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# Carbon accumulation in cultivated macauba trees can be estimated and projected using allometric equations

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ABSTRACT

This study aimed to propose the first allometric equations to estimate total carbon accumulation (below-ground and above-ground biomass) and project this variable for a 30-year commercial cycle of the macauba palm *(Acrocomia aculeata)*. These proposals are crucial for promoting the sustainable expansion of macauba cultivation, supporting studies on carbon credits and global climate change mitigation. We measured the total height, canopy diameter, and the total number of palm leaves of macauba seedlings aged eight months and palms aged 19, 58, 108, and 176 months growth in the field. Following destructive sampling, we obtained the biomass and carbon accumulation for both above-ground and root biomass. Our results support that the carbon accumulated (C1) in macauba palms can be estimated by the total height (h1) during the first 176 months of cultivation by the equation: C1 = 0.127580 h1ˆ3.078920 (RMSE: 7.72). The relationship between the current total plant height (h1) and current age (A1) can be defined by the equation: h1 = 14.198301 (0.984995 – eˆ- 0.012666A1) (RMSE: 0.87). We propose a model that is applicable to different regions and allows to estimate over a 30-year cycle the future carbon accumulation (C2) at each age (A2) based on the current total height (h1) and the current age (A1), using the equation C2 = 0.127580 {h1[(0.984995 - eˆ- 0.012666A2) / (0.984995 - eˆ-0.012666A1)]} ˆ3.078920. For all equations, height is in meters, age in months, and carbon mass accumulation is kg per plant.

## 1. Introduction

Estimating carbon accumulation across diverse plant species is of significant interest, especially to discussions involving global climate change and the opportunity to market carbon credits associated with clean development mechanism (CDM) projects (Rutishauser et al., 2013; Cassol et al., 2016; Diédhiou et al., 2017; Rao et al., 2017; Mohamed et al., 2018; Prayogo et al., 2018).

In order to quantify carbon stocks in the different compartments of the vegetation (litter, branches, trunks, leaves, roots), it is necessary to know the biomass of each of these components (Salomão et al., 1996). Biomass is the quantification of the matter of biological origin, living or dead, animal or vegetable (Silveira et al., 2008), which can be described as fresh mass or dry matter (Caldeira, 2003).

Two methods of quantifying plant biomass are commonly found in the literature. The direct (destructive) method, regarded as standard, requires destructive collection of the plant and subsequent formulation of the total mass of its different compartments. Due to its operational characteristics, it is considered a laborious and time-consuming method. The indirect (non-destructive) method delivers faster estimates without the plant's demise, and consists of the use of allometric equations that correlate plant biomass with one or more variables that are easily measurable in the field (Higuchi and Carvalho, 1994; Ratuchne et al., 2016).

The indirect method has been used in a variety of studies to estimate plant biomass and carbon in several plant species, which has facilitated a number of carbon stock studies. In palm trees, this method has been applied to the oil palm plants - *Elaeis guineensis* Jacq. (Aholoukpè et al., 2013; Asari et al., 2013; Khasanah et al., 2015), in addition to babaçu -

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*Attalea speciosa* C. (Gehring et al., 2011), pinang nut - *Areca catechu* L. (Prayogo et al., 2018), and in generalizations encompassing various palm trees (Goodman et al., 2013).

Palm trees (palms) are widely distributed throughout tropical and subtropical regions in the world (Dransfield et al., 2008). Their considerable ecological and economic potential (Eiserhardt et al., 2011) and in particular the presence of oil, starch, vitamins and proteins in the fruits of many of their species, which also offer the possibility of palm heart extraction (Clement et al., 2005), are worth investigating. Thus, this group of plants is an important source of food for human consumption (Lorenzi, 1996), as well as the fruits produced by a number of species are attractive to the fauna (Faustino and Paula, 2014).

The main predictor variables in allometric equations used in assessments of the accumulated palm tree biomass are the height of the main shoot, the total height of the plant, and the diameter of the stem. Findings based on the first two parameters, either alone or combined, often yield the best results (Gehring et al., 2011; Goodman et al., 2013; Syafinie and Ainuddin, 2013; Silva et al., 2015; Cassol et al., 2016; Prayogo et al., 2018).

