BIOSCIENCE JOURNAL

BIOMETRIC ASSESSMENT OF EARLY STEM GROWTH AT A COMMERCIAL STAND OF AFRICAN MAHOGANY (*Khaya grandifoliola*)

Renan Krupok MATIAS[1], Camilla Nascimento BRITO[2], Rafael Tassinari RESENDE[3,6], Jovan Martins RIOS[2], Gabriel Mendes SANTANA[4], Guilherme Murilo DE OLIVEIRA[5], Fábio VENTUROLI[5]

[1] Agronomy, Universidade UniAraguaia, Goiânia, Goiás, Brazil.
[2] Graduate Program in Agronomy, Universidade Federal de Goiás, Goiânia, Goiás, Brazil.
[3] School of Agronomy/Plant Improvement, Universidade Federal de Goiás, Goiânia, Goiás, Brazil.
[4] Department of Forest Engineering, Universidade Federal do Paraná, Curitiba, Paraná, Brazil.
[5] School of Agronomy/Plant Improvement, Universidade Federal de Goiás, Goiânia, Goiás, Brazil.
[6] Forest engineering, Universidade de Brasília, Brasília, Distrito Federal, Brazil.

Corresponding author:
Renan Krupok Matias
renan.krupok@gmail.com

How to cite: MATIAS, R.K., et al. Biometric assessment of early stem growth at a commercial stand of African mahogany (*Khaya grandifoliola*). *Bioscience Journal*. 2023, **39**, e39002. https://doi.org/10.14393/BJ-v39n0a2023-62994

Abstract

African mahogany species (*Khaya spp.)* have proven to be promising in the Brazilian forestry scenario, replacing native mahogany owing to their medium-fast growth and relevant timber value. This study aimed to carry out forest inventory and assessments of a *Khaya grandifoliola* plantation in the first years after planting, test hypsometric models to describe tree growth, and identify the maximum commercial stem yield (i.e., greater than 6 m in height). The stand was located in the municipality of Piracanjuba (GO), where seedlings of seed origin were used. Twenty random plots with a 15 m radius were allocated, and the total height (H_T), stem height (H_S), diameter at breast height (DBH), crown area, and forest canopy were measured. Four hypsometric models were employed in this study. The best equation was selected based on determination coefficients and standard errors. Further, the models were cross-validated to evaluate predictability and bias. At four years of planting, the largest class of H_S was found to range from 3.1 to 4.1 m, and most trees had a DBH ranging from 0.084 to 0.126 m. The percentage of trees with stems > 6 m was 8.35%. The linear model ensured more consistent results for estimating H_T, while the quadratic and Weibull models led to more consistent results for H_S. By using models, stem measurements can be measured based on DBH, ultimately aiding the selection of stem management strategies for the growth of forests with greater commercial value.

Keywords: Forest Modeling. Hardwood. Production. Tree Crops. Validation Study.

1. Introduction

Currently, the Brazilian industry, with raw materials from planted trees, has garnered global attention for its performance regarding innovation and sustainability. During the production of wood panels, cellulose, charcoal, paper, and biomass, planted trees provide hundreds of products and by-products.

Planted trees are essential for mitigating the effects of climate change, reducing the pressure on native forests in terms of wood supply, conserving biodiversity, capturing atmospheric CO_2, and producing oxygen (Bolfe et al. 2020). Despite the national preference for eucalyptus planting, some producers may opt for alternative species, such as the *Khaya* genus. Brazilian mahogany (*Swietenia macrophylla* King) is one of the species with the greatest commercial value in the world, possessing great beauty, exhibiting rapid growth, and producing high-quality wood (Silva et al. 2016).

In recent decades, new studies have increasingly been performed in this area (Oliveira and Franca 2020). Brazilian mahogany is a species with several desirable characteristics for both the reforestation segment and the timber industry; however, it has been replaced by African mahogany (*Khaya grandifoliola* C. DC.), which has great production potential, high commercial value, and low incidence of pests. African mahogany, which was previously introduced in Brazil, has a wide genetic diversity that is comparable to that of natural species (Soares et al. 2020). The growing demand for tropical wood from reputable and responsible origins has led to new investments in plantations throughout the country, ultimately directing the forest market toward new potential species (Reis et al. 2019). In Brazil, the first plantation of this species was performed in the northern region in 1976 (Ribeiro et al. 2017), but was wrongly called *K. ivorensis*. Recently, the species was reclassified as *K. grandifoliola* (Pennington and Cheek 2015). Owing to the recent change, *K. ivorensis* is still commonly used in commercialization, but is expected to naturally and gradually change (da Silva et al. 2020).

