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Allometric equations to estimate aboveground biomass of *Dalbergia cearensis* species in the Brazilian seasonally dry tropical forest

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ABSTRACT

The semiarid savannas, in particular the Caatinga Biome, are important components of the terrestrial carbon cycle in terms of global carbon storage. Despite this importance, little information is available regarding biomass production potential of caatinga species. The objective of the study was to develop allometric equations to estimate aboveground biomass of *Dalbergia cearensis* Ducke trees. The semi-destructive method was used to collect samples in which the diameter at breast height (D), wood density (ρ), and tree height (H) were the aboveground dry biomass (AGB) estimation variables. The research was conducted in three different localities of the semiarid region in the state of Ceará, Brazil. Fresh biomass measurement was divided in two parts: trimmed fresh biomass and untrimmed fresh biomass. Measurements were taken for 30 trees. Height, trunk diameter, and branch diameters were measured for each individual. Leaf and small branch aliquots were taken. The volume of branch aliquots was utilized to calculate wood density. Tree dry biomass was obtained by adding trimmed dry biomass and untrimmed dry biomass (AGB, in kg). In all, eight allometric equations were developed for *D. cearensis* and tested for goodness-of-fit statistics. The best allometric equations were selected based on each model's performance statistics (R^2-adj, RSE, and AIC). Of the eight regression models developed and tested to estimate aboveground biomass of *Dalbergia cearensis* trees, six attained acceptable performance statistics. The regression model for *D. cearensis* that utilized the single compound predictive variables DH (model 1) was the most robust, followed by the model using single compound variables ρDH (model 2), and multiple variables D + H (model 3). The methodology applied in this study can be adopted to estimate biomass and volume of a broader set of other species from the Brazilian seasonally dry tropical forest.

1. Introduction

The semiarid savannas, in particular the Caatinga Biome, are important components of the terrestrial carbon cycle in terms of global carbon storage (Pereira Júnior et al., 2016; Santos et al., 2014). Globally, the savannas are undergoing rapid changes in land cover that threaten biodiversity and affect ecosystem productivity through loss of habitat, biomass, and through carbon emissions into the atmosphere with heavy impacts on climate change (Dimobe et al., 2018; Santos et al., 2011; Santos et al., 2014).

The Brazilian seasonally dry tropical forest (caatinga) has a high diversity of woody plants despite the extreme water restriction imposed by the environment in which it is located (Araújo et al., 2007, Albuquerque et al., 2012). Excepting legally protected areas, most vegetation is cut for the use of low input agriculture and native pasture (Figueirôa et al., 2006; Araújo Filho et al., 2018) and for the production of charcoal and firewood (Ramos et al., 2008; Albuquerque et al., 2012). Indeed, the caatinga is the least protected of all Brazilian ecosystems, with only about 7% of its territory in conservation units, and only 1% under full protection (Santos et al., 2014). Despite this anthropic pressure, little information is available regarding biomass production potential and carbon stocks of caatinga species (Santos et al., 2011). From the perspective of ecological economics, this gap in knowledge is troubling. Considering the economy as a subsystem of society, and society as a subsystem of nature, it is imperative to understand the importance of the vegetation to the survival of the biome on a larger scale, and to

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address regional societal and economic issues within that framework, rather than allowing the anthropic pressure of short-term survival needs to continue to destroy unchecked a biome that appears to be more and more essential in terms of carbon store capacity in the context of a warmer, drier planet (Costanza, 2020; Albuquerque et al, 2012).

Furthermore, given the present global scenario of rampant deforestation and forest fires, it is essential to invest in strategies to preserve the planet's forest cover (Gardner et al., 2012). To this end, forest biomass assessment can be used as an indicator of forest productivity and nutrient cycling (Clark and Murphy, 2011), as well as for estimating carbon stocks for payment (Alongi, 2011), mapping carbon stocks (Scolforo et al., 2015) and renewable biomass as a potential for mitigating global warming (Dhillon and von Wuehlisch, 2013).

An assessment of forest carbon can be achieved by applying reliable allometric equations in order to estimate aboveground biomass (Picard et al., 2012; Henry et al., 2013). Accomplishing this requires local allometry and such biomass models require data at tree level, generally registered in forest inventories (Brown et al., 1989; Teobaldelli et al., 2009). To estimate biomass or volume of aboveground components of trees, allometric equations based on different independent variables, such as diameter, height, and wood density, are utilized (Chave et al., 2014).

Biomass estimation equations, or regression models, are being developed for many plants of semiarid and desert ecosystems in various regions of the planet (Huff et al., 2017; Feyisa et al., 2018; Ifo et al., 2018; Ma and Wang, 2020), for moist tropical forests (Djomo and Chimi, 2017), for estimating plant crown (Aholoukpè et al., 2013), for monospecific stands (Brunori et al., 2017), stands of uniform age (Skovsgaard and Vanclay, 2008), stands with trees of varying ages (Sillett et al., 2019), and forest stands of unequal size (Pukkala et al., 2009). Few studies, however, have been developed to predict the aboveground biomass using allometric models in semiarid savannas, such as the caatinga (Scolforo et al., 2015), and no studies have been conducted on biomass prediction for *Dalbergia cearensis* Ducke, a forest species endemic to the semiarid region of the Northeast of Brazil.

While still limited, some efforts have been undertaken over the last two decades to derive specific and local models for estimating caatinga biomass (Sampaio et al., 2010; Mendonça et al., 2013). Sampaio and Silva (2005) developed equations to estimate total biomass and biomass of different parts of the plants for ten of the main caatinga species. Such locally-developed regression models for specific species are significant, because aboveground biomass assessment is influenced by the types of forest structure, soil, and land use (Picard et al., 2012). Allometric models vary among species and for a given species in different ecological regions (Yen and Lee, 2011; Alvarez et al., 2012; Vahedi et al., 2014).

Our study utilized the semi-destructive method for attaining the following objective: to develop the best species-specific allometric equations for estimating aboveground biomass *Dalbergia cearensis* trees.

2. Materials and methods

2.1. Focal species

The species *Dalbergia cearensis*, Fabaceae family, characteristic of the caatinga of the Brazilian Northeast, is known by the common names Brazilian kingwood, *jacarandá-violeta, miolo-de-negro, pau-violeta* and *violeta* (Carvalho, 1997). The tree has a lightly aromatic wood, and in its fresh state, possesses brown-light purple regularly spaced stripes (Didier, 1992). This tree historically has had high economic value due to its various specialty uses: furniture, ornaments, notched boxes and cases, knife handles and decorative objects (Rizzini, 1978). Its wood was frequently used by the *ebéniste* cabinetmakers during the reigns of Louis XIV and Louis XV in France, as well as during the entire Georgian period in England. *Dalbergia cearensis* is credited with having contributed enormously to the heyday of French marquetry in the 18th century. Where once it was abundant all along coastal Ceará, extending into some central areas of the state as well, nowadays it is practically extinct, because, in addition to being trafficked by pirates for use in European woodworking, farmers utilized the wood for fence construction due to its resistance to moisture and pest attacks and diseases present in the soil (Campos, 1994). The data from the Ceará forest inventory reinforce and confirm the scarcity of *D. cearensis* in the state of Ceará (CEARÁ, 2016). Today its main commercial uses include antique furniture restoration and the manufacture of musical instruments.

2.2. Area characteristics

The study was conducted in the Brazilian Northeast, in the state of Ceará. Three areas in three different municipalities were chosen based on the state of vegetation conservation and the presence of the species *D. cearensis*:

Area 1 - *Lagoa de Dentro* Farm, with an area of 1149.74 ha. The farm is located in the municipality of Itapipoca, with the following geographic coordinates: Latitude − 03°15′12.16″ S and Longitude − 39°40′49.3″ W (Fig. 1). The farm was transformed into a rural worker settlement by the National Institute of Colonization and Land Reform – INCRA. The climate of Itapipoca is classified as Semiarid Hot Tropical and Mild Semiarid Hot Tropical, with an annual average rainfall of 1130.40 mm, concentrated in the months of January to May, with significant drought for 4 to 6 months, and an average temperature of 26 °C to 28 °C (IPECE, 2017a). The area presents an altitude of 50 m above sea level, located on coastal tablelands whose surface is made up of minimally lithified sediment deposition, with a predominance of pedogenetic processes and well-drained thick, sandy, and sandy-clayey soils. The predominant soil classes in the area are Arenosols, Ferralsols, and Acrisols, per IUSS Working Group WRB (2015) classification. Forest cover is mainly semi-deciduous seasonal forests.

