Tree equations and climatic variables effect in the growth of planted forest of Calophyllum brasiliense in Brazil

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Abstract

Understanding the effect of climatic variations in tree growth is fundamental in the scenario of climate change. The objectives of this work were to adjust allometric equations to estimate volume and aboveground biomass in a planted forest of Guanandi (*Calophyllum brasiliense*), a species that has a large potential to be planted in tropical regions because of its potential high growth and its wood quality and to evaluate the influence of meteorological monthly seasonality on its growth. Volumetric was well adjusted with Schumacher-Hall model, with good fit indicators (R^2_{adj} = 0.89 and $S_{yx\%}$ = 9.74) and both for estimating the aboveground biomass and the plant compartments (leaves, branches and stem) the best fit model was Meyer's. The total wood volume obtained was 100 m^3 ha^{-1} and an average annual increment for the stand of 10.3 m^3 ha^{-1} $year^{-1}$ at 9.8 years of age. It was observed that the growth of *C. brasiliense* trees was influenced by meteorological seasonality, and the variation in its growth was better correlated with the subset of the variables maximum and minimum temperature, potential evapotranspiration, actual evapotranspiration and water deficit. From a practical point of view, the study shows that ongoing climate change is going to affect wood growth in this tropical region of Brazil, reducing the potencial of this tropical specie in Carbon sequestration.

Introduction

Species selection is one of the key decisions in the formation of pure even aged stands [24]. Globally, exotic species represent 44% of the total area of planted forests and in South America this value is even more representative (97%), influenced by the predominance of *Eucalyptus* and *Pinus* planted forests in Brazil, where the two genera occupy about 94% of the planted area of 10 million hectares [6].

Other genera have been planted as alternative mainly for the production of solid wood, such as species of the genera *Tectona*, *Khaya* and *Toona*. Among the native species, *Calophyllum brasiliense* is considered economically promising in planted forests mainly because of its highly resistant and durable wood, widely used in civil construction, carpentry and shipbuilding [15]. The species has a natural occurrence from Central America (18º N) to South America (28º 10' S). In Brazil, it is found in the Amazon, Cerrado and Atlantic Rainforest [32]. *C. brasiliense* has been studied in the seedling stage [19, 26] or in relation to its biochemical characteristics due to the fact that it has antioxidant characteristics [13] and even pharmacological compounds related to the HIV virus [18], but with rare studies reporting silvicultural aspects in adult stands, which are essential to identify the adaptation of the species to a given region.

The estimation of the volume and stock of biomass and carbon in trees and the population consists of the fundamental steps in the management planning of planted forests, being of great importance the application of methodologies that can generate accurate and reliable estimates of these dendrometric variables. Indirectly, volume and biomass can be obtained from allometric equations, derived from regression analyses. These mathematical models emerge as a practical and low-cost alternative to obtain accurate estimates of these variables.

It is important to highlight that among the main factors responsible for variations in production in forest stands during the cutting cycle are climatic variables (precipitation, air temperature, humidity, solar radiation, photoperiod and wind) [5], which, in addition to having a direct influence on the growth and future productivity of plantations, can lead to the occurrence of pests and diseases [14]. Air temperature and precipitation are the climatic variables that have the greatest influence on the diameter growth of several species from temperate and subtropical climates, in addition to tropical climates [22]. Thus, understanding the interaction of these natural factors with the growth of *C. brasiliense* in planted forests is essential for successful planting.

There is no record of studies that address the effects of climatic elements on planting conditions of *C. brasiliense*, which are essential for a better understanding of how this species develops depending on the conditions of the environment in which it is inserted, as they are also important for assist in the planning of silvicultural activities for future plantations. The present study aims to adjust allometric equations to estimate the volume and biomass of *Calophyllum brasiliense*, in addition to evaluating the influence of meteorological seasonality on its growth in planted forests in the northeast region of Brazil in the state of Pernambuco. Our hypothesis is that the variation in the growth of *C. brasiliense* will correspond to the seasonality of the meteorological variables and will be influenced mainly by the variables precipitation and temperature, as in studies in Eucalyptus, Pine and native rainforest species [7].

Methods

Site characterization

The present study was carried out in a commercial plantation of 2.5 hectares of the *Calophyllum brasiliense* species, implanted in May 2012. The study area is located in Pernambuco, Brazil, has an approximate altitude of 19.0 meters and is located at the geographical coordinates 7º 53'18" south latitude and 34º 59' 25" west longitude. The climate in the region is tropical hot and humid (Köppen's As'), the average annual precipitation is 1,634.2 mm and the average annual temperature is 24.9°C, with the rainy season starting in February and ending in October. Its relief belongs to the Coastal Tableland unit group that follows the coast of the entire Northeast [4].

The implantation of *C. brasiliense* seedlings in the study area took place in May 2012. Soil was cleaned and prepared by plowing the surface layer to a depth of 30 cm, in addition, the soil was corrected with dolomitic limestone (2.6 t ha^{-1}) and we applied phosphate fertilization with simple superphosphate (1 t ha^{-1}). When planting the seedlings, holes of 40 x 40 x 40 cm were opened in a spacing of 3 x 2 m and bovine manure was added at approximately 10 liters per hole.

Weeding was carried out whenever necessary until the fifth year to eliminate weeds and not harm the growth of seedlings, in addition to other silvicultural treatments such as the control of ants and termites. Manual irrigation was carried out until the third year of planting, in addition to annual soil chemical fertilization with 100 kg ha^{-1} of NPK 4-14-8 until the sixth year of planting. In addition, about 20% of the trees were thinned in June 2019. Soil was collected in October in 2021 for chemical analysis, revealing a typical soil used for forest plantation in Brazil, with low fertility and high acidity.

Measurements

For analysis of growth and productivity, measurements were taken from February 2021 to February 2022. Permanent plots were randomly allocated in the study area. In order to define the intensity of the necessary sample, a pilot inventory in eight plots was initially carried out. To analyze the sample sufficiency, the sample error was calculated, adopting an admissible error of 10% at a probability level of 95%.

With a measuring tape, plots of 400 m² (20m x 20m) were demarcated for measuring the height and diameter of the trees. The method used was the fixed area and the sampling process the simple casual, in which the plots were drawn randomly in the study area. The diameter at 1.30 m from the ground (DBH, in centimeters) of all individuals in the plot and total height (H in meters) were measured monthly.

Tree sampling for cubage and biomass sampling

A total of 53 trees were selected to carry out rigorous cubing and 12 trees to quantify the biomass using the destructive method. For the selection of sample trees, the criterion of diametric distribution by frequency of each class was used. The number of trees for rigorous cubage and biomass was proportional to the distribution of stand frequency by diameter class.

