonstrated that using specific wood density from a global database has little impact on biomass estimates. On the other hand, despite the difficulty in accurately assessing tree heights in tropical forests (occurrence of giant trees and very dense crowns), integrating these data in the biomass assessment can reduce uncertainties in estimates (Rutishauser et al., 2013b). Therefore, the most significant amount of information and characteristics must be considered to estimate biomass accurately in tropical forests. In this sense, the equations Ch05, Ch14, and Fe12 stand out, as mentioned above, because they consider the conventional dendrometric explanatory variables (DBH and height) and wood density. As for C stocks, equations Br97 and Bic reached the highest values for the standard error of the mean

(Figure 3). The average estimates of C with the Br97 equation differed significantly from the averages of C obtained by the Ch05, Ch14, and Fe12 equations; coincidentally, the only ones that use in their scope the three variables DBH, height, and density (concurrently) as input parameters of the model allometric.

In Eastern Amazonia, Nunes (2012) compared nine equations to estimate biomass and carbon and concluded that there was no statistical difference between the estimates; generally, the equations presented similar estimates for AGB and carbon. The authors also used the Br97 equation, which showed mean values of ~225 Mg ha^{-1} for biomass and ~106 Mg ha^{-1} for the C stock. Similar results were obtained by Azevedo et al. (2018) in a remnant of the Atlantic Forest in Rio de Janeiro, in which AGB and C were quantified using the Br97 equation, identifying stocks of ~130 Mg C ha^{-1}; values very similar to those reported in the present study in Northeastern Brazil. Torres et al. (2013) also tested methodologies to estimate biomass and C; the authors concluded that the pantropical or general equation underestimated AGB and C compared to regional methods. Despite this, the authors highlighted that the pantropical approach could be used by adopting the conservative principle in the estimates recommended in carbon projects, especially when there are no specific allometric equations for each region. In the Amazon region, Aguiar et al. (2017) compared the performance of allometric equations (local and general) and concluded that the estimated mean carbon values differed significantly, indicating that all equations had a statistical difference; in this scenario, the authors opted for the local equation because it was adjusted for the State of Pará. Lima et al. (2012) emphasize that allometric models must be carefully selected, mainly considering the type of forest for which it is intended to estimate the AGB and the C. The results observed for C stocks in Northeast Brazil are consistent with AGB and C data from other works in the Atlantic Forest Biome with the same forest typology. For example, Diniz et al. (2015) estimated carbon stocks ranging from 20.9 to 70.6 Mg ha^{-1}; Ribeiro et al. (2009) estimated a carbon stock of ~83.3 Mg ha^{-1} in an Atlantic Forest fragment in Minas Gerais; and Silva et al. (2018) quantified ~107 Mg C ha^{-1} stocks in a piece of Atlantic Forest in Rio de Janeiro, characterized as dense rainforest. In Atlantic Forest, considering different vegetation in different regions of Brazil, Amaro et al. (2013) reported C stocks ranging from 28.84 t ha^{-1} to 192.09 t ha^{-1} (Figure 3). On the other hand, Silveira et al. (2019) said a variation on the order of 25.52 to 238 Mg C ha^{-1} in different areas of this biome. However, the estimates obtained in this study for C stocks in an Atlantic Forest fragment are within this range (~75 Mg C ha^{-1}). Furthermore, c stocks were similar between Br97, Bic, and Ti (Figure 3). However, C values are overestimated, especially with Br97, which seems to drive the high C stocks of trees with higher DBH, a common situation considering the limit (maximum diameter allowed) of each equation for its correct application (Table 3). Therefore, Chave et al. (2005) recommend not using biomass regression models beyond their validity range. Regarding the local equation (Ti), a critical point is in the range of diameters of the sampled trees (ranging from 4-116 cm). As reported above, some trees extrapolate this limit of DBH for biomass data in our study area for which the equation has been fitted. Additionally, equation (Ti) obtained a good fit of the data, with R^2=0.91 (Table 3), demonstrating that the variation explains more than 90% of the variation observed in the biomass data only in the DBH of the tree. According to Vieira et al. (2008), the simplest allometric models (those with only an independent variable, usually DBH) can be used when the focus is to monitor the variation in carbon storage over time. Chave et al. (2005) concluded that the most important predictors of biomass were, in decreasing order of importance, trunk diameter, wood density, total height, and forest type (humid, dry, or flooded). Furthermore, wood density proved an essential variable in all regressions tested. According to Chave et al. (2009), wood density is defined as kiln-dry mass divided by green volume, limited by 0 and 1.5 g cm^{-3}; it also describes the investment or storage of C per unit of tree stem volume. Feldpausch et al. (2012) reinforce that the tree's total height (H) is a crucial allometric factor that needs to be integrated into the estimates. In addition, the inclusion of height data reduced the errors of 41.8 Mg ha^{-1}. The AGB was about 13% smaller when including height estimates. However, a negative point for applying this Fe12 equation in the Atlantic Forest would be the lack of sampling data in the Atlantic Forest Biome. Chave et al. (2014) added a factor that summarizes the climatic characteristics of the place where the equation is applied; this factor inserted into the model made the equations more precise for estimating forest biomass when the variable height could not be reliably estimated at the collection sites (biomass inventories).