The accumulation of biomass makes it possible to estimate the amount of carbon stored by the plants. This information is pertinent to an assessment of the role of vegetation in the context of global climate change as a carbon sink and has already been proven in studies on various palm species (Khasanah et al., 2015; Prayogo et al., 2018). However, they do not take into account an important species of palm that has been a recent focus of research, namely, macauba (*Acrocomia aculeata* Mart.).

The macauba palm is native to the tropical region of the Americas (Dransfield et al., 2008), naturally occurring from Brazil to México (Henderson et al., 1995) and has considerable potential for economic use since its fruit has a high oil content, which is a source of raw material for biodiesel production (Dias et al., 2011) and other products. Macauba is characterized by excellent drought resistance (Motoike et al., 2013; Souza et al., 2017) and its ability to grow in degraded areas (Mota et al., 2011), which gives it special attributes for scenarios with reduced water availability and degraded soils, as predicted by climate change models for large parts of the world.

So far, there are only two studies in literature, that reported on biomass and carbon accumulation of macauba (Tolêdo, 2010; Ferreira et al., 2013). Both studies were conducted in areas where Macauba occurs naturally, without developing allometric equations from the data collected. Therefore, this important tool for understanding the carbon sequestration of this palm is missing, which is hampering work on its carbon sequestration potential, with production currently increasing in relation to the area under cultivation. Allometric equations represent the most widely used method for quantifying carbon accumulation in cultivated and forested areas (Mohamed et al., 2018), forming the basis for certifying many carbon credit projects worldwide (Verra, 2024). In this context, the present study aimed to generate allometric equations to estimate carbon accumulation in commercial macauba plantations in Brazil.

## 2. Materials and methods

### *2.1. Study area*

The study was carried out in 2018 in the municipality of Araponga, in the state of Minas Gerais, Brazil, in an experimental area located at coordinates 20° 39' 6" S and 42° 32' 14" W, at an altitude of 839 m.a.s.l, with a mean annual temperature of 18 °C and annual average rainfall (mean annual rainfall) of 1338 mm (Rueda, 2014). The soil in the experimental area was classified as "Latossolo Vermelho-Amarelo Alumínico argissólico", according to the Brazilian Soil Classification System (Santos et al., 2018), which corresponds to an Ferralsol class in the World Reference Base (WRB-FAO, 2015).

In the field, macauba palms were planted at spacing of 5 m x 5 m and annually received maintenance fertilization according to the soil analysis and recommendation (Pimentel et al., 2011). No supplemental irrigation is provided. Macauba seedlings were cultivated in substrates, and the chemical and physical characteristics of the substrate and soil of the experimental area were presented in the literature (Moreira et al., 2019).

### *2.2. Criterion for selection of representative plants*

For this study, macauba plants (*Acrocomia aculeata*), aged 8, 19, 58, 108, and 176 months were selected. The youngest age group comprises palm tree seedlings cultivated in a nursery, while the others were grown under field conditions.

The selection criterion for a representative palm of each age group was based on the average total height, measured from 20 plants per age group using a graduated ruler in the nursery and a telescopic rod in the field. This average height was used to choose the individual plants used in this study to be collected destructively.

The low standard deviation values for total height (ranging from 0.02 to 1.12 m) across the 20 measurements per age group (Table 1) and the consistency observed in subsequent analyses provide reliability in the results.

### *2.3. Measurements in the selected plants*

Each pre-selected representative plant, ranging in age from 8 to 176 months, was evaluated through destructive sampling. Measurements included total height (m), crown diameter (m) (Fig. 1), total number of leaves, and cultivation age.

The total height of the macauba palms (distance from the base of the stem to the maximum curvature of the highest expanded leaf) was measured with a graduated ruler in the seedlings and a telescopic rod in the field (Fig. 1). The crown diameter was obtained with a tape measure. The total number of leaves was counted after the destructive sampling of the selected palms.