In the rigorous cubage, the analytical method was used through the Smalian procedure, where circumferences of the stem were measured in heights: 0 = ground, 0.30; 0.50; 0.70; 1.00; 1.30 m, after, every 1.0 meter to the top of the tree. The volume of each section was obtained using Eq. 1 and the tip volume was obtained using the cone formula (Eq. 2). The actual volume of each tree was obtained using Eq. 3.

$$v_i = \left(\frac{g_i + g_{i+1}}{2}\right) l$$

1

$$v_p = \frac{g_n l_p}{3}$$

2

$$T_V = \sum v_i + v_p$$

3

Where: TV = Total volume per tree (m³); g = calculated cross-sectional area (m²) from g = (πd2)/40,000, where "d" is the diameter of the section; v_i = section volume (m³); v_p = tip volume (m³); g_i = cross-sectional area at the beginning of the section (m²); $g_{(i+1)}$ = cross-sectional area at the end of the section (m²); gn = cross-sectional area at the base of the tip (m²); l_p = tip length (m); l = section length (m).

For biomass analysis, all tree compartments (stem, branches and leaves) were removed and weighed separately to obtain their total wet weight in the field using a scale with a maximum capacity of 100.0 kg and accuracy of 0.1 kg. Then, samples of 0.3 kg of leaves and branches were taken for subsequent determination of their dry weight.

For the stem, samples of wood discs with bark approximately 3.0 cm thick were taken for later determination of dry biomass. Discs were removed at different heights, at DBH, at the base (0% of the height of the stem), and at 25%, 50%, 75% and 100% (diameter of 2 cm) of the total height of the stem. Each disk had its green weight measured in the field with a precision scale of 0.1 kg.

For the determination of dry biomass, the dry weight of the samples (leaves, branches, discs) was determined by means of drying in a renewal oven and forced air circulation at a temperature of 65°C until reaching its constant weight (lesser difference than 0.5 g from one measurement to another). The dry biomass of tree trunks with bark, such as branches and leaves, was obtained using Eq. 4.

$$B_i = \frac{Pu\,(c) * Ps\,(a)}{Pu\,(a)}$$

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Where: i = the index that refers to the tree; B_i = the biomass of leaves, branches or trunk (kg); $Pu\,(c)$ = Total wet weight in the field (kg); $Ps\,(a)$ = Sample dry weight (kg); $Pu\,(a)$ = Sample wet weight (kg).

Adjustments of biomass and volume equations and wood growth

Equations of individual volume (V_i) and biomass (B_i) as the dependent variable were adjusted through regression analysis and DBH (Diameter at breast height at 1.30m from the ground (cm) of the i-th tree) and total height of the i-th treet (H_i) as independent variables. Six models were tested totaling 30 adjusted equations. The models tested for estimating volume and total dry biomass are presented below.

Meyer → $(V_i; B_i) = \beta_0 + \beta_1 . DBH_i + \beta_2 . DBH_i^2 + \beta_3 . (DBH_i . H_i) + \beta_4 . \left(DBH_i^2 . H_i\right) + \epsilon_i$ (5)

Schumacher-Hall →$(LnV_i; LnB_i) = \beta_0 + \beta_1 . Ln\,(DBH_i) + \beta_2 . Ln\,(H_i) + \epsilon_i$ (6)

Spurr → $(V_i; B_i) = \beta_0 + \beta_1 . (DBH_i^2 . H_i) + \epsilon_i$ (7)

Stoate → $(V_i; B_i) = \beta_0 + \beta_1 . DBH_i + \beta_2 . \left(DBH_i^2 . H_i\right) + \beta_3 . H_i + \epsilon_i$ (8)

Hohenadl-Krenn → $(V_i; B_i) = \beta_0 + \beta_1 . DBH_i + \beta_2 . DBH_i^2 + \epsilon_i$ (9)

Näslund → $(V_i; B_i) = \beta_0 + \beta_1.\left(DBH_i^2.H_i\right) + \beta_2.\left(DBH_i.H_i^2\right) + \beta_3.H_i^2 + \epsilon_i$ (10)

Where: *Vi* = Volume (m³) of the i-th tree; *Bi* = Total dry biomass (kg) of the i-th tree or i-th tree compartment; β_0, β_1, β_2, β_3, β_4 = Model coefficients; Hi = Total height (m) of the i-th tree; *DBHi* = Diameter at breast height at 1.30m from the ground (cm) of the i-th tree; *Ln* = Neperian logarithm; ε_i = Estimation error for i-th tree.

The choice of the best equations for estimating volume and biomass with the database under study was based on the adjusted coefficient of determination (R^2_{aj}); in the standard error of the relative estimate ($S_{xy\%}$) and in the graphical analysis of the residuals to verify the presence of bias in the estimates. The significance of the models was verified by calculating the F value considering a significance level (α – 0.05). Such adjustment and precision statistics are widely known in the forest environment [10].

Meteorological variables

Meteorological data were obtained from the National Aeronautics and Space Administration / Prediction of Worldwide Energy Resources - (NASA/POWER platform), from the geographic coordinates of the study area. To analyze the relationship between diametric growth and meteorological variables, daily data were obtained on an hourly scale for the entire study period of mean air temperature (T_{md}), maximum air temperature (T_{mx}), minimum air temperature (T_{mn}), air humidity (AH) and rainfall (R). Daily data were organized to correspond to the period of dendrometric measurements and compiled into the respective months of growth. With the meteorological data, the vapor pressure deficit (VPD) was calculated from the values of temperature and relative humidity of the air, used to determine the saturation pressure of water vapor in the air and the partial pressure of vapor d' water in the air (Tetens, 1930). The potential evapotranspiration (PET) of each period was calculated based on Thornthwaite's methodology [36]. The water balance was calculated based on an adaptation of the work by Thornthwaite & Mather [37, 25]. With this, the real evapotranspiration (AET), the surplus and the water deficit (WD) was estimated.

Statistical analysis

To analyze tree growth as a function of meteorological variables, monthly DBH measurements were performed, and the cross-sectional area was calculated (cm² tree^{-1}). The increment in sectional area was calculated by subtracting the measurement of the month considered and its previous one, and the cumulative increment was calculated by adding all the values of the monthly increments over the study period.

Multiple linear regression analysis was applied to estimate tree growth rate as a function of meteorological seasonality, according to Eq. 11[7].

$$\text{ITCSA} = \widehat{\beta}_0 + \widehat{\beta}_1 T_{md} + \widehat{\beta}_2 T_{mx} + \widehat{\beta}_3 T_{mn} + \widehat{\beta}_4 R + \widehat{\beta}_5 ETP + \widehat{\beta}_6 ETR + \widehat{\beta}_7 WD + \widehat{\beta}_8 DPV$$

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Where: ITCSA = Increment of Trunk Cross-sectional Area (cm² tree^{-1} month^{-1}); T_{md} = mean air temperature (°C); T_{mx} = maximum air temperature (°C); T_{mn} = minimum air temperature (°C); R = rainfall (mm); PET = corrected potential evapotranspiration (mm); AET = actual evapotranspiration (mm); WD = water deficit (mm); VPD = vapor pressure deficit (kPa); β_0 to β_8 are estimates of the adjusted regression equation coefficients.