Area 2 – Conservation Unit known as the *Não me Deixes* Farm Private Natural Heritage Reserve (RPPN), in the municipality of Quixadá, with the following geographic coordinates: Latitude − 04°49′34″ S and Longitude − 38°58′9″ W. The *Não Me Deixes* Farm has a total area of 928 ha. In 1998, 300 ha of the farm were turned into a Conservation Unit, in perpetuity, by the Brazilian Institute of Environment and Renewable Natural Resources – IBAMA. The climate of Quixadá is classified as Semiarid Hot Tropical with dry winter and rainy summer - BSh according to Köppen-Geiger, with an annual average rainfall of 731 mm, concentrated in the months of January to June (FUNCEME, 2020). The average annual temperature is 28.2 °C, the average high is 33.4 °C and the average low is 22.9 °C (INMET, 2020). Annual sunlight is 3143.8 h, with the lowest amount registered in March (216.5 h month^{-1}) and the highest in October (368.1 h month^{-1}) (EMBRAPA, 2004). Geologically, the area of study is located within the Ceará Complex – Canindé Unit: paragneisses at different levels of metamorphism-migmatization, including acidic orthogneisses, metabasic rocks, dioritic, metagabrous, metaultramafic, quartzite, and metacalcareous gneisses (CPRM, 2003). The water resources present at the farm consist of three natural lakes, one artificial lake (reservoir), and small intermittent streams. Forest cover is mainly thorny deciduous arborous Caatinga vegetation. The area has an altitude of 210 m above sea level, with a significantly flattened topography, typical of terrains that have undergone processes of pediplanation imposed by the rigorous conditions of semiaridity. Luvisols, Lixisols, and Acrisols are the predominant soil classes in the area, per IUSS Working Group WRB (2015) classification.

Area 3 – *Normal* Farm, with an area of 1507.65 ha, located in the municipality of Quixeramobim, Ceará, belonging to the Technical Assistance and Rural Extension Company of Ceará – EMATER/CE, with the following geographic coordinates: Latitude − 5°07′12.1″ S and Longitude − 39°10′33.3″ W. Forest cover at *Normal* Farm has been modified extensively as a result of agricultural research activities, but there remain areas of forest reserve that have undergone minimal human intervention. The climate of Quixeramobim is classified as Semiarid Hot Tropical, with annual average rainfall of 707.7 mm,

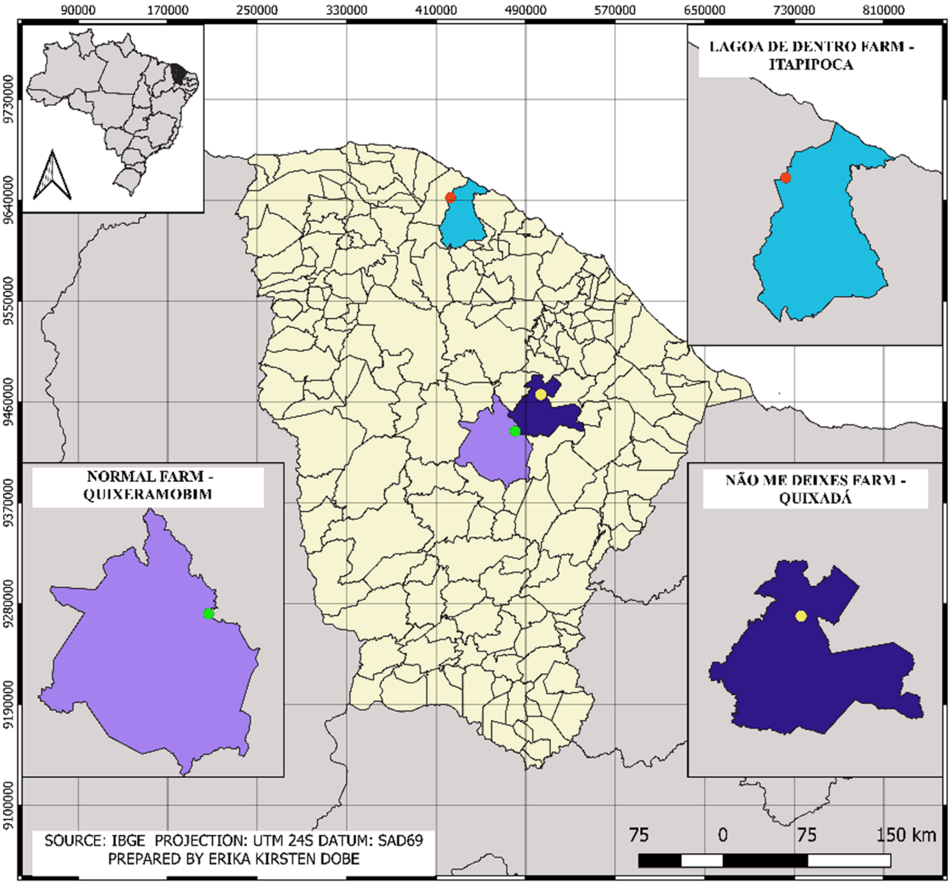

Fig. 1. Location map of Areas 1, 2 and 3, respectively, in the municipalities of Itapipoca, Quixadá and Quixeramobim, state of Ceará, Brazil.

concentrated between the months of February and April, and average temperature of 26 °C to 28 °C (IPECE, 2017b). The area presents an altitude of 302 m above sea level, with a significantly flattened topography, typical of terrains that have undergone processes of pediplanation imposed by the rigorous conditions of semiaridity. Luvisols and Planosols are the predominant soil classes at the farm, following IUSS Working Group WRB (2014) classification, and the vegetation is classified as shrubby, thorny deciduous Caatinga.

2.3. Data collection

Trees were selected within three previously identified areas according to species abundance until reaching the number of 30 individuals. The trees had diameters at breast height that varied from a minimum of 5 cm to 20.05 cm. In Area 1, 12 individuals of *D. cearensis*, with DBH between 7.32 cm and 20.05 cm, were randomly chosen from those identified within the Legal Reserve of the *Lagoa de Dentro* Settlement In Area 2, we selected 14 trees at sites with a greater abundance of *D. cearensis* according to Nogueira et al. (2014). From Area 3, we chose four individuals, with diameters between 7 cm and 20 cm, within the *Normal* Farm Legal Reserve. The criteria we followed during sampling were to avoid trees that were hollow, that had a twisted trunk or that had a damaged crown.

2.4. Field measurements

Field data collection followed the Manual for Building Tree Volume and Biomass Allometric Equations (Picard et al., 2012), as well as Kebede and Soromessa (2018), and Daba and Soromessa (2019). Fresh biomass measurement (kg) was divided into two parts: trimmed fresh biomass and untrimmed fresh biomass. Trunks and large branches (basal diameter (BD) $\geq$ 5 cm) were not cut; only small branches were trimmed (diameter $<$ 5 cm). This diameter was chosen due to the architecture and size of the trees.

In the field, dendrometric variables were measured, including tree height (H, in m), diameter at ground level (DGL, in cm, measured at 20 cm from the ground, for the purpose of calculating trunk volume) and diameter at breast height (D, in cm, measured at 1.30 m from the ground) of the trunk. For large branches, we measured basal diameter (BD, in cm), diameter at the upper extremity (UD, in cm), and length (L, in cm). The criterion used for measuring the diameter of branches was the distance from the base to the first bifurcation. The diameter of trunk, large branches, and small branches was measured using a manual caliper. On trunks where the aperture of the caliper was too small, we utilized a measuring tape. In this case, the circumference was divided by π (pi). Tree height was measured using a measuring tape. In trees with multiple trunks, each trunk was considered a separate tree.

2.5. Measuring trimmed fresh biomass

A ladder was utilized to reach the upper extremities of the trees. In the first area, three branches of each plant were trimmed for measurement, with the help of a handsaw. Next, leaves were separated from trimmed branches. Fresh leaf biomass and fresh wood biomass from trimmed branches were weighed and determined separately. Weight was registered using an electronic field scale. Wood and leaf aliquots were collected for lab analysis. In areas 2 and 3, located in a region with less moisture than area 1, we felt that cutting three branches would cause too much harm to the architecture of the trees and, therefore, opted to cut only one branch from each tree. From this single branch, we extracted three wood aliquots.

It was only feasible to collect leaves for building the leaf aliquots in

Area 1. Random leaf samples from three different trimmed branches were collected to make up the aliquot and, following that, the fresh leaf weight was measured (g). No leaf collection was possible in Areas 2 and 3 because *D. cearensis* trees are deciduous and at that point no longer had any foliage.

Three wood aliquots (15 cm each) and three leaf aliquots (250 g each, Area 1 only) were taken from the trimmed material of each individual tree. This material was taken to the lab for analysis of dry weight and moisture content. Volume of wood aliquots was calculated on the day they were collected. Graduated tube and scale were transported to the field for this evaluation. The wood aliquot volume (cm^3) was determined using water displacement in a 1000 mL graduated tube, and later used in calculating mean wood density ($g\ cm^{-3}$). Oven temperature was set to 75 °C for leaf aliquots and 105 °C for wood aliquots in order to determine dry weight. Aliquots were dried until constant weight was achieved. Leaf aliquots reached constant weight in approximately 48 h while the wood aliquots took approximately 72 h.

2.6. Measuring untrimmed fresh biomass

Fresh biomass for untrimmed small branches was measured by means of the relationship between dry biomass and branch basal diameter. This was done by formulating an allometric model that was fitted for a set of regressive dry biomass data for small trimmed branches in relation to their basal diameter. Biomass for trunk and large branches was estimated by means of volume (*Vi* in $cm^{\ 3}$) and mean wood density (ρ in $g\ cm^{\ -3}$) measurements.