### *2.4. Destructive collection of plants and estimates of total dry matter and accumulated carbon*

Following the cutting of each pre-selected representative palm, the fresh biomass was separated into leaves (including leaflets, rachis, petiole, and sheath), stem (the compartment located between the soil surface and the meristem), bunch (comprising fruit, rachis per bunch, rachilles), and roots. The root systems of the 19-, 58-, 108-, and 176-month-old plants were collected in the macauba crown-projection areas and up to the maximum growth depth of roots in each age group, which corresponded to depths of 0.6, 1.0, 1.4, and 2.2 m, respectively, under field conditions (Moreira et al., 2019).

The root system of the seedling stage (8 months) was evaluated in the nursery after total substrate removal and root washing with tap water (Moreira et al., 2019).

After the collection and separation of the four compartments, all plant material was weighed in the field to obtain the fresh mass. Representative subsamples of known mass were sent to the laboratory to obtain the dry matter, which was determined after drying in a forced circulation oven at 65°C to constant weight. To ascertain the stem moisture, subsamples were collected from five sections: base and position corresponding to 25 %, 50 %, 75 %, and 100 % relative to the compartment height. In each of these positions, cross-sectional discs,

**Table 1**
Average total height of macauba (*A. aculeata*) palm age groups (n = 20) growth in Araponga (MG).

| Age group (months) | Environment | Total Height (standard deviation) (m) |
|---|---|---|
| 8 | Nursery | 0.93 (0.02) |
| 19 | Field | 2.80 (0.14) |
| 58 | Field | 7.26 (0.86) |
| 108 | Field | 10.28 (0.99) |
| 176 | Field | 12.50 (1.12) |

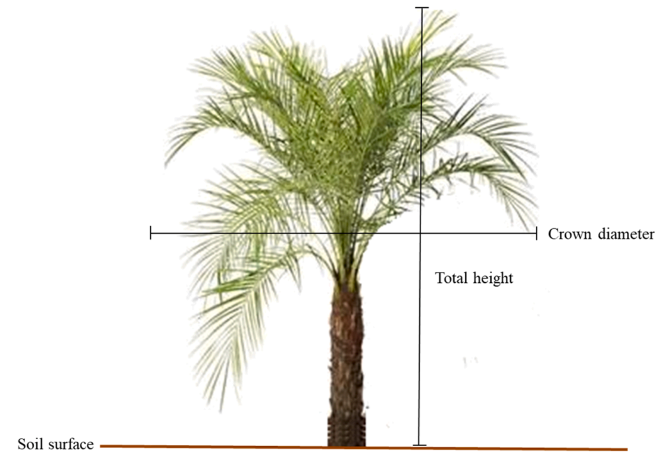


**Fig. 1.** Illustration how total height and crown diameter of macauba (*A. aculeata*) plants were measured in the field.

0.05 m thick, were removed and weighed to obtain fresh mass and, after drying in the oven to constant weight, its dry matter.

The dry matter of each compartment was ascertained by the formula: *DM* = *TFM** 1-[(*FMs-DMs)/FMs*], where *DM* is the dry matter of each compartment of the plant; *TFM* is the total fresh mass of each compartment of the plant; *FMs* is the fresh mass of subsamples of each compartment of the plant; and *DMs*, dry matter of the subsamples of each compartment of the plant after oven drying at 65 °C. The total dry matter of each individual palm was ascertained by summing up the dry matter values of each compartment sampled. The carbon content in each compartment of the macauba plants was determined by the calcination method in a muffle furnace at 500 °C for three hours (Carmo and Silva, 2012). For this process dry, previously milled subsamples of each compartment of the palm tree were passed through 2 mm mesh sieve.

The carbon accumulation in each compartment was obtained by multiplying the carbon content by the dry matter of the respective structure. On the other hand, total carbon accumulation was obtained by summing up the carbon accumulation values in each compartment sampled.

### 2.5. Adjustment of the allometric model

In order to adjust the allometric model of total carbon accumulation in macauba plants, the following independent variables were considered individually: plant age, total height, total number of leaves and crown diameter.