Regression analysis of the best subsets was performed in order to obtain the best regression model, testing subsets of specified predictors, considering a probability of 5%. This analysis makes it possible to select the best subsets of variables to elaborate a given model with expressive precision. This procedure is called “bestsubsets”, present in the Minitab® software version 19, and allows identifying which variable(s) are sufficient for a better explanation of the response variable.

In addition to the adjusted coefficient of determination (R^2_{adj}), the root mean square error (RMSE) was used to assess the quality of the fit of the growth regression as a function of meteorological variables. To evaluate the performance of the regressions, a graphical analysis of the residuals was performed, thus making it possible to verify the presence of bias in the estimates.

Results

Volumetric and biomass equations

Values of the adjusted coefficient of determination varied between 76 and 89% and the standard error of the estimate varied between 9.21 and 11.84%, showing a good level of precision for individual volume estimates (Table 1). Model 5 (Hohenadl-Krenn) showed a lower quality of fit, with a lower adjusted coefficient of determination (R^2_{adj} – 0.76) and a higher standard error (S_{yx} – 11.84%). It can be observed that this is the only model based only on the DBH independent variable, suggesting that the DBH and height variables combined present a better correlation to estimate the volume.

Table 1
Estimates of the parameters of the equations tested to estimate the individual volume of *Calophyllum brasiliense* in a planted forest in Pernambuco, Brazil.

Models	Coefficients					R^2_{adj}	S_{yx}%	P value
	$\widehat{\beta}_0$	$\widehat{\beta}_1$	$\widehat{\beta}_2$	$\widehat{\beta}_3$	$\widehat{\beta}_4$			
(1)	-0,053011	0,003938	0,000107	0,000812	-0,000032	0,85	9,29	2,8E-20
(2)	-9,584021**	1,697182**	1,121157**			0,89	9,74	1,0E-24
(3)	0,006581*	0,000038**				0,84	9,77	4,7E-22
(4)	-0,081729*	0,007774*	-0,000003	0,005317**		0,86	9,21	2,7E-21
(5)	-0,138675*	0,024875*	-0,000700			0,76	11,84	9,0E-17
(6)	-0,012501	0,000065*	-0,000075	0,000687		0,84	9,62	2,3E-20

Where: R^2_{adj} = adjusted coefficient of determination; $S_{yx\%}$ = standard error of relative estimate in m³; β_0, β_1, β_2, β_3, β_4 = Model coefficients; P value - value of significance. Models of Meyer (1), Schumacher-Hall (2), Spurr (3), Stoate (4), Hohenadl-Krenn (5), Näslund (6).

For the choice of the most adequate model, the analysis of the coefficients and the goodness-of-fit statistics provide an important subsidy, however, these criteria alone do not guarantee a good conclusion about the performance of the models. Thus, for a better assessment of the quality of adjustments, the graphical distribution of residuals is observed [23]. Thus, in Fig. 1 it can be seen that the equations by Spurr (3) and Näslund (6) showed a slight tendency to overestimate the volume. The others had a good distribution of residuals, with no trends in the estimates.

Equation 2 (Schumacher-Hall) presented the best fit for the data set among the tested equations, with R^2_{adj} = 0.89 and $S_{yx\%}$ = 9.74, in addition to a satisfactory graphical distribution of residuals (Fig. 1), evidencing the selection of this model to estimate the volume.

The quality of the fit can also be verified by the relationship between the observed volume and the estimated volume (Fig. 2), with good overlapping of values throughout the data range for the equation with the best fit.

Biomass analysis

The results presented in Table 2 were obtained by calculating the average dry biomass for each compartment and for the total biomass of the sampled trees, the variations are expressed by the standard deviation and the coefficients of variation and the minimum and maximum values give an idea of the range of biomass values. It is observed that the greatest amplitude between the compartments occurred in the stem, where the variation between the maximum and minimum value was 19.01 kg, followed by the branches, with an amplitude of 17.16 kg and leaves of 7.05 kg. For total dry biomass, the range was 39.92 kg (Table 2).

The compartment with the greatest data variability in relation to the mean was the bole, with the highest standard deviation, but its coefficient of variation was lower, showing that its data set is more homogeneous. The compartments of leaves and branches showed lower values of standard deviation and high coefficients of variation, indicating a high heterogeneity in their datasets.

Table 2
Average values of total dry biomass and in the different compartments (Leaves, Branches and Stem), followed by the standard deviation, coefficient of variation (CV%), Maximum and Minimum weight in trees of *Calophyllum brasiliense* in planted forest in in northeast of Brazil.

Dry biomass (kg tree^{-1})					
Session	**Average**	**Standard Dev.**	**CV%**	**Max.**	**Min.**
Leaves	5,0	2,1	42,7	8,69	1,64
Branches	13,8	5,6	40,2	21,88	4,72
Stem	28,3	6,4	22,6	35,22	16,21
Total biomass	47,1	12,5	26,6	63,11	23,19

The highest concentration of above-ground dry biomass among the compartments *in Calophyllum brasiliense* trees is found in the stem, followed by the branches, while the leaves had the lowest amount (Table 2). In percentage terms, the above-ground dry biomass is distributed in the plants as follows: 60% in the stem, 29% in the branches and 11% in the leaves (Fig. 3).

The equations selected to estimate the leaf biomass showed unsatisfactory statistical adequacy, however, they were the ones that presented the best results among those that were tested, with the R^2_{adj} oscillating between 36% and 43%. The S_{yx} was high, ranging from 32.1–40.26%, indicating a low level of precision in the estimates of leaf biomass for all tested models (Table 3).

This was possibly due to the irregularity in the architecture of the tree canopies, causing a high heterogeneity in the leaf biomass among the trees. This fact can be observed by the high coefficient of variation (Table 2). Meyer's model (1) had the best fit among those analyzed to estimate leaf biomass, with the best graphical distribution of residues (Fig. 4), however, it did not show satisfactory fit indicators.

Table 3
Estimates of the parameters of the equations tested to estimate the total biomass and the different compartments (Leaves, Branches and Stem) in *Calophyllum brasiliense* trees in a planted forest in in northeast of Brazil.

Compar-timentos	Modelo	Coeficientes					R^2_{adj}	S_{yx}%	P value
		$\widehat{\beta}_0$	$\widehat{\beta}_1$	$\widehat{\beta}_2$	$\widehat{\beta}_3$	$\widehat{\beta}_4$			
Leaves	(1)	240,573	-80,062	5,286	4,106*	-0,368*	0,43	32,10	0,091
	(2)	-6,645	-0,379	4,130			0,37	40,26	0,051
	(6)	-47,024	0,092	-0,221	1,845		0,36	34,19	0,093
Branches	(1)	810,576*	-261,483*	17,166**	12,772**	1,158**	0,64	24,25	0,022
	(2)	-4,761	-0,212	3,558			0,32	38,99	0,072
	(6)	$^{-1}$55,274*	0,320*	-0,754*	6,108*		0,54	27,28	0,027
Stem	(1)	109,407	-56,997	4,216	4,390	-0,365	0,87	8,26	0,001
	(4)	$^{-1}$65,863*	14,167	-0,057	11,273*		0,86	8,33	0,000
	(6)	-80,403*	0,166*	-0,381	3,307*		0,86	8,51	0,000
Total biomass	(1)	1160,555*	-398,542**	26,668**	21,267**	1,891**	0,87	9,67	0,001
	(2)	-3,060	0,500	2,585*			0,70	18,31	0,002
	(6)	-282,701**	0,578**	$^{-1}$,356**	11,260**		0,83	10,99	0,001

Where: R^2_{adj} - adjusted coefficient of determination; $S_{yx\%}$ - standard error of relative estimate in m³; β_0, β_1, β_2, β_3, β_4 = Model coefficients; P value - value of significance; Models of Meyer (1), Schumacher-Hall (2), Stoate (4), Näslund (6).