According to the above authors, Ch14 can be applied to estimate the AGB in tropical forests, regardless of forest typology, whether humid, dry or flooded forest. This result contrasts with what was proposed by Chave et al. (2005) when the authors developed specific equations for each forest typology (humid, flooded, and dry forest). For cases where the full height of the tree is not available, Chave et al. (2014) developed an allometric equation based on the environmental stress variable (E). According to the authors, the performance of the Bic equation is worse than the estimates by the Ch14 equation (Table 3). However, it is an excellent alternative to estimate the AGB when there is no data on the height variable. When comparing the performance of AGB estimates by the models by Chave et al. (2014) with those of Chave et al. (2005), Ch14 presented results similar to those obtained with Ch05, both with the independent variables H, DBH, and p, a fact also verified in the biomass data in Northeastern Brazil (Figure 2). Therefore, the equations proposed by Chave et al. (2014) are considered reliable in estimating the AGB in these fragments. Furthermore, Fayolle et al. (2013) demonstrated that the pantropical equation developed for rainforests could produce accurate estimates of biomass and C stocks from diameter measurements in forest inventory. Therefore, on a logical scale of methodologies that can be applied to estimate AGB in tropical forests, the first indication would be using equations adjusted and tested for the site, that is, local models. Thus, as it is impossible to carry out destructive sampling of the tree component to adjust specific equations for the Atlantic Forest biome, selecting general pantropical equations developed with the comprehensive sample is suggested.

CONCLUSION

Pantropical allometric models are reliable strategies to estimate BAS and C in fragments of Dense Ombrophilous Lowland Forest in Northeast Brazil, confirming the central hypothesis of the work. Estimates using pantropical equations, having DBH and height as main variables, showed similar results in terms of C and biomass, confirming the working hypothesis. Furthermore, the estimates from using the local equation did not lead to higher estimates of BAS and C, not differing from the estimates from the pantropical equations. Thus, if H, DBH, and wood-density data are available after the forest inventory, the Ch14 equation should be used to quantify the AGB. Otherwise, equation (Ti) is a viable alternative.

Acknowledgments

To Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco/FACEPE for the financial support (scholarship). To the Federal Rural University of Pernambuco, the Department of Forest Science, and the Graduate Program in Forest Sciences. To Usina Trapiche S/A for all the help offered in the field surveys. We are very grateful to Usina Trapiche S/A employees Mr. Amaro and Mr. Dudé for their support in the field.

Funding Information:

Not available.

Conflict Of Interest:

The authors declare no conflict of interest.

Author's Contribution

Adriano Santos, Maria Freire, Luiz Marangon, and Fernando Freire: writing manuscript, data collection, data analysis, and interpretation; Lucca Mossio, Rosival Lima, Giovana Melo, and Ane Silva: data collection, data analysis; Luciedi Tostes, César Borges, João Freitas: reviewing and editing of the manuscript.

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