2.7. Calculations

Tree dry biomass was calculated as the sum of trimmed dry biomass and untrimmed dry biomass:

$$(B_{trimmed\_dry} + B_{untrimmed\_dry}) \tag{1}$$

2.7.1. Calculating trimmed biomass

Wood moisture content (X_{wood}) was calculated from $B_{aliq\_dry\_wood}$ (dry wood biomass aliquot) divided by $B_{aliq\_fresh\_wood}$ (trimmed fresh wood biomass aliquot), including the bark, as follows:

$$X_{wood} = B_{aliq\_dry\_wood} / B_{aliq\_fresh\_wood} \tag{2}$$

Similarly, leaf moisture content (X_{leaf}) was calculated by dividing the dry leaf aliquot $B_{aliquot\_dry\_leaf}$ by the fresh leaf aliquot $B_{aliquot\_fresh\_leaf}$, as follows:

$$\mathrm{X}_{leaf} = B_{aliquot\_dry\_leaf} / B_{aliquot\_fresh\_leaf} \tag{3}$$

Trimmed dry biomass ($\mathrm{B}_{\_trimmed\_dry}$) was calculated as follows:

$$B_{\_trimmed\_dry} = B_{aliq\_fresh\_wood} x \mathrm{X}_{wood} + B_{trimmed\_fresh\_leaf} x \mathrm{X}_{leaf} \tag{4}$$

where $B_{trimmed\_fresh\_wood}$ is the fresh wood biomass from the trimmed branch and $B_{trimmed\_fresh\_leaf}$ is the fresh leaf biomass from the trimmed branch.

2.7.2. Calculating untrimmed biomass

The trunk, main branches, untrimmed small branches, and leaves are the main components of untrimmed dry biomass. The mean fresh leaf biomass from trimmed branches was multiplied by the total untrimmed small branches and by leaf moisture content in order to obtain the dry leaf biomass from untrimmed branches (B_{dry_leaves}). The sum of the three results gives us the untrimmed dry biomass ($\mathrm{B}_{untrimmed\_dry}$):

$$\mathrm{B}_{\mathrm{untrimmed\backslash\_dry}} = \mathrm{B}_{\mathrm{untrimmed\backslash\_dry\backslash\_branch}} + \mathrm{B}_{\mathrm{dry\backslash\_trunk}} + \mathrm{B}_{\mathrm{dry\backslash\_leaves}} \tag{5}$$

where $B_{untrimmed\_dry\_branch}$: untrimmed dry branch biomass, B_{dry_leaves}: untrimmed dry leaf biomass, and B_{dry_trunk}: dry trunk biomass.

For purposes of analyzing the volume of dry sections, each *i* section of trunk and large branch was considered a cylinder and calculated using Smalian's formula.

$$V_i = (\pi / 8)\ L_i(D_{1i}^2 + D_{2i}^2) \tag{6}$$

where *Vi* is the volume of section *i*, L_i its length, and D_{1i} is the diameter at base (BD) and D_{2i} is the diameter at upper extremity (UD) of section *i*. Because this species forms branches very close to one another, each section *i* of the trunk and large branches were considered as follows: trunk – the distance from ground level to the first ramification and large branches – the distance between two ramifications.

Dry trunk and large branch biomass ($\mathrm{B}_{\mathrm{dry\ section}}$) was calculated the same way (product of mean wood density and total large branch and trunk volume).

$$B_{dry\_section} = \rho\ x \sum iVi \tag{7}$$

The sum corresponds to all the sections of large branches and trunks and mean wood density was calculated as:

$$\rho = B_{aliquot\_dry\_wood} / V_{aliquot\_fresh\_wood} \tag{8}$$

Small branch biomass was calculated using a model between dry biomass and the basal diameter of trimmed small branches. This model was established following the same procedure utilized for developing an allometric model (Picard et al., 2012).

The following linear equation was used:

$$B_{dry\_branch} = a + bD \tag{9}$$

where *a* and *b* are the model parameters and *D* is the basal diameter of the branch. Using this model, the untrimmed dry branch biomass was calculated as:

$$B_{untrimmed\_dry\_branch} = \sum_j (a + bDj) \tag{10}$$

where $B_{untrimmed\_dry\_branch}$ is the sum of all the untrimmed small branches and D is the basal diameter of branch *j*.

2.8. Data analysis and model selection

After field and lab measurements were concluded, the data were compiled in Excel worksheets. The summarized data for D, H, wood density, and AGB were utilized to develop the biomass regression models. The software Statistical Package R (version R 3.3.0) was used to formulate the allometric equations.

Biomass regression models were selected based on goodness-of-fit statistics, including coefficient of determination ($R^{\ 2}$ adjusted), residual standard error (RSE), Akaike Information Criterion (AIC), and *p*-value. AIC is an estimator of the relative quality of statistical models for a given set of data. The comparison of models with the same response variables was conducted for model selection purposes. A perda do poder de previsão de R2 ajustado foi avaliado para os modelos 1 a 4 através da ANOVA. The AIC estimated the quality of each model in relation to each other.

AIC is expressed as:

$$AIC = -2ln\ (L) + 2p$$

where *L* is the likelihood of the fitted model and p is the total number of parameters in the model. In comparing two models, the better one has the lower AIC value.

3. Results

Allometric equations were developed from the relationship of AGB to variables D, H, and wood density (ρ), individually and in combination. Data on the principal variables (D and H) were generated from direct field measurements, while data for AGB and ρ were calculated from field samples and laboratory measurements. A descriptive summary of the principal variables is presented in Table 1.

Replicating Daba and Soromessa (2019), regressed models for biomass were formulated relating AGB to predictive variables (D, H, and ρ). Each of these dendrometric variables, and their combinations, were used to fit the allometric equations. In all, eight allometric equations were developed for *D. cearensis* and tested for goodness-of-fit statistics. Of the models selected, seven achieved model performance statistics with a value over 50% of the coefficient of determination (R^2-adjusted) and lower value (≤ 0.721) of the residual standard error (RSE) and lower value (≤ 69.44) of the Akaike information criterion (AIC). The relationships between AGB and the dendrometric variables were statistically significant ($p < 0{,}000$), as summarized in Table 2.

We evaluated the relationship between the main variables considered by correlating AGB with individual predictive variables (D, H); AGB with single compound variables (D^2H, DH, ρDH); AGB with multiple variables ($D + H + \rho$, $D^2H + \rho$, $D + H$). Each biomass regression model was fitted based on data transformed logarithmically and each achieved goodness-of-fit statistics for the model. However, based on the high AIC value for model 8, the relationship between AGB and H (as a simple predictive variable) was considered the poorest model. The best allometric equations were selected based on a model's performance statistics (R^2-adj, RSE, and AIC). The models that performed the best *D. cearensis* biomass regressions are listed below in decreasing order of importance based on AIC value.

Model 1 ($AGB = 0.024 \times (DH)^{1.878}$) for *D. cearensis,* which predicts AGB variation in relation to the single compound predictors DH, is the best model (Fig. 2). The R^2-adj value tells us how much AGB variance can be credited to the model if it is derived from the population from where the sample was taken. In this model, the predictive variables explain 66.80% of AGB variation. However, the ANOVA tells us that model 1 adheres significantly to the data ($F_{value} = 59.399$, $p < 0.000$), and the hypothesis of normal residual distribution is verified visually in the quartile-quartile graph (Fig. 2). Its lower AIC value indicates that this model is the best in comparison with the other models.

The second best-fitted biomass regression was model 2 ($AGB = 0.036 \times (\rho DH)^{1.876}$), which related AGB to the single compound variable (ρDH) (Fig. 3). The predictive variable of this model explains 65.70% (R^2-adj) of AGB variation (ANOVA, $F_{value} = 56.733$, $p < 0.000$). This model also achieved a satisfactory goodness-of-fit performance statistic, considering the values of RSE and AIC.

Model 3 ($AGB = 0.016 \times (D)^{1.713} \times (H)^{2.325}$), which relates AGB to the multiple variables diameter at breast height (D) and height (H) was the third best allometric equation (Fig. 4), considering its goodness-of-it statistics. The value of R^2-adj also indicates that the predictive variable in this model explained 66% of the AGB variation of the tree species *D. cearensis* (ANOVA, $F_{value} = 50.116$, $p < 0.000$).

Model 4 ($AGB = 0.063 \times (D^2H)^{1.055}$), Fig. 5, which relates AGB to the single compound variable (D^2H) was the fourth best-fitted allometric equation, considering its goodness-of-fit statistics. The R^2-adj value also indicates that the predictive variable of this model explained 64.10% of AGB variation for the tree species *D. cearensis* (ANOVA, $F_{value} = 52.922$, $p < 0.000$).

Model 5 ($AGB = 0.011 \times (D)^{1.676} \times (H)^{2.356} \times (\rho)^{-1.993}$), Fig. 6a, model 6 ($AGB = 0.049 \times (D^2H)^{1.047} \times (\rho)^{-1.477}$), Fig. 6b, and model 7 ($AGB = 0.286 \times (D)^{2.280}$), Fig. 6c, achieved a goodness-of-fit statistic inferior to the first four models (AIC, RSE, and R^2-adj). Model 8 ($AGB = 0.025 \times (H)^{4.252}$), Fig. 6d, which related AGB to H as the single predictive variable explained 42.30% (R^2-adj) of AGB, and was the lowest value among all the other models.

The relationship between AGB and predictive variables (D, H, ρ) is not linear and biomass variance increases when the diameter increases, for example. By working with data transformed algorithmically, the residual variance stabilizes. Fig. 7 shows that the biomass logarithm ln (B) in relation to the diameter logarithm ln (D), to the height logarithm ln (H), and to the wood density logarithm ln (ρ) corresponds to a linear relationship for the 30 individuals of *D. cearensis*.