The allometric model (Eq. 1) was adjusted in accordance with the independent variables described previously (*x*):

$$y = \beta_0 x^{\beta 1} + \varepsilon \quad (1)$$

where: *y* is the dependent variable (carbon accumulation); $\beta_0$ and $\beta_1$ are parameters to be estimated; *x* is the independent variable (plant age, total height, total number of leaves and crown diameter); and $\varepsilon$ is the random error, $\varepsilon \sim NID(0, \sigma^2)$.

This model is considered parsimonious (Seasholtz and Kowalski, 1993) and meets the demand for simpler allometric models. It is based on a few variables that are easy to obtain and effectively represents the trend of increasing carbon production over time, bringing a balance between simplicity and efficiency. This is a key factor in facilitating the model interpretation and, consequently, its application. The independent variable (*x*) best linked to carbon in the adjusted equation was selected based on the values of the correlation coefficients (*r*) between the observed (*y*) and estimated ($\hat{y}$) carbon, root mean square error (*RMSE*) (absolute and percentage), and, mainly, in the consistency between the observed values and adjusted curves.

In addition, we propose an equation to estimate the palm tree's total height based on the plant's age and expressions based on allometric equations to project carbon accumulation for future ages of cultivation, considering a 30-year cycle, which corresponds to the crop's commercial cycle considered nowadays by Brazilian companies.

## 3. Results

### 3.1. General characteristics of the macauba palms collected

The values of all the measured variables for each plant studied are described in Table 2. The macauba palms presented a total height from 0.9 to 12.5 m, crown diameter from 0.72 to 6.42 m, and a total number of leaves from 4 to 65 leaves. The dry matter accumulation in the macauba plants ranged from 0.174 kg for eight-month-old seedlings to 549.40 kg for the 176-month-old plants, corresponding to a carbon accumulation of 0.094 kg and 308.13 kg, respectively.

### 3.2. Allometric equations for carbon accumulation of macauba palms

The allometric equations obtained for estimating the carbon accumulation for each independent variable indicated that the model efficiently describes the carbon accumulation response in relation to the variables analyzed (Fig. 2). Other details of this estimative procedure are provided in the supplementary material. All the equations obtained from the independent variables tested were able to appropriately describe the relationship with the carbon accumulation through the power function model (Fig. 2), with emphasis on the variableś age (Fig. 2A), total height (Fig. 2B), and total number of leaves (Fig. 2C), which presented lower RMSE values in comparison to the crown diameter variable (Fig. 2D).

### 3.3. Allometric equations for total height of macauba palms

For situations where measuring plant height in the field is not feasible, the equation $h = 14.198301(0.984995 - e^{-0.012666A})$ can be used to estimate total height in meters (*h*) by substituting the age (*A*) in months. Fitting this equation resulted in a 97.3 % correlation between observed and estimated heights, with an RMSE of 0.87. This equation was derived from data on 20 plants measured in the field at the ages of 19 (1.58 years), 58 (4.83 years), 108 (9.0 years), and 176 (14.67 years) months (Fig. 3).

The previous equation can also be used to project the total height (*h2*) in meters of a macauba tree in the future age (*A2*) in months based on the total height in meters (*h1*) and age in months (*A1*) currently observed. In this case, the following expression can be used to project the total height of a palm tree at a future age of interest:

$$\hat{h}_2 = \hat{h}_1(0.984995 - e^{-0.012666A_2})(0.984995 - e^{-0.012666A_1})^{-1}.$$

Fig. 4 indicates the total palm tree height variation projected for a 360-month (30-year) commercial cycle.