For the dry biomass of branches, the adjusted coefficient of determination ranged from 32 to 64%. All models showed high $S_{yx\%}$ and modest R^2_{adj}. Models (1) and (6) were significant at the 5% probability level by the F test, while model (2) was not significant, indicating a low correlation of its independent variables with the dependent variable.

The best fit model for dry biomass of branches was Meyer's (1), with a more homogeneous graphical distribution of residues (Fig. 4), however, it presented reasonable fit indicators, therefore, it can be stated that the biomass estimates for twigs are modest, so their use requires parsimony.

To estimate the stem biomass, the models with the best performance showed good adjustment indicators, considering the R^2_{adj} and $S_{yx\%}$, with very close values, ranging from 86 to 87% and 8.26 to 8.51%, respectively (Table 3). The model that best fitted the data was again Meyer's (1), which presented a graphical distribution of residuals without trends (Fig. 4) and better performance in the adjustment indicators, with a higher adjusted coefficient of determination (R^2_{adj} – 0.87) and the lowest standard error of the estimate ($S_{yx\%}$ – 8.26%) among the tested models.

In estimating the total dry biomass, it can be seen that, among the models with the best fit, model (2) was the one that presented the lowest quality in the estimates, that is, the lowest adjusted coefficient of determination and the highest standard error of the estimate (Table 3). Comparing models (1) and (6), the model by Meyer (1) was shown to be more appropriate due to the adjustment indicators, with a higher adjusted coefficient of determination (R^2_{adj} – 0.87) and a lower standard error of the estimate ($S_{yx\%}$ – 9.67), in addition to a more balanced graphical distribution of residuals (Fig. 4). In addition, model (1) met the statistical criteria, with a significant F value at 1% significance, and can be used to estimate the total dry biomass for the *C. brasiliense* population.

Influence of climatic variables on growth

The increment in trunk cross-sectional area (ITCSA) of *Calophyllum brasiliense* varied over the study period and showed influence of meteorological variables (Fig. 5b). The lowest current monthly growth rate (ITCSA < 0.4 cm² per tree) occurred in March/2021 and in the period from September/2021 to February/2022) (Fig. 5b). At the same time, less precipitation and negative water balance were observed in this period, causing water deficit in the soil, consequently causing a decrease in growth.

During the evaluation period, the greatest growth in trunk cross-sectional area (TCSA) occurred from April 2021 to August of the same year (Fig. 5b). It was during this period that the highest monthly rainfall occurred and it is observed that these are months that did not show water deficit in the soil (Fig. 5c).

The month with the highest TCSA increment was April 2021 (ITCSA = 2.32 cm² $tree^{-1}$). It was seen that this is the first month that there is no water deficit in the soil after a few months with a negative water balance, causing a quick response from the trees, obtaining greater growth (Figs. 5b and c).

This fact can also be attributed to the rehydration of the trunk, since during the driest periods (Fig. 5e) it may have contracted, due to the higher temperatures and low relative humidity of the air that this region presents during the dry period.

A low variation in the average temperature, monthly maximums and minimums was observed throughout the period of analysis, however, it was seen that the lowest average temperatures of the maximums occurred between the months of April to October 2021, a period in which the greatest increase was observed cumulative TCSA of the plants. Similar behavior is seen with the VPD, during this period lower VPD and greater accumulated increment were observed (Fig. 5a to d).

According to the multiple linear regression analysis, it was possible to verify that subsets 4 and 5 presented the best adjustment statistics with higher adjusted determination coefficients and smaller errors (Table 4). To assess the quality of the growth regression, a graphical distribution of the residuals was performed (Fig. 6), thus, it was possible to observe the presence of bias in the estimation by the models. It was observed that subsets 3, 5 and 6 tend to underestimate the TCSA growth, while subset 2 showed a tendency to overestimate the increment. Subsets 1 and 4 showed no trend in estimating growth.

Table 4
Estimates of multiple regression parameters between trunk cross-sectional area growth versus climatic data and statistical indices of *Calophyllum brasiliense* in planted forest in Pernambuco, Brazil.

Subsets	$\widehat{\beta}_0$	**T_{md}**	**T_{mx}**	**T_{mn}**	**R**	**PET**	**AET**	**WD**	**VPD**	**R^2_{adj}**	**RMSE**	**F**
	(cm² $tree^{-1}$)	**(°C^{-1})**			**(mm^{-1})**				**(kPa^{-1})**			
1	19,556		0,885**			-0,062*	0,021**			0,69	0,29	0,006
2	19,134		0,858*		0,002	-0,059*	0,019*			0,66	0,28	0,018
3	18,718	1,489	2,193		0,006	-0,070*	0,019*			0,69	0,25	0,027
4	24,727		3,935**	3,263*	0,019*	0,151**	0,039**	0,020*		0,89	0,14	0,004
5	24,508		3,834**	3,176*	0,019*	0,161**	0,045**	0,021*	1,821	0,89	0,12	0,012
6	23,283	3,057	2,933	-5,473	0,022	-0,165*	0,049*	0,022*	1,948	0,86	0,41	0,046

Multivariate Equation: ITCSA = $\widehat{\beta}_0 + \widehat{\beta}_1 T_{md} + \widehat{\beta}_2 T_{mx} + \widehat{\beta}_3 T_{mn} + \widehat{\beta}_4 R + \widehat{\beta}_5 PET + \widehat{\beta}_6 AET + \widehat{\beta}_7 WD + \widehat{\beta}_8 VPD$. ITCSA - trunk cross-sectional area increment (cm² $tree^{-1}$ $month^{-1}$); T_{md} - mean air temperature (°C); T_{mx} - maximum air temperature (°C); T_{mn} - minimum air temperature (°C); R - rainfall (mm); PET - potential evapotranspiration (mm); AET - actual evapotranspiration (mm); VPD - vapor pressure deficit (kPa); $\widehat{\beta}_0$ to $\widehat{\beta}_6$ are coefficients of the multivariate regression equation; R^2_{adj} - adjusted coefficient of determination; RMSE - Root Mean Square Error; P value - value of significance.