Table 1

Statistical summary of the main dendrometric variables.

Variables*	Min.	Max.	Mean	SD
AGB	9.29	1296.53	110.31	230.41
D	5.00	20.05	10.58	4.02
H	4.30	8.30	6.13	1.05
ρ	0.76	0.88	0.81	0.02

* AGB = aboveground biomass (kg), D = diameter at breast height (cm), H = height (m), ρ = wood density (g cm^{-3}), SD = standard deviation.

4. Discussion

There is a worrisome lack of both sustainable policies and multidisciplinary research in the caatinga biome (Santos et al., 2014; Santos et al., 2011). From an ecological-economic perspective, this poses challenges to the development of climate change mitigation strategies in the context of the extreme anthropic pressure the caatinga faces. The strategy of sequestering carbon (C) in terrestrial ecosystems, by means of the natural photosynthetic process of transferring atmospheric CO_2 to biomass, is essential to lowering the risks of global warming and environmental degradation (Lal, 2008). It has been suggested that caatinga plants under increased CO_2 concentration have increased water-use efficiency and tolerance to periods of prolonged drought (Santos et al., 2014), and a recent study indicated that the Brazilian seasonally dry tropical forest (caatinga) acts as an atmospheric carbon sink (Mendes et al., 2020). For this reason, precise estimation of caatinga tree biomass provides a powerful tool for planning the mitigation of climate change. Hence, the construction of allometric equations for calculating volume and biomass, predicted by means of dendrometric variables, are key elements in estimating the contribution of forest ecosystems to the carbon cycle (Picard et al., 2012).

In this study, we benefitted from a set of measured data of the trimmed and untrimmed fresh biomass of the species *D. cearensis*. These data included the dendrometric variables diameter at breast height and tree height, and allowed us to calculate wood density. Using these variables, we were able to generate models to predict AGB.

The regression model for *D. cearensis* that utilized the single compound predictive variables DH (model 1) was the most robust, followed by the model of single compound variables ρDH (model 2), and multiple variables D + H (model 3). The R^2-adjusted for model 1 (R^2-adj = 0.668), for model 2 (R^2-adj = 0.657), and for model 3 (R^2-adj = 0.660) tells us how much biomass variance can be credited to the models. These values are modest when compared to those found by Sampaio and Silva (2005) to estimate the biomass of ten species of caatinga plants. One likely reason for the uncertainty identified by the statistic was the consideration of wood density as identical for all tree components, though wood aliquots were collected solely from small branches. However, both tree architecture as well as legal considerations due to our conducting the research in environmentally-protected areas limited our ability to measure wood density using larger branches.

Similar studies explain the robustness of allometric models that consider the combined predictive variables of D, H, and ρ applied to a single species in the Mediterranean (Brunori et al., 2017), in moist Afromontane forests (Kebede and Soromessa, 2018; Daba and Soromessa, 2019), in dry tropical forests (Návar, 2009) and in carbon assessments in tropical forests (Ploton et al., 2016; Chave et al., 2014).

Among the models that utilized wood density, models 5 and 6, which related biomass to multiple variables, were less efficient than the single compound variable model (model 2). In model 2, the wood density exponent is positive, whereas for models 5 and 6 this exponent is negative. From a biological point of view, a positive exponent is more satisfactory than a negative one since the biomass is the product of a volume that depends exclusively on the tree dimensions and its density.

Table 2
Regression models with goodness of fit for predicting AGB of *Dalbergia cearensis.*

Model	Allometric equations	Coefficients		Performance statistics			
		Symb.	Value	R^2_{adj}	RSE	AIC	p-value
1	$\ln(AGB) = a + b_1\ln(DH)$	a	−3.710	0.668	0.635	61.85	< 0.000
		b_1	1.878				
2	$\ln(AGB) = a + b_1\ln(\rho DH)$	a	−3.310	0.657	0.645	62.78	<0.000
		b_1	1.876				
3	$\ln(AGB) = a + b_1\ln(D) + b_2\ln(H)$	a	−4.135	0.660	0.643	63.48	<0.000
		b_1	1.713				
		b_2	2.325				
4	$\ln(AGB) = a + b_1\ln(D^2H)$	a	−2.763	0.641	0.660	64.16	<0.000
		b_1	1.055				
5	$\ln(AGB) = a + b_1\ln(D) + b_2\ln(H) + b_3\ln(\rho)$	a	−4.524	0.651	0.651	65.11	<0.000
		b_1	1.676				
		b_2	2.356				
		b3	−1.993				
6	$\ln(AGB) = a + b_1\ln(D^2H) + b_2\ln(\rho)$	a	−3.018	0.630	0.670	65.97	<0.000
		b_1	1.047				
		b_2	−1.477				
7	$\ln(AGB) = a + b_1\ln(D)$	a	−1.249	0.572	0.721	69.44	<0.000
		b_1	2.280				
8	$\ln(AGB) = a + b_1\ln(H)$	a	−3.676	0.423	0.837	78.44	<0.000
		b_1	4.252				

AGB: aboveground tree biomass (kg); D: diameter at breast height (cm); H: total tree height (m); ρ: wood density (g cm^{-3}); a: intercept; b_1,b_2,b_3: slopes; R^2-adj: R square adjusted; RSE: residual standard error; AIC: Akaike information criterion.

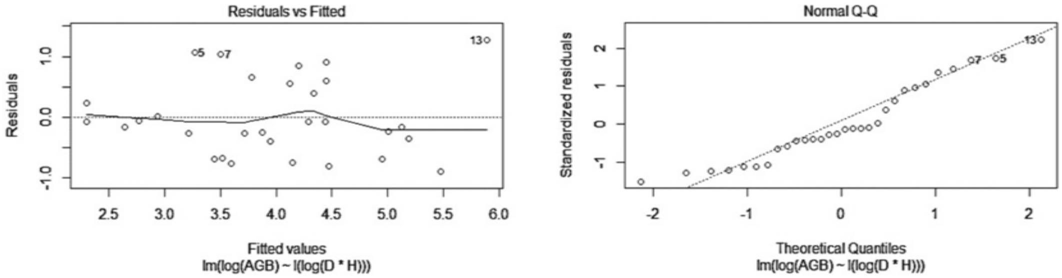

Fig. 2. Graph of residuals as a function of fitted values (left) and quantile–quantile graph (right) of residuals from simple linear regression of ln(AGB) in relation to ln (DH) (model 1), fitted for the 30 *D. cearensis* trees.

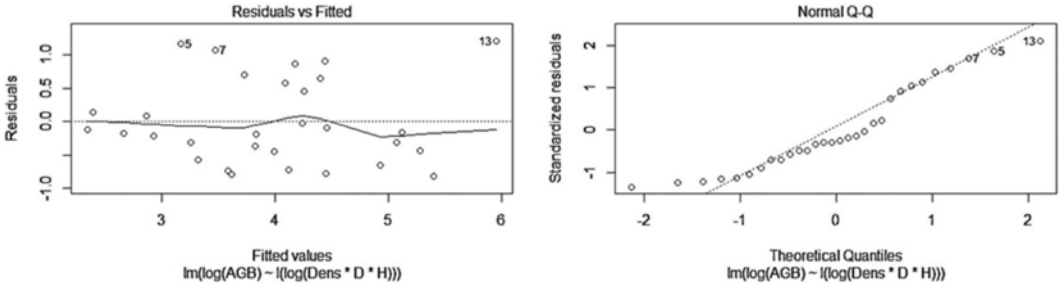

Fig. 3. Graph of residuals as a function of fitted values (left) and quantile–quantile graph (right) of the residuals from the simple linear regression of ln(AGB) in relation to ln(ρDH) (model 2), fitted for the 30 *D. cearensis* trees.

The result of multiplying volume times density with a negative exponent is lower than the result of multiplying the volume times density with a positive exponent.

Biomass regression model 8, where H was the only predictor of *D. cearensis* AGB, achieved terrible results. Daba and Soromessa (2019) obtained a similar result when evaluating AGB biomass allometric equations for *Diospyros abyssinica*. Not only is variable H hard to measure in the field, but environmental factors such as soil, ecological succession, and type of forest affect tree development and growth (Picard et al, 2012). Furthermore, the adaptive morphology of some species points to a weak relationship between AGB and H (Kohyama et al., 2003). On the other hand, the incorporation of variable H guarantees greater precision of the allometric estimation in some species of trees and has been emphasized by several authors (Ketterings et al., 2001; Chave et al., 2014; Molto et al., 2014).