### 3.4. Expressions for estimating and projecting carbon through total height and age

By replacing the hypsometric equation that allows the calculation of total height as a function of age, $\hat{h} = \hat{\beta}_0(\hat{\beta}_1 - e^{-\hat{\beta}_2 A})$, in the equation for

**Table 2**
General characteristics of selected macauba (*A. aculeata*) palms of different ages groups collected in Araponga (MG).

| Age (months) | 8 | 19 | 58 | 108 | 176 |
|---|---|---|---|---|---|
| Total height (m) | 0.93 | 2.80 | 7.10 | 10.25 | 12.50 |
| Crown diameter (m) | 0.72 | 4.00 | 5.43 | 6.25 | 6.42 |
| Total number of leaves | 4.00 | 17.00 | 37.00 | 54.00 | 65.00 |
| Total dry matter mass accumulation (kg) | 0.174 | 16.85 | 116.90 | 275.49 | 549.40 |
| Total carbon accumulation (kg) | 0.094 | 9.25 | 64.34 | 154.07 | 308.13 |
| Average carbon content (%) | 54.02 | 54.90 | 55.04 | 55.93 | 55.22 |

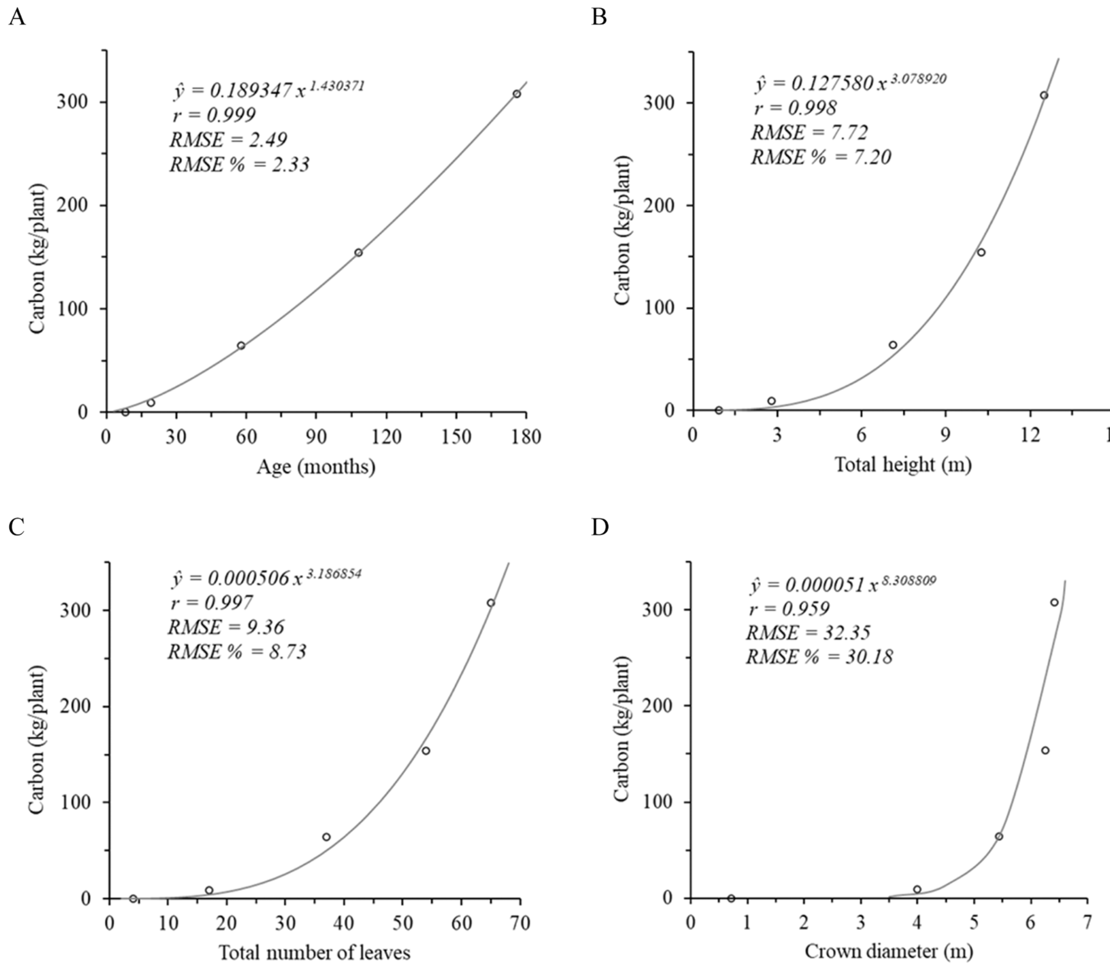


**Fig. 2.** Carbon accumulation trends for macauba (*A. aculeata*) palms of planted in Araponga (MG) based on age, total height, total number of leaves, and crown diameter. Data collected in 2018. Dots in the