Thus, subset (4), ITCSA = -24.72682 + 3.93539 (T_{mx}) -3.26276 (T_{mn}) + 0.01888 (R) -0.15052 (PET) + 0.03947 (AET) -0.02002 (WD) was the best to explain the variation in the growth of *Calophyllum brasiliense*, which showed a significant relationship ($P < 0.01$), with an adjusted coefficient of determination (R^2_{adj} – 89%) and root of Mean Squared Error (RMSE – 0.14). According to the distribution of residues, there was no tendency to estimate growth (Fig. 6).

Discussion

There is limited literature available on the adjustment of volumetric models for *Calophyllum brasiliense*. In the present study, volumetric modeling yielded satisfactory results with R^2_{adj} and $S_{yx\%}$ values comparable to those found in previous research on *Hymenea courbaril* and *Tectona grandis*[23, 10]. A study conducted in Dueré (Tocantins, Brazil) [32], adjusting volumetric equations for *Calophyllum brasiliense* at 94 months of age reported even better results. These differences can be attributed to the heterogeneity of stands, including edaphoclimatic characteristics and planting conditions, underscoring the importance of adjusting volume equations for specific regions or populations with similar characteristics.

The Schumacher-Hall model was found to have the most satisfactory performance for estimating the individual volume of *Calophyllum brasiliense* in this study. Similar findings have been reported for the same species in the region [33]. The Schumacher-Hall model is widely used in estimating individual volume in commercial plantations of forest species, particularly in genus *Eucalyptus* and *Pinus*, as demonstrated in previous studies [31, 34]. However, when it comes to biomass allocation, information for *C. brasiliense* is scarce, making this study one of the pioneering attempts to apply biomass modeling to this species. It is worth mentioning that other studies, faced challenges in obtaining good adjustments for leaves and branches, similar to the findings in the present study. However, satisfactory adjustments were achieved for stem and total biomass [3].

Leaf biomass showed the poorest performance among all compartments. This result aligns with the findings for *Eucalyptus*[17], who also observed the lowest determination coefficient for foliage, lower than that reported in the present study. In a study on *Tachigali vulgaris* in Dom Eliseu (PA) [11], identified Meyer's equation as one of the top three equations for estimating total biomass and different compartments of the plant, similar to the results of this research.

The individual modeling of *Calophyllum brasiliense* biomass holds significance in several aspects. It enables quantification for the non-wood products industry, particularly the pharmaceutical industry, which has shown great interest in this species due to its chemical composition and various properties such as analgesic, antiviral, and anticancer effects [18]. Additionally, obtaining biomass data for different tree compartments is crucial for estimating carbon stock, a vital aspect of carbon sequestration projects. These projects require accurate projections of carbon stock, closely linked to the biomass of different plant compartments.

The present study, along with research conducted in a commercial Eucalyptus plantation in Boa Esperança do Sul, São Paulo – Brazil [8], reveals that the growth rate of the trunk's sectional area is influenced by meteorological variables. The period of lowest growth coincided with the lowest precipitation and negative soil water balance. In the study area, the highest average maximum temperature corresponded to the lowest precipitation period, resulting in reduced water availability in the soil and water deficit, leading to a decrease in the trunk's cross-sectional area growth.

Transpiration is directly regulated by stomata and water vapor in the air, through the interaction between leaves and air. In tree species, the negative impact of VPD on stomatal conductance reduces CO2 absorption, carbohydrate production, and stem growth [21]. During the dry season in a study with Eucalyptus, Pinus and species native to the tropical forest [7], a smaller growth of TCSA was observed, corroborating the findings of the present research. Water availability in the soil is the primary restriction on plant growth, and mechanisms related to water availability play a significant role in nutrient and light capture by trees, influencing growth over the years.

The study observed a rapid response from plants soon after the onset of the rainy season during their study period, resulting in the highest growth rates of TCSA [8]. This rapid recovery in trunk diameter was attributed to hormone and carbohydrate production, distributed along the phloem, which induced cell division in the cambial layer and consequently increased trunk diameter. Additionally, the rehydration of the trunk, which may have contracted during the dry season, contributed to this growth. Evaluating growth in relation to meteorological seasonality within the growth year is crucial for understanding production limits and assisting in decision-making regarding the most suitable locations and performance of specific species for future planting plans.

Simulations indicate the potential occurrence of climate changes in South America [39], including variations in rainfall distribution and amount, as well as temperature increases. If confirmed, there is a high probability that the productivity of forest plantations in the study region will be negatively affected. Therefore, improving our understanding of how *Calophyllum brasiliense* responds to meteorological variables is essential for long-term planning of future plantations in the region.

Conclusion

Schumacher-Hall model is identified as the most satisfactory for estimating individual volume in *Calophyllum brasiliense*. However, foliage biomass modeling proves to be challenging, with lower performance compared to stem and total biomass. The individual modeling of biomass is crucial for various purposes, such as supplying raw materials for non-wood products and estimating carbon stock for carbon sequestration projects. Meteorological variables, particularly temperature and precipitation, significantly influence the growth of *Calophyllum brasiliense*, with high temperatures and water deficit limiting plant growth. Understanding the relationship between meteorological variables and growth patterns is essential for future plantation planning, especially considering the potential impacts of climate change on forest productivity in the study region.

Declarations

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Plant material statement

We declare we comply with all institutional, national, and international guidelines and legislation about plant material used in this study.

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Author contributions

Data collection: W.C.F.; L.P.S.; M.C.B.L.; J.C.S.; I.G.M. Data processing and analysis: W.C.F.; R.E.H. Manuscript writing: W.C.F.; R.E.H.; L.P.S., with contributions from all authors. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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Figures