The most common allometric equations make use of predictive variables D, H, and ρ, and their combinations, for a more precise estimation of AGB. Diameter at breast height (D) is easy to measure in the field; H captures the variation of volume among trees; and wood density is used to convert volume into biomass (Brown et al., 1989). Models that include diameter and wood density, but not height, tend to overestimate the aboveground biomass (Alvarez et al., 2012) while Aabeyir et al. (2020) found diameter at breast height and wood density to be the main predictors significantly influencing AGB variability. Chave et al. (2014)

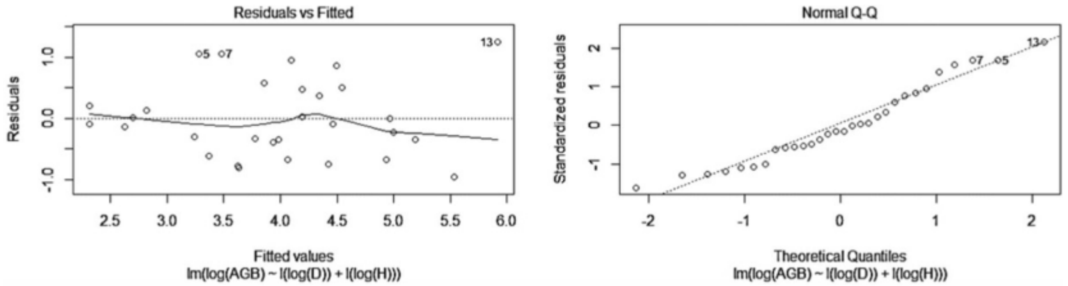

Fig. 4. Graph of residuals as a function of fitted values (left) and quantile–quantile graph (right) of residuals from the simple linear regression of ln(AGB) in relation to ln(D + H) (model 3), fitted for the 30 *D. cearensis* trees.

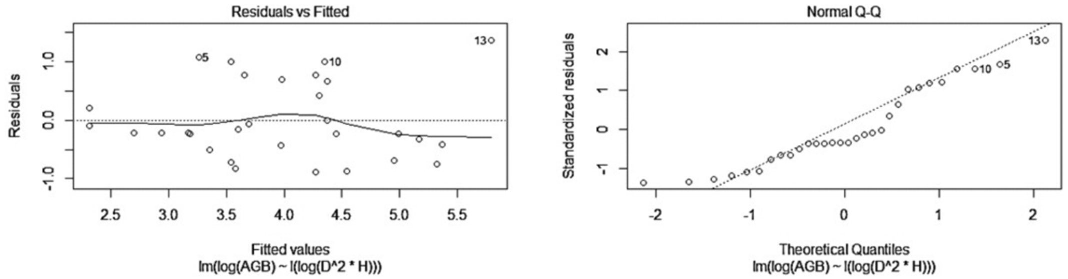

Fig. 5. Graph of residuals as a function of fitted values (left) and quantile-quantile graph (right) of residuals from the simple linear regression of ln(AGB) in relation to ln(D^2H) (model 4), fitted for the 30 *D. cearensis* trees.

suggested that a single AGB model based on D, H, and ρ would have a wide range of applications in a tropical forest.

Wood density was suggested as the reason for improved goodness of fit of allometric models when used as a predictor in combination with D and H (Chave et al., 2014; Basuki et al., 2009). On the other hand, the inclusion of wood density did not provide significant gains for the equation involving the variables height, crown diameter, and diameter at breast height (Araújo et al., 2018). Complementarily, when utilizing wood density as a single variable in predicting AGB of *D. abyssinica,* Daba and Soromessa (2019) did not find the allometric equation to be statistically significant, and thus rejected it. Given these contradictory findings, it would seem that wood density as a predictive variable of biomass will continue to generate debate, and, therefore, remains a subject worthy of further study. Wood density is one of the physical properties that are inherent to a species. However, in different environments wood density varies between individuals, between species, and between individuals of the same species. Therefore, wood density reflects the physiological strategies related to tree growth and survival. As such, variations of location and individual adaptation strategy may be the reason wood density did not correlate with the AGB of the species *D. abyssinica* (Daba and Soromessa, 2019).

Model 7, constructed with the diameter at breast height (D) of *D. cearensis*, as its single predictive variable, explained 57.20% of AGB (R^2-adj). We considered this prediction low, given the results of the previous models. However, other studies suggest that models built using diameter at breast height (D) as the single predictive variable guarantee a significant level of AGB prediction. Kuyah et al. (2016) and Kebede and Soromessa (2018) emphasize that the diameter at breast height in itself is a good predictor of biomass. These authors state that diameter, as a single predictive variable, is better than models that include height and crown area, when taking into account the cost and practicability of measurement. Moreover, the use of models in which tree biomass is determined solely by diameter at breast height has a practical advantage in that most inventories include diameter measurements as they are easy to collect with precision in the field (Segura and Kanninen, 2005; Kebede and Soromessa 2018; Feyisa et al., 2018).

Sampaio and Silva (2005) used plant height, trunk diameter at ground level, and trunk diameter at breast height to develop allometric equations of caatinga trees. Two distinct locations were selected within the *Sertaneja* Depression, the geoenvironmental unit most typical of the northeastern semiarid region, one located in the municipality of Santa Luz, Bahia and the other in the municipality of Petrolina, Pernambuco. The estimated biomass presented a high coefficient of determination (R^2) and there was negligible difference in the assessment of aboveground biomass (AGB) when using height (H) and diameter at breast height (D) or height (H) and diameter at ground level.

The second most robust regression model for *D. cearensis* was the one that utilized wood density (ρ), diameter, and height as a single compound variable predicting aboveground biomass. Wood density varied among the 30 individuals of *D. cearensis*. This variation was unsurprising and expected, as it is attributable to local environmental conditions, age, and the stage of succession of the trees (Aabeyir et al., 2020). The specific wood density is an important predictor of aboveground biomass, especially when one includes a much more ample variety of vegetation types (Chave et al. 2014). On the other hand, wood density differs for the same species due to differing locations (Kim et al., 2011) and its value can vary depending on the method employed for its calculation.

Care must be taken when including wood density as a biomass predictor at the time of sample collection in the field, because the tree's upper section near the crown is made up of younger wood and has a different density from the lower part, whose wood is more mature (Burdon et al., 2004). Lorenzi (2009) describes wood density for *D. cearensis* as 1.01 g cm^{-3} and Oliveira et al. (2019) obtained a density of 0.73 g cm^{-3} for the same species, while we obtained a value of 0.81 g cm^{-3}. In our own study, we utilized wood aliquots collected from branches in the upper section of the trees. So, while wood density is certainly an important characteristic in determining the physical and mechanical properties of woody tree species, the construction of biomass regression models based on wood density as the single predictive variable of AGB has no practical use, because in that case we would need to measure each tree whose biomass we would like to predict (Picard et al., 2012).

For Stegen et al. (2009), understanding the spatial variation of aboveground biomass as a function of wood density, both within and

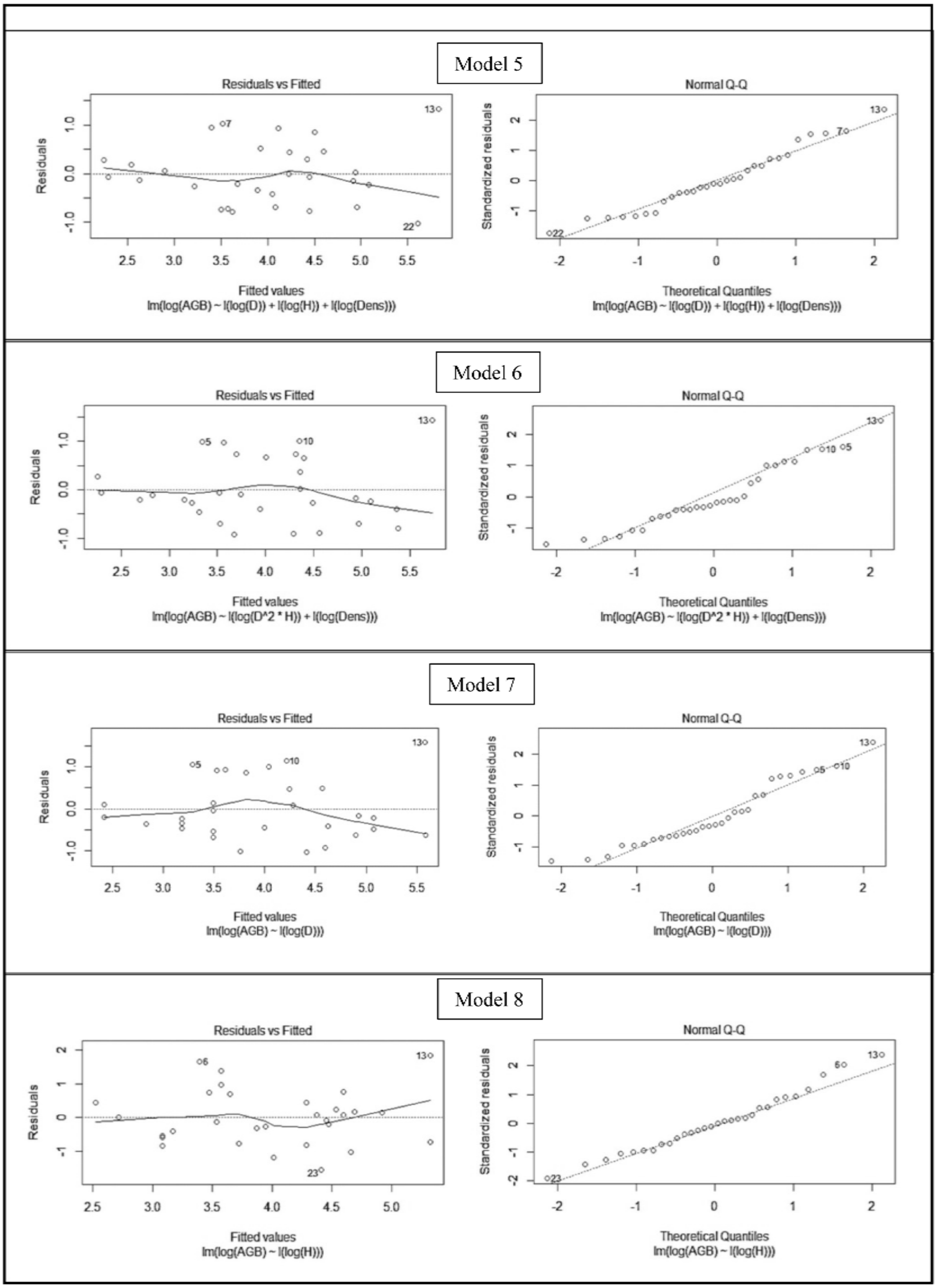

Fig. 6. Graph of residuals as a function of fitted values (left) and quantile–quantile graph (right) of residuals from the simple linear regression of ln(AGB) in relation to ln(D) + ln(H) + ln(ρ) (model 5), ln(D^2H) + ln(ρ) (model 6), ln(D) (model 7), and ln(H) (model 8), fitted for the 30 *D. cearensis* trees.

among forests, is important in predicting changes in stored carbon in response to climate change. However, according to the authors, there is no general relationship between forest biomass and the mean wood density of the forest community. In some forests, stored carbon is higher where the wood density is lower. Therefore, it can no longer be assumed that there is a direct correlation between forest biomass and wood density or between wood density and carbon stores.