graphs are the observed data. ($r$ = correlation coefficient between observed ($y$) and estimated ($\hat{y}$) carbon values; *RMSE* = root mean squared error absolute; *RMSE* % = root mean squared error percentage).

estimating accumulated carbon as a function of total height, $\widehat{C} = \widehat{\alpha}_1 h^{\widehat{\alpha}_2}$, it was possible to generate an equation of the type $\widehat{C} = \widehat{\alpha}_0(\widehat{\beta}_0(\widehat{\beta}_1 - e^{-\widehat{\beta}_2 A}))^{\widehat{\alpha}_4}$. Therefore, a carbon accumulation curve for macauba can be constructed to project future scenarios by applying this last expression for different ages. In this way, considering the estimates $\alpha_i$and$\beta_j$, $i = 0$ and 1 and $j = 0$, 1 and 2, we have:

$$C = 0.127580(14.198301(0.984995 - e^{-0.012666A}))^{3.078920}.$$

By applying this equation and extrapolating up to 30 years of cultivation age, the carbon accumulation curve of macauba palms up to this

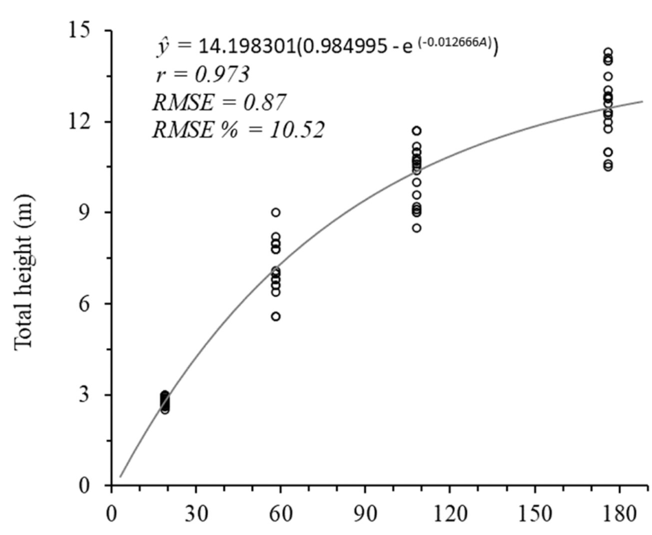


**Fig. 3.** Total height in macauba (*A. aculeata*) palms of in function of cultivation age. Data were collected in Araponga (MG).