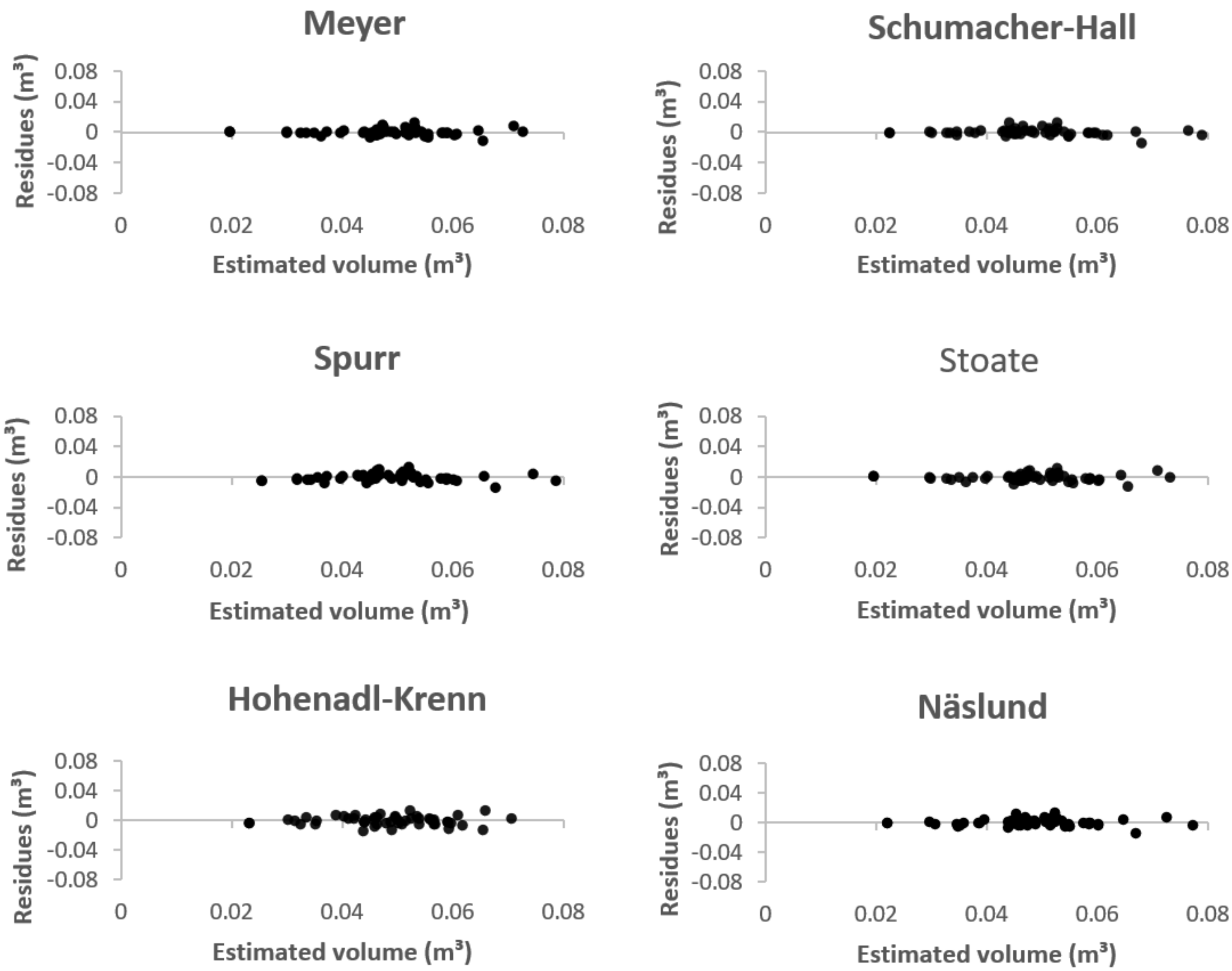

Figure 1

Graphical distribution of the residues of the tested models for the estimates of the individual volume of *Calophyllum brasiliense*.

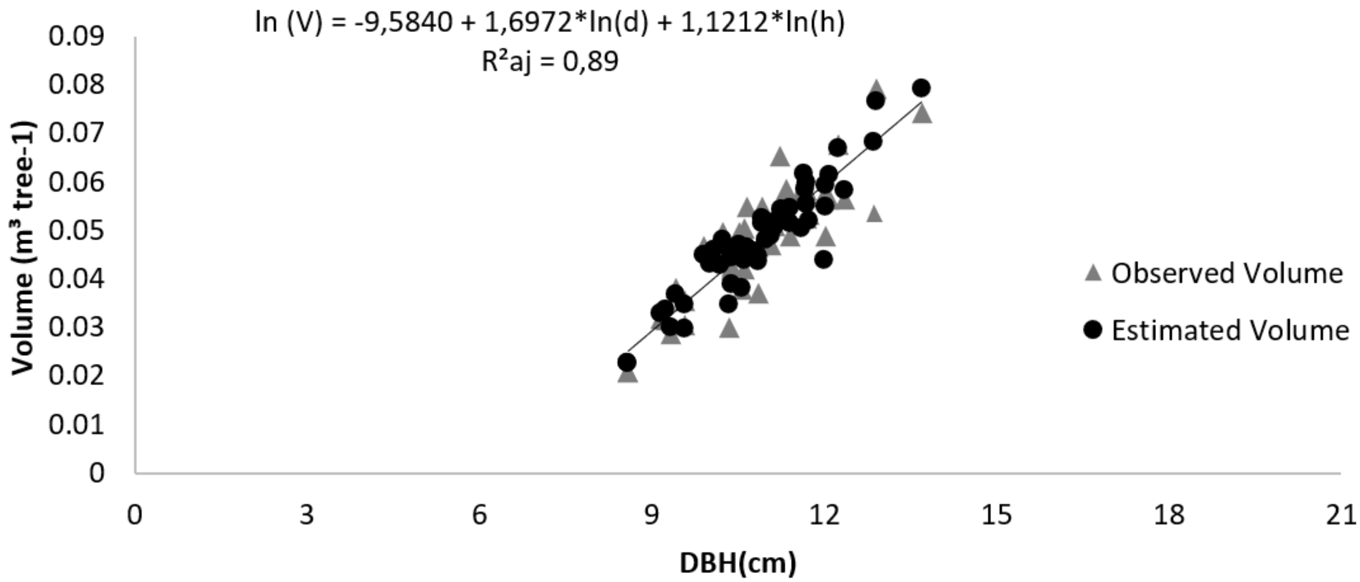

Figure 2

Best fit equation (Schumacher-Hall) with observed and estimated values *for Calophyllum brasiliense* in planted forest in northeast of Brazil.