The use of local specific allometric models, rather than generalized models, is recommended whenever possible. Romero et al. (2020) developed allometric equations to quantify volume, biomass, and carbon in the southwest of the Brazilian amazon forest. The estimates for commercial trunks of large trees were made by using diameter, commercial trunk length, wood density, and carbon content as explanatory variables. The study showed that the use of linear and non-linear allometric equations for the estimation of volume, biomass, and carbon could reduce errors and improve the estimation of commercial species in southwest Amazonia.

As mentioned, environmental conditions influence tree growth.

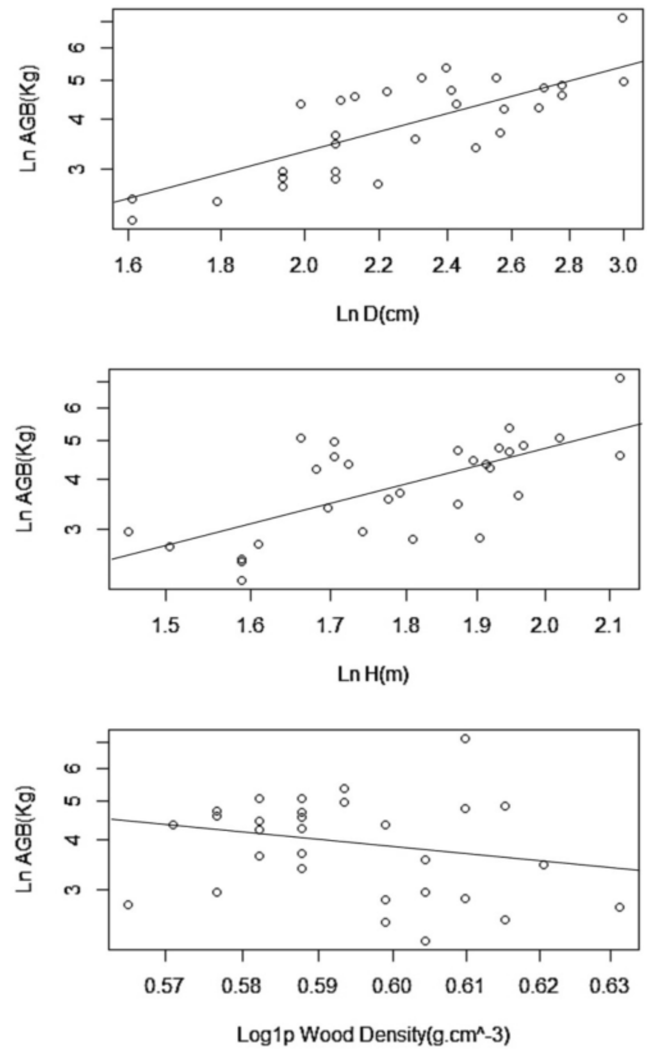

Fig. 7. Point cloud (data transformed algorithmically) of total dry biomass (kg) based on diameter at breast height (D, cm), tree height (H, m), and wood density (ρ, g cm^{-3}) for *D. cearensis*.

Consequently, the production of aboveground biomass will not be the same for trees of the same age. These environmental variations associated to the intrinsic (genetic) development of the tree promote variations in aboveground biomass. Alves et al. (2010) indicates the variation in terrain topography associated with the greater influence of large-diameter trees as causes for aboveground biomass variations.

Ketterings et. al. (2001) state that a common method for estimating forest biomass is by means of allometric equations that relate individual tree biomass to non-destructive measurements that are easily obtainable in the field, such as for example, diameter. One common form is $B = aD^b$ for biomass B, diameter D, and parameters a and b. Data collected in Sumatra, by the authors, and compared to previous publications showed that the values of a and b vary among different locations. These variations are likely the main sources of uncertainty in estimating biomass by using equations that are not calibrated to a specific place. Plant species differ in their capacity to capture, store, and release carbon because of their functional diversities, meaning that the collective functional characteristics of plant communities are likely a major driver of carbon accumulation in terrestrial ecosystems (Conti and Díaz, 2013). For this reason, the formulation of allometric equations for a particular species and its local habitat should be encouraged in order to guarantee greater precision in biomass estimation. As the allometry of trees depends on environmental and genetic factors that vary from region to region, the theoretical models that include very few dendrological explanatory variables in specific locations, most likely will not produce precise tree biomass estimates in other locations (Vieilledent et al., 2012). Therefore, in developing allometric equations for determining aboveground biomass, the idea is to determine the part associated to the intrinsic development of the tree (ontogeny), distinguishing it from that associated to environmental factors (Picard et al., 2012).

5. Conclusion

The semi-destructive method generated a set of data that allowed us to estimate the aboveground biomass of *Dalbergia cearensis* and can contribute to the quantification of the species' contribution to the carbon cycle in the semiarid region of the Brazilian Northeast. Of the eight biomass regression models developed and tested to estimate the aboveground biomass of *Dalbergia cearensis* trees, six achieved acceptable goodness-of-fit statistics. The regression model for *D. cearensis* that utilized the single compound predictors DH (model 1) was the most robust, followed closely by the model of single compound predictors ρDH (model 2), and multiple variables D + H (model 3).

6. Recommendations

The methodology applied in this study can be adopted to estimate the biomass and volume of a larger set of species in the Brazilian seasonally dry tropical forest. These equations should be particularly useful for the semiarid region of the Brazilian Northeast, which does not yet have individual equation models for the various species that compose its typical forest formation, that is, the caatinga.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Aabeyir, R., Adu-Bredu, S., Agyare, W.W., Weir, M.J.C., 2020. Allometric models for estimating aboveground biomass in the tropical woodlands of Ghana. West Africa. For. Ecosyst. 7, 41. https://doi.org/10.1186/s40663-020-00250-3.

Aholoukpè, H., Dubos, B., Flori, A., Deleporte, P., Amadji, G., Chotte, J.L., Blavet, D., 2013. Estimating aboveground biomass of oil palm: Allometric equations for estimating frond biomass. For. Ecol. Manage. 292, 122–129. https://doi.org/10.1016/j.foreco.2012.11.027.

Albuquerque, U., Araújo, E., El-Deir, A., Lima, A., Souto, A., Bezerra, B., Ferraz, E., Freire, E., Sampaio, E., Las-Casas, F.M., Pereira, G., Melo, J., Ramos, M., Rodal, M., Schiel, N., Lyra-Neves, R., Alves, R., Azevedo-Júnior, S., Severi, W., 2012. Caatinga Revisited: Ecology and Conservation of an Important Seasonal Dry Forest. The Scientific World Journal. 2012 https://doi.org/10.1100/2012/205182.

Alongi, D.M., 2011. Carbon payments for mangrove conservation: ecosystem constraints and uncertainties of sequestration potential. Environ. Sci. Policy 14, 462–470. https://doi.org/10.1016/j.envsci.2011.02.004.

Alvarez, E., Duque, A., Saldarriaga, J., Cabrera, K., de las Salas, G., del Valle, I., Lema, A., Moreno, F., Orrego, S., Rodríguez, L., 2012. Tree above-ground biomass allometries for carbon stocks estimation in the natural forests of Colombia. For. Ecol. Manage. 267, 297–308. https://doi.org/10.1016/j.foreco.2011.12.013.

Alves, L.F., Vieira, S.A., Scaranello, M.A., Camargo, P.B., Santos, F.A.M., Joly, C.A., Martinelli, L.A., 2010. Forest structure and live aboveground biomass variation along an elevational gradient of tropical Atlantic moist forest (Brazil). For. Ecol. Manage. 260, 679–691. https://doi.org/10.1016/j.foreco.2010.05.023.

Araújo, E.L., Castro, C.C., Albuquerque, U.P., 2007. Dynamics of Brazilian caatinga - a review concerning the plants, environment and people. Fun. Eco. Com. 1, 15–28. https://doi.org/10.1100/2012/205182.

Araújo, E.J.G., Loureiro, G.H., Sanquetta, M.N.I., Corte, A.P.D., Péllico Netto, S., Behling, A., 2018. Allometric models to biomass in restoration areas in the Atlantic rain forest. Floresta Ambient. 25, e20160193 https://doi.org/10.1590/2179-8087.019316.