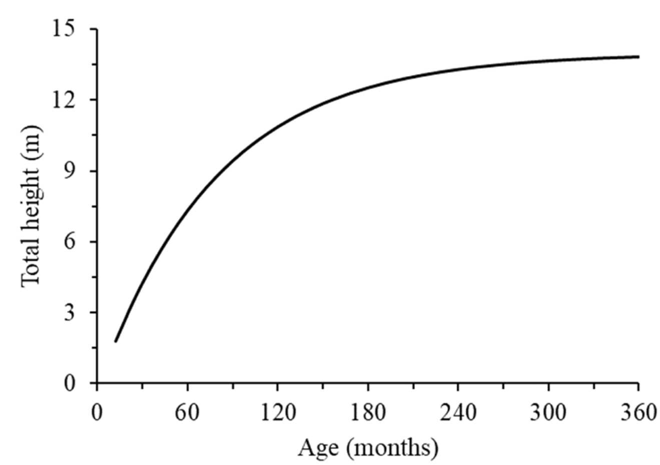


**Fig. 4.** Variation in the total height of macauba (*A. aculeata*) palms projected for a 360-month commercial cycle.

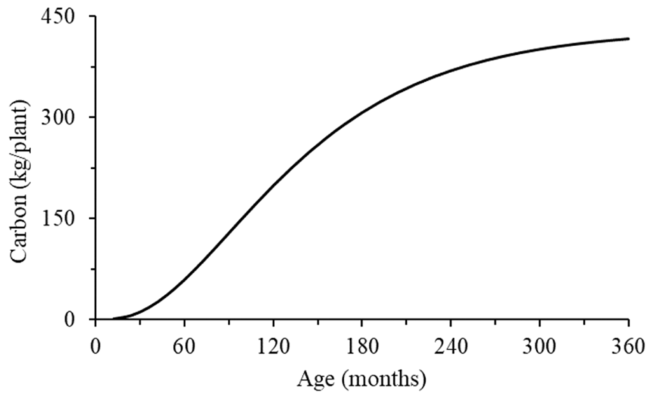


**Fig. 5.** Carbon accumulation curve in macauba (*A. aculeata*) plants for a commercial cycle of 360 months (30 years).


**Fig. 6.** Annual carbon accumulation rate in macauba (*A. aculeata*) palms (solid line) and average carbon productivity per plant (dotted line).

age is obtained, which is equal to the commercial cycle of the crop (Fig. 5). Therefore, this expression can be used to project carbon accumulation in macauba plants (kg/plant) using only the palm tree's cultivation age in months.

The data obtained and the equations produced also allow us to estimate the annual rates of carbon accumulation ($C_i - C_{i-1}$) and the average productivity in terms of carbon in the plant ($CA^{-1}$) (Fig. 6). The visualization of these curves of annual rates of carbon accumulation and productivity are biologically coherent and mathematically consistent.

This entire approach also allows for other estimates. Thus, based on the observed height in meters (*h1*) at a current age in months (*A1*), the carbon stock accumulated in macauba can be estimated for a future age in months (*A2*), according to the following expression:

$$\hat{C}_2 = 0.127580\left(h_1\frac{0.984995 - e^{-0.012666A_2}}{0.984995 - e^{-0.012666A_1}}\right)^{3.078920}$$

## 4. Discussion

The results highlighted that all tested models presented adequate adjustments, with emphasis on the variables age, total height, and total number of leaves. Although the age variable presented a robust performance (r = 0.999, RMSE = 2.49), it is necessary to remark that it is unsuitable for estimating carbon accumulation outside the study area. The 'age' variable is specific to the edaphoclimatic conditions of the study area, and its application in other regions could result in significant inaccuracies.

The variable 'total number of leaves' demonstrated potential for estimating carbon accumulation (r = 0.997, RMSE = 9.36) but posed challenges due to labour-intensive measurement techniques. Additionally, cultivation practices can alter the number of leaves on the palm. This issue arises because *A. aculeata* present indehiscent leaves, meaning the leaves remain attached to the palm stem during the plant growth, and often, they are removed in practices of crop management.

The use of the variable crown diameter was also suitable for estimating carbon accumulation. However, this estimative presented RMSE = 32.35, a high value in comparison to the age (RMSE=2.49), total height (RMSE=7.72), and total number of leaves (RMSE=9.36) estimatives. Despite being easy to measure with a measuring tape, determining the crown diameter may cause mistakes in the field measurement. Consequently, other ways of measuring this variable should be considered, such as using remote sensing techniques and drones that can speed up the measurement process and be more trusted.

The diameter on breast height (dbh) variable was considered the best independent one ($R^2$ = 0.946 and standard residual error = 12.09) to estimate the individual carbon stock in *Euterpe oleracea* Mart (Miranda et al., 2012) considering the model c= β0 + β1 dbh + β2 dbh 2sh + ε, where sh is the stem height. On the other hand, the adjusted models that performed best in estimating carbon in a set of reforestation trees were the ones that used a combination of the variables dbh, age, and height, reaching an $R^2$ = 0.957 and standard residual error = 31.19 (Miranda et al., 2011). Combined variables were also used to estimate the carbon stock in oil palm cultivation (*Elaeis guineenses* Jacq.) (Yulianti et al., 2010), and the best-adjusted equation ($R^2$ = 0.99) was the one that made use of dbh values combined with total plant height.