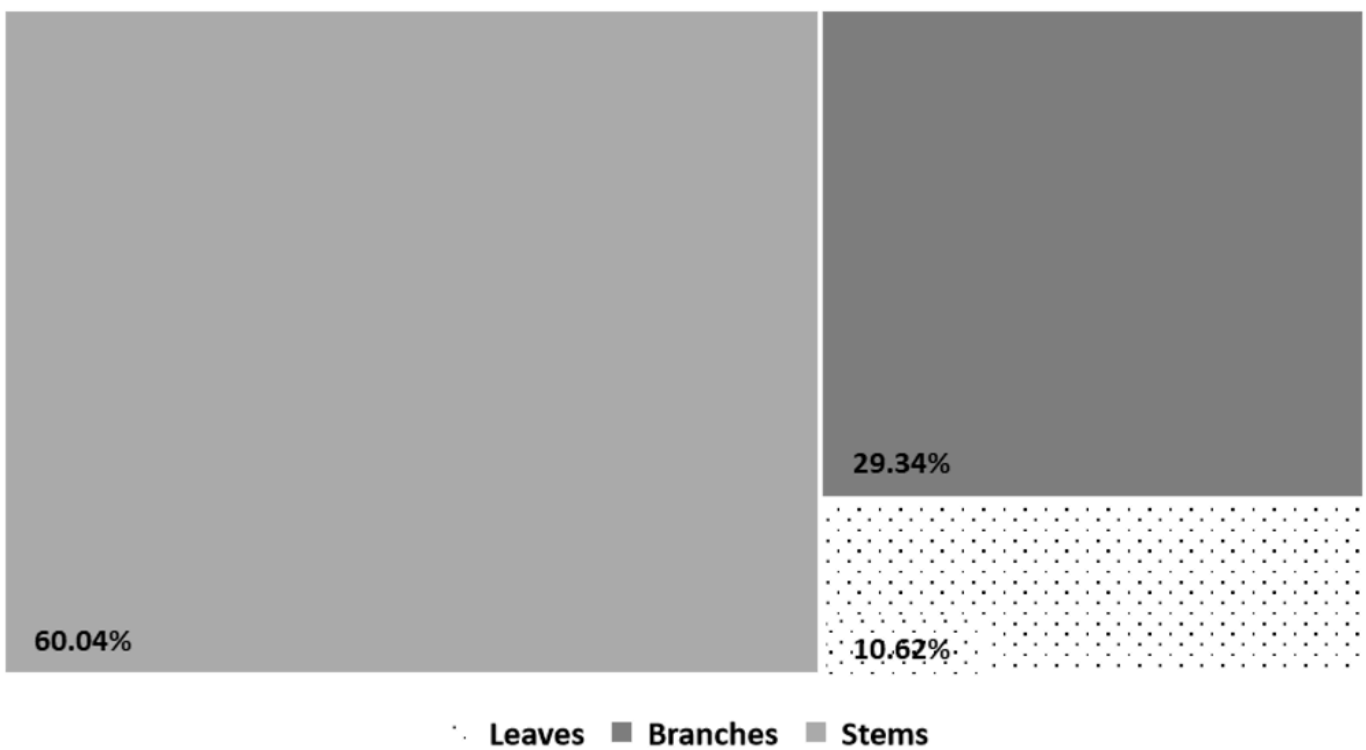

Figure 3

Relative distribution of above-ground dry biomass between compartments in *Calophyllum brasiliense* trees in a planted forest in the northeast of Brazil.

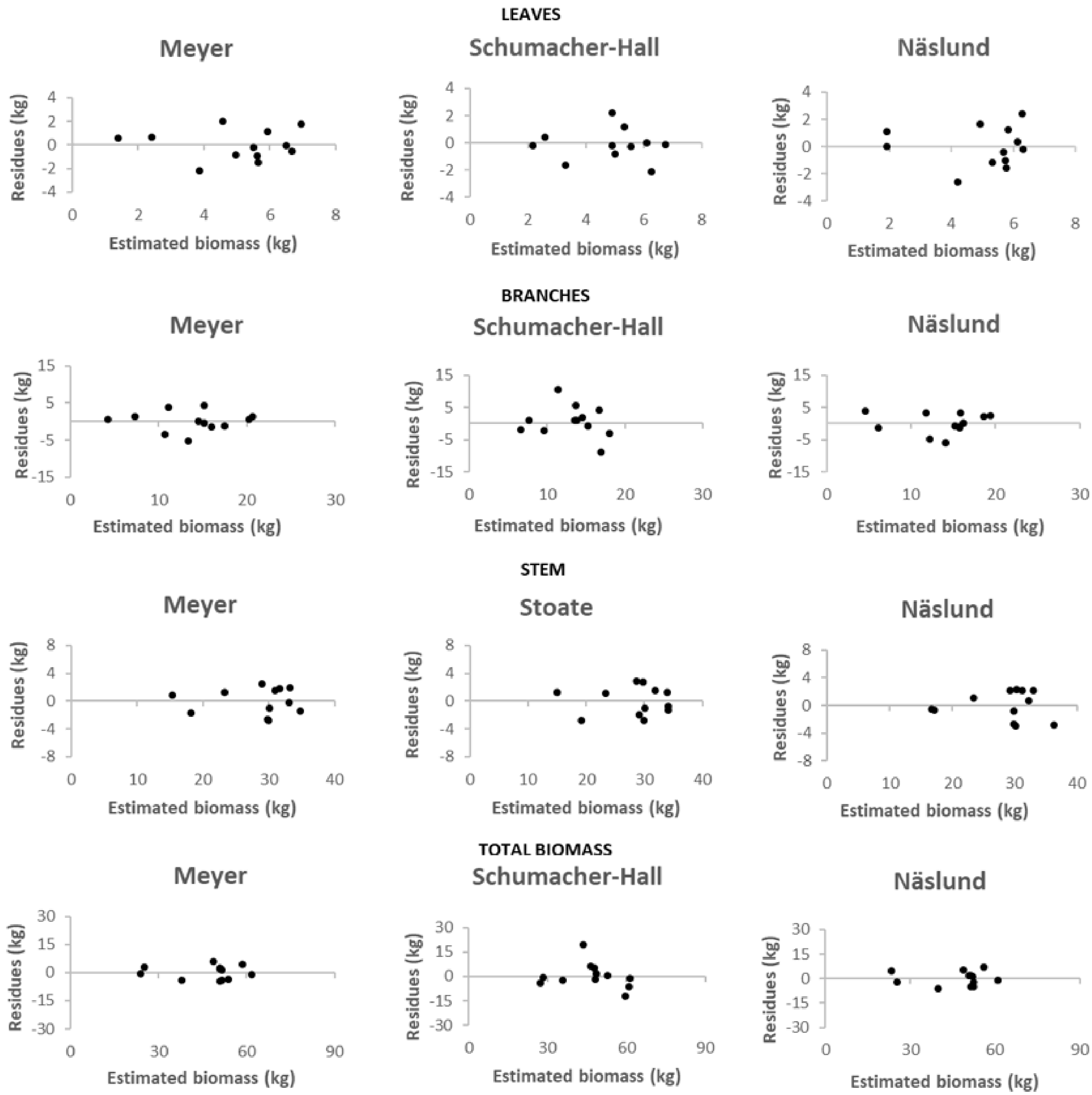

Figure 4

Graphical distribution of the residues of the best fit models to estimate the total dry biomass and the different compartments of *Calophyllum brasiliense* in a planted forest in in northeast of Brazil.