Araújo Filho, R.N., Freire, M.B.G.S., Wilcox, B.P., West, J.B., Freire, F.J., Marques, F.A., 2018. Recovery of carbon stocks in deforested caatinga dry soils requires at least 60 years. For. Ecol. Manag. 407, 210–220. https://doi.org/10.1016/j.foreco.2017.10.002.

Basuki, T.M., Van Laake, P.E., Skidmore, A.K., Hussin, Y.A., 2009. Allometric equations for estimating the aboveground biomass in tropical lowland Dipterocarp forests. For. Ecol. Manage. 257, 1684–1694. https://doi.org/10.1016/j.foreco.2009.01.027.

Brown, S., Gillespie, A., Lugo, A.E., 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. For. Sci. 35, 881–902. https://doi.org/10.1093/forestscience/35.4.881.

Brunori, A., Dini, F., Cantini, C., Sala, G., La Mantia, T., Caruso, T., Marra, F. P., Trotta, C., Nasini, L., Regni, L., Proietti, P., 2017. Biomass and volume modeling in Olea europaea L. cv "Leccino". Trees. https://doi.org/10.1007/s00468-017-1592-9.

Burdon, R.D., Kibblewhite, R.P., Walker, J.C.F., McGraw, E.R., Crown, D.J., 2004. Juvenile versus mature wood: a new concept, orthogonal to corewood versus outerwood, with special reference to *Pinus radiata* and *P. taeda*. For. Sci. 50, 399–415. https://doi.org/10.1093/forestscience/50.4.399.

Campos, J.A., 1994. Degradação ambiental, manejo ecológico de solos e de algumas "pragas" das plantas cultivadas. SEMACE, Fortaleza.

Carvalho, A.M., 1997. A synopsis of the genus *Dalbergia* (Fabaceae, Dalbergieae) in Brazil. Brittonia 49, 87–109.

CEARÁ, 2016. Inventário florestal nacional: principais resultados / Ministério do Meio Ambiente. Serviço Florestal Brasileiro. Brasília: MMA, 106p. Available at: http://www.florestal.gov.br/documentos/informacoes-florestais/inventario-florestal-nacional-ifn/resultados-ifn/2195-principais-resultados-ifn-ce/file.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Global Change Biol. 20, 3177–3190. https://doi.org/10.1111/gcb.12629.

Clark, J., Murphy, G., 2011. Estimating forest biomass components with hemispherical photography for Douglas-fir stands in northwest Oregon. Can. J. For. Res. 41, 1060–1074. https://doi.org/10.1139/x11-013.

Conti, G., Díaz, S., 2013. Plant functional diversity and carbon storage – an empirical test in semi-arid forest ecosystems. J. Ecol. 101, 18 – 28. https://doi.org/10.11111365-2745.12012.

Costanza, R., 2020. Ecological economics in 2049: Getting beyond the argument culture to the world we all want, Ecological Economics, Volume 168. ISSN 106484, 0921–8009. https://doi.org/10.1016/j.ecolecon.2019.106484.

CPRM – Companhia de Pesquisa de Recursos Minerais, 2003. Atlas digital de geologia e recursos minerais do Ceará. Mapa na escala de 1:500.000. Fortaleza: Serviço Geológico do Brasil/Ministério das Minas e Energia. 1 CD-ROM.

Daba, D.E., Soromessa, T., 2019. Allometric equations for aboveground biomass estimation of *Diospyros abyssinica* (Hiern) F. White tree species. Ecosyst. Health Sustain. 5, 86–97. https://doi.org/10.1080/20964129.2019.1591169.

Dhillon, R.S., von Wuehlisch, G., 2013. Mitigation of global warming through renewable biomass. Biom. Bioe. 48, 75–89. https://doi.org/10.1016/j.biombioe.2012.11.005.

Dimobe, K., Kouakou, J.L.N., Tondoh, J.E., Zoungrana, B.J.-B., Forkuor, G., Ouédraogo, K., 2018. Predicting the potential impact of climate change on carbon stock in semi-arid west African savannas. Land. 7, 1–21. https://doi.org/10.3390/land7040124.

Djomo, A.N., Chimi, C.D., 2017. Tree allometric equations for estimation of above, below and total biomass in a tropical moist forest: case study with application to remote sensing. For. Ecol. Manage. 391, 184–193. https://doi.org/10.1016/j.foreco.2017.02.022.

Didier, N., 1992. Le commerce des bois d'Amérique tropicale. In: Cahiers d'outre-mer. N° 179-180 - 45e année, Juillet/décembre 1992. Les plantes américaines à la conquête du monde. pp. 249-261. https://doi.org/10.3406/caoum.1992.3443.

EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária, 2004. Dados climatológicos: Estação de Quixadá, 2003. Fortaleza: Embrapa. Centro Nacional de Pesquisa de Agroindústria Tropical. Ministério da Agricultura, Pecuária e Abastecimento. Documentos 88.

Feyisa, K., Beyene, S., Megersa, B., Said, M.Y., Jan, de, L., Angassa, A., 2018. Allometric equations for predicting aboveground biomass of selected woody species to estimate carbon in East African rangelands. Agrofor. Syst. 92, 599–621. https://doi.org/10.1007/s10457-016-9997-9.

Figueirôa, J.M., Pareyn, F.G.C., Araújo, E.L., Silva, C.E., Santos, V.F., Cutler, D.F., Baracat, A., Gasson, P., 2006. Effects of cutting regimes in the dry and wet season on survival and sprouting of woody species from the semi-arid caatinga of northeast Brazil. For. Ecol. Manage. 229, 294–303. https://doi.org/10.1016/j.foreco.2006.04.008.

FUNCEME – Fundação Cearense de Meteorologia e Recursos Hídricos, 2020. Dados dos postos pluviométricos do Ceará. Available at: http://www.funceme.br/app/calendario/produto/municipios/maxima/diario?data=hoje.

Gardner, T.A., Burgess, N.D., Aguilar-Amuchastegui, N., Barlow, J., Berenguer, E., Clements, T., Danielsen, F., Ferreira, J., Foden, W., Kapos, V., Khan, S.M., Lees, A.C., Parry, L., Roman-Cuesta, R.M., Schmitt, C.B., Strange, N., Theilade, I., Vieira, I.C.G., 2012. A framework for integrating biodiversity concerns into national REDD+ programmes. Biol. Conserv. 154, 61–71. https://doi.org/10.1016/j.biocon.2011.11.018.

Henry, M., Bombelli, A., Trotta, C., Alessandrini, A., Birigazzi, L., Sola, G., Vieilledent, G, Santenoise, P., Longuetaud, F., Valentini, R., Picard, N., Saint-André, L., 2013. GlobAllomeTree: international platform for tree allometric equations to support volume, biomass and carbon assessment. iForest – Biogeosci. For. (early view): e1-e5. https://doi.org/10.3832/ifor0901-006.

Huff, S., Ritchie, M., Temesgen, H., 2017. Allometric equations for estimating aboveground biomass for common shrubs in northeastern California". For. Ecol. Manage. 398, 48–63. https://doi.org/10.1016/j.foreco.2017.04.027.

Ifo, A.S., Gomat, H.Y., Wenina, Y.E.M., Lokegna, D.L., Nzonzi, O.R.M., Ngala, G.C.A., Henry, M., Boundzanga, G.C., Jourdain, C., Picard, N., Loumeto, J.J., 2018. Carbon stocks and tree allometries in the Savannahs of the plateau Batéké, Central Africa. For. Ecol. Manage. 427, 86–95. https://doi.org/10.1016/j.foreco.2018.05.065.

INMET– Instituto Nacional de Meteorologia, 2020. Banco de Dados Meteorológicos para Ensino e Pesquisa. Available at: http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep.

IPECE – Instituto de Pesquisa e Estratégia Econômica, 2017a. Perfil básico municipal: Itapipoca. Fortaleza: IPECE. Available at: https://www.ipece.ce.gov.br/wp-content/uploads/sites/45/2018/09/Itapipoca_2017.pdf.

IPECE – Instituto de Pesquisa e Estratégia Econômica, 2017b. Perfil básico municipal: Quixadá. Fortaleza: IPECE. Available at: https://www.ipece.ce.gov.br/wp-content/uploads/sites/45/2018/09/Quixada_2017.pdf.

IUSS Working Group WRB. World Reference Base for Soil Resources 2014, up date 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome. 2015.

Kebede, B., Soromessa, T., 2018. Allometric equations for aboveground biomass estimation of *Olea europaea* L. subsp. *cuspidata* in Mana Angetu forest. Ecosyst. Health Sustain. 4, 1–12. https://doi.org/10.1080/20964129.2018.1433951.

Ketterings, Q.M., Coe, R., van Noordwijk, M., Ambagau 'Y., Palm, C.A., 2001. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. For. Ecol. Manage.146, 199 – 209. https://doi.org/10.1016/S0378-1127(00)00460-6.

Kim, C., Jeong, J., Kim, R., Son, Y., Lee, K.H., Kim, J.-S., Park, I.-H., 2011. Allometric equations and biomass expansion factors of Japanese red pine on the local level. Landsc. Ecol. Eng. 7, 283–289. https://doi.org/10.1007/s11355-010-0131-2.