In the literature, the predominant allometric models were those that predicted carbon for palms considering dbh for *Euterpe oleracea* Mart (Miranda et al., 2012), total height and stem height for *Attalea speciosa* C. (Gehring et al., 2011), total height (Khalid and Anderson, 1999) or a combination of dbh variables and total height for *Elaeis guineenses* Jacq. (Yulianti et al., 2010), and total height or a combination of the total height with the dbh for *Areca catechu* L. (Prayogo et al., 2018).

As no data was available for cultivated macauba trees, the present study assumed the importance of evaluating new independent variables to estimate carbon accumulation in macauba plants, avoiding using the dbh one. Although it performs well for various palm species, in the case of macauba plants, this variable can generate large measurement errors since these palms present sheaths adhered to the stem during growth, which makes the precision of the estimation of stem diameter difficult.

Based on these findings, it is recommended that the variable 'total height' can be well used to estimate carbon accumulation in macauba plants. Total height is easier to measure in the field and less prone to measurement errors than variables like the number of leaves and crown diameter. In contrast, the 'age' variable is considered site-specific, meaning it applies only to the soil and climate conditions of the study area and should not be widely applied.

On the other hand, the 'total height' variable demonstrates a greater degree of universality, allowing for model extrapolation. This occurs, beyond its field applicability and error minimization, because total height integrates the effects of plant growth, making the relationship between total height and carbon accumulation applicable to various conditions.

Finally, the expressions produced in this study from the combination of total height and cultivation age can be generalized to contrasting macauba palm cultivation areas, making it possible to be used to project the height (h2, in m) of a macauba tree of not measured ages, exceeding the age range of our study (A2, in months) based on the height (h1, in m) and age (A1, in months) currently observed:

$$\hat{h}_2 = \hat{h}_1(0.984995 - e^{-0.012666A_2})(0.984995 - e^{-0.012666A_1})^{-1}.$$

We could also estimate the carbon accumulation from age (A, in months) in the expression:

$$C = 0.127580(14.198301(0.984995 - e^{-0.012666A}))^{3.078920},$$

which incorporates the coefficients of the carbon allometric equation from the total height in its composition. Moreover, we could adjust carbon accumulation depending on the current total height (h1) observed at the current (A1) and projected (A2) age:

*C2* = 0.127580 {h1[(0.984995 - eˆ-0.012666A2) / (0.984995 - eˆ-0.012666A1)]} ˆ3.078920.

This finding of generalization of expressions is based on the demonstrated confirmation that there is a growth pattern that does not change but depends on the magnitude of the height of the macauba palms.

It is essential to acknowledge the challenges faced due to limitations in labor, time, and financial resources. Despite these constraints, this study's findings are substantial. This research represents the first attempt to develop an allometric model to estimate carbon accumulation in cultivated macauba plants.

## 5. Conclusions

The model $y = \beta_0 x^{\beta_1} + \varepsilon$ is recommended for analyzing the relationship between carbon accumulation and dendometric variables in macauba palms in the first 176 months under cultivation, with a preference to use the total height of the plant as the independent variable. The total height of the macauba and the carbon accumulation can be estimated using the plants' age (months under cultivation) as an independent variable at a future age of interest during all palm commercial cycles of 30 years. The carbon accumulation of the macauba at any cultivation age can be estimated for different palm cultivation regions using the current total height and age. The proposed equations are applicable and relevant for carbon credit projects in macauba cultivation.

## CRediT authorship contribution statement

**Alves Fernandes Raphael Bragança:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Silva Gabriela Cristina Costa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis. **dos Santos Rosemery Alesandra Firmino:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Pimentel Leonardo Duarte:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Formal analysis, Conceptualization. **Leite Helio Garcia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Imbuzeiro Hewlley Maria Acioli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Moreira Sandro Lucio Silva:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

## 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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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2025.120682.

## Data Availability

Data will be made available on request.

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