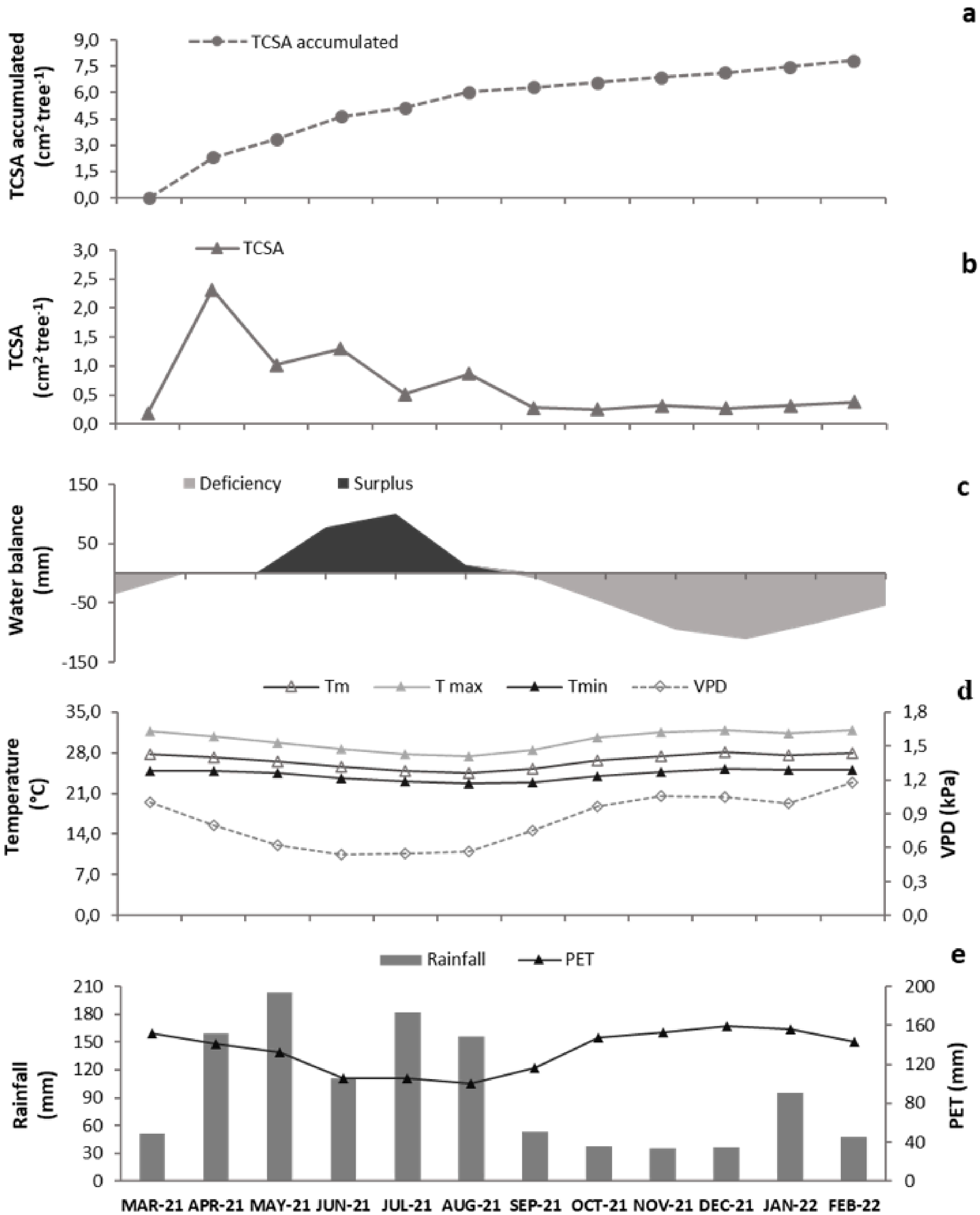

Figure 5

Growth of the cross-sectional area of the accumulated (a) and current (b) stem of *Calophyllum brasiliense*, sequential water balance (c), temperature and vapor pressure deficit (d) and rainfall and evapotranspiration (e) (from top to bottom) in in northeast of Brazil.

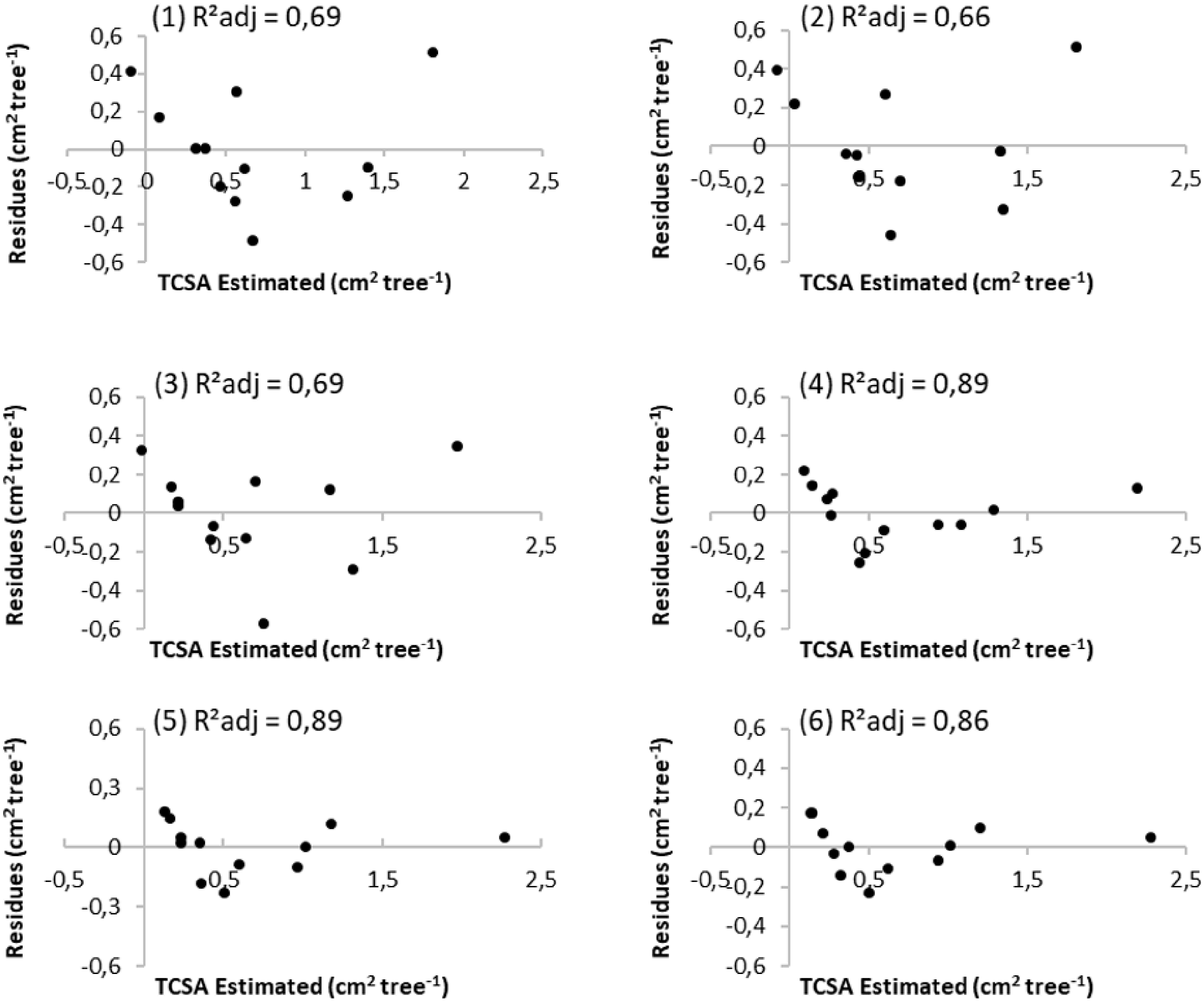

Figure 6

Graphical distribution of the residues of the best subsets to estimate the variation of the monthly Trunk Cross Section Area Increment (ITCSA) of *Calophyllum brasiliense* in a planted forest in Pernambuco, Brazil.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table.docx
- DataColophyllumFerreira.xlsx