Kohyama, T., Suzuki, E., Partomihardjo, T., Yamada, T., Kubo, T., 2003. Tree species differentiation in growth, recruitment and allometry in relation to maximum height in a Bornean mixed dipterocarp forest. J. Ecol. 91, 797–806. https://doi.org/10.1046/j.1365-2745.2003.00810.x.

Kuyah, S., Sileshi, G.W., Rosenstock, T.S., 2016. Allometric models based on bayesian frameworks give better estimates of aboveground biomass in the miombo woodlands. Forests. 7, 1–13. https://doi.org/10.3390/f7020013.

Lal, R., 2008. Sequestration of atmospheric CO_2 in global carbon pools. Energy Environ. Sci. 1, 86–100. https://doi.org/10.1039/B809492F.

Lorenzi, H., 2009. Árvores brasileiras: manual de identificação e cultivo de plantas arbóreas nativas do Brasil. Nova Odessa: Instituto Plantarum 3, 384p.

Ma, X.-Z., Wang, X.-P., 2020. Biomass partitioning and allometric relations of the *Reaumuria soongorica* shrub in Alxa steppe desert in NW China. For. Ecol. Manage. 468, 1–10. https://doi.org/10.1016/j.foreco.2020.118178.

Mendonça, A.V.R., Souza, J.S., Giulietti, A.M., van den Berg, C., 2013. Estimação de biomassa aérea da caatinga do norte da Bahia. Pesq. Flor. Bras. 33, 355–368. https://doi.org/10.4336/2013.pfb.33.76.579.

Mendes, K.R., Campos, S., Silva, L.L., Mutti, P.R., Ferreira, R.R., Medeiros, S.S., Perez-Marin, A.M., Marques, T.V., Ramos, T.M., Vieira, M.M.L., Oliveira, C.P., Gonçalves, W.A., Costa, G.B., Antonino, A.C.D., Menezes, R.S.C., Bezerra, B.G., Silva, C.M.S., 2020. Seasonal variation in net ecosystem CO_2 exchange of a Brazilian seasonally dry tropical forest. Scientific Rep. 10, 9454. https://doi.org/10.1038/s41598-020-66415-w.

Molto, Q., Hérault, B., Boreux, J.J., Daullet, M., Rousteau, A., Rossi, V., 2014. Predicting tree heights for biomass estimates in tropical forests - a test from French Guiana. Biogeosciences 11, 3121–3130. https://doi.org/10.5194/bg-11-3121-2014.

Návar, J., 2009. Allometric equations for tree species and carbon stocks for forests of northwestern Mexico. For. Ecol. Manage. 257, 427–434. https://doi.org/10.1016/j.foreco.2008.09.028.

Nogueira, F.C.B., Medeiros-Filho, S., Baldoni, R.N., Sampaio, T.A.S., 2014. Is the seed dispersal related to spatial pattern of individuals in populations? The case of *Dalbergia cearensis*. Am. J. Plant Sci. 5, 2997–3004. https://doi.org/10.4236/ajps.2014.520316.

Oliveira, H.G.B., Sousa, M.V.C., Silva, L.S., Ferraz Filho, A.C., Ribeiro, A., 2019. Propriedades energéticas da madeira e casca *de Dalbergia cearensis* Ducke. Agropec. Cient. Semiarid. 15, 232–237. https://doi.org/10.30969/acsa.v15i3.1188.

Pereira Júnior, L.R., Andrade, E.M., Palácio, H.A.Q., Raymer, P.C.L., Ribeiro Filho, J.C., Pereira, F.J.S., 2016. Carbon stocks in a tropical dry forest in Brazil. Ver. Ciênc. Agron. 47, 32–40. https://doi.org/10.5935/1806-6690.20160004.

Picard, N., Saint-André, L., Henry, M., 2012. Manual for Building Tree Volume and Biomass Allometric Equations. From Field Measurement to Prediction. FAO, Rome, Italy and CIRAD, Montpellier, France. http://www.fao.org/docrep/018/i3058e/i3058e.pdf.

Ploton, P., Barbier, P., Stéphane, M.T., et al., 2016. Closing a gap in tropical forest biomass estimation: taking crown mass variation into account in pantropical allometries. Biogeosciences 13, 1571–1585. https://doi.org/10.5194/bg-13-1571-2016.

Pukkala, T., Lähde, E., Laiho, O., 2009. Growth and yield models for uneven-sized forest stands in Finland. For. Ecol. Manage. 258, 207–216. https://doi.org/10.1016/j.foreco.2009.03.052.

Ramos, M.A., Medeiros, P.M., Almeida, A.L.S., Feliciano, A.L.P., Albuquerque, V.P., 2008. Use and knowledge of fuelwood in an area of Caatinga vegetation in NE Brazil. Biom. Bioe. 32, 510–517. https://doi.org/10.1016/j.biombioe.2007.11.015.

Rizzini, C.T., 1978. Árvores e madeiras úteis do Brasil – manual de dendrologia brasileira. Editora Edgard Blucher Ltda, Porto Alegre.

Romero, F.M.B., Jacovine, L.A.G., Ribeiro, S.C., Torres, C.M.M.E., Silva, L.F., Gaspar, R.O., Rocha, S.J.S.S., Staudhammer, C.L., Fearnside, P.M., 2020. Allometric equations for volume, biomass, and carbon in commercial stems harvested in a managed forest in the Southwestern Amazon: a case study. Forests 11, 874. https://doi.org/10.3390/f11080874.

Sampaio, E., Gasson, P., Bacarat, A., Cutler, D., Pareyn, F., Lima, K.C., 2010. Tree biomass estimation in regenerating areas of tropical dry vegetation in northeast Brazil. For. Ecol. Manage. 259, 1135–1140. https://doi.org/10.1016/j.foreco.2009.12.028.

Sampaio, E.V.S.B., Silva, G.C., 2005. Biomass equations for Brazilian semiarid caatinga plants. Acta Bot. Bras. 19, 935–943. https://doi.org/10.1590/S0102-33062005000400028.

Santos, J.C., Leal, I.R., Almeida-Cortez, J.S., Fernandes, G.W., Tabarelli, M., 2011. Caatinga: the scientific negligence experienced by a dry tropical forest. Tropical Conservation Sci. 4 (3), 276–286. https://doi.org/10.1177/194008291100400306.

Santos, M.G., Oliveira, M.T., Figueiredo, K.V., Falcao, H.M., Arruda, E.C., Almeida-Cortez, J., Pompelli, M.F., 2014. Caatinga, the Brazilian dry tropical forest: can it tolerate climate changes? Theoretical Experim. Plant Physiol. 26 (1), 83–99. https://doi.org/10.1007/s40626-014-0008-0.

Scolforo, H.F., Scolforo, J.R.S., Mello, C.R., Mello, J.M., Ferraz Filho, A.C., 2015. Spatial distribution of aboveground carbon stock of the arboreal vegetation in Brazilian biomes of savanna, atlantic forest and semi-arid woodland. PLoS ONE 10 (6), e0128781. https://doi.org/10.1371/journal.pone.0128781.

Segura, M., Kanninen, M., 2005. Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica. Biotropica 37 (1), 2–8. https://doi.org/10.1111/j.1744-7429.2005.02027.x.

Sillett, S.C., Van Pelt, R., Carroll, A.L., Campbell-Spicklera, J., 2019. Allometric equations for *Sequoia sempervirens* in forests of different ages. For. Ecol. Manage. 433, 349–363. https://doi.org/10.1016/j.foreco.2018.11.016.

Skovsgaard, J.P., Vanclay, J.K., 2008. Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. Forestry. 81, 13–31. https://doi.org/10.1093/forestry/cpm041.

Stegen, J., Swenson, N., Valencia, R., Enquist, B.J., Thompson, J., 2009. Above-ground forest biomass is not consistently related to wood density in tropical forests. Global Ecol. Biogeogr. https://doi.org/10.1111/j.1466-8238.2009.00471.x.

Teobaldelli, M., Somogyi, Z., Migliavacca, M., Usoltsev, V.A., 2009. Generalized functions of biomass expansion factors for conifers and broadleaved by stand age, growing stock and site index. For. Ecol. Manage. 257, 1004–1013. https://doi.org/10.1016/j.foreco.2008.11.002.

Vahedi, A.A., Mataji, A., Babayi-Kafaki, S., Eshaghi-Rad, J., Hodjati, S.M., Djomo, A., 2014. Allometric equations for predicting aboveground biomass of beech-hornbeam stands in the Hyrcanian forests of Iran. J. For. Sci. 60, 236–247. https://doi.org/10.17221/39/2014-JFS.

Vieilledent, G., Vaudry, R., Andriamanohisoa, S.F.D., Rakotonarivo, O.S., Randrianasolo, H.Z., Razafindrabe, H.N., Rakotoarivony, C.B., Ebeling, J., Rasamoelina, M., 2012. A universal approach to estimate biomass and carbon stock in tropical forests using generic allometric models. Ecol. Appl. 22, 572–583. https://doi.org/10.1890/11-0039.1.

Yen, T.-M., Lee, J.-S., 2011. Comparing aboveground carbon sequestration between moso bamboo (*Phyllostachys heterocycla*) and China fir (*Cunninghamia lanceolata*) forests based on the allometric model. For. Ecol. Manage. 261, 995–1002. https://doi.org/10.1016/j.foreco.2010.12.015.