When quantitative and qualitative assessments of the wood resources in a given area must be performed, the performance of a forest inventory check is of paramount importance to guarantee such assessments (Resende et al., 2018). Different methods are employed to enable the measurement and collection of different fundamental variables, including the potential of timber and non-timber resources in the area (Sanquetta et al. 2014). Height is the second independent variable used in estimation methods for volume tables, taper functions, and other dendrometric relationships. When forest inventories are generated, tree heights that are not measured within the plot are estimated using a hypsometric (height-diameter) relationship expressed by an adjusted equation (Sanquetta et al. 2014; Ribeiro et al. 2018).

Adjustments of hypsometric models for the culture of African mahogany (*Khaya grandifoliola* C. Dc) or similar cultures, such as *Khaya ivorensis* A. Chev., are scarce in the literature. Accordingly, a lack of content in the culture was identified, thereby warranting better adjustments of the tested models. Of note, the stand is of seminal origin, and is thus compatible with previously obtained results, originating from data with high variability (Silva et al. 2016). This study aimed to analyze early stem growth in a commercial stand (four years old) and test different hypsometric models to estimate the total height (H_T) and stem height (H_S) based on diameter at the breast height of African mahogany (*K. grandifoliola* C. DC.) trees.

2. Material and Methods

This study was conducted at Fazenda Felicidade in the municipality of Piracanjuba, GO. The area is located within the phytogeographic domain of the cerrado in the Brazilian savannah. Notably, remnants of *Cerradão* type forests exist on and around the property. The area has an average altitude of 740 m above sea level, and is located at 17°29’36.86’’S and 49° 14’38.64’’”O. The Köppen classification is *Aw* (Alvares et al. 2013). African mahogany (*Khaya grandifoliola* C. Dc.) was planted as a monoculture in 2014, with a planting spacing of 5 × 4 m, resulting in 7,800 trees covering the total area. African mahogany seedlings were produced in tubes with 260 cm³ of commercial substrate enriched with chemical fertilizer (8-28-16) for seedling formation.

The forest inventory was assembled in April 2017 and the same month in 2018. Dendrometric data were collected and analyzed in partnership with the Forest Inventory Laboratory of the Forest Engineering sector of the Universidade Federal de Goiás. Data on the H_T, H_S, diameter at breast height (DBH), crown area (Ac), and canopy cover (Cc) were collected. A simple random sampling process was used for the inventory, allocating 20 circular plots with a radius of 15 m. In each plot, a random tree and a point referring to the location in the GPS were marked as the central tree of the plot. Within each plot, there were, on average, 30 trees, totaling 580. Sampling sufficiency was determined using the Student’s t-test, with a 5% probability, admitting a maximum error of 10% of the sampled average, as recommended by Pellico, Netto, and Brena (1997).

A tree caliper was used to measure the DBH of the trees within the plots, disregarding dead plants or those with an H_T below 1.30 m at the ground level. To determine Ac, two measurements were carried out, from one end to the other of the crown in the north-south direction and then in the east-west direction, using a measuring tape. To obtain the area value, the formula for the area of an ellipse was employed. An electronic clinometer (*Haglöf*) was used at a standard distance of 15 m from the target tree to measure the H_S and H_T of the trees.

To estimate canopy cover (Cc), the indirect method was selected using Lemmon's convex densiometer (Forestry Suppliers, Inc.). For the collection, the operator was positioned 1 m away to the east of the central tree, and four measurements were performed, one for each cardinal point, giving a 90° turn in the same place after the recording of each measurement. The averages obtained were multiplied by 1.04 as a correction factor for the device, as indicated by the manufacturer.

Linear regression statistical analysis was performed to determine whether the collected variables were related to each other. Histograms were generated using DBH, H_T, and H_S to identify the more frequent class intervals in the area for each variable. A descriptive analysis of the DBH, H_T, and H_S data was performed to verify the degree of homogeneity of the data. Thereafter, Pearson's correlation indices (r) were evaluated to verify the existence of correlations between the variables to continue the model adjustments.

The data were adjusted using linear regression, where four hypsometric (height-diameter) relationship models (arithmetic) obtained in the literature were tested. The tested models were linear, Henricksen, quadratic, and Weibull, as revealed in Equations 1–4, respectively:

$$H_T = \beta_0 + \beta_1 DBH + e \quad \text{(Eq. 1)}$$

$$H_T = \beta_0 + \beta_1 \ln(DBH) + e \quad \text{(Eq. 2)}$$

$$H_T = \beta_0 + \beta_1 DBH + \beta_2 DBH^2 + e \quad \text{(Eq. 3)}$$

$$H_T = \beta_0 + \beta_1 \exp^{(-\beta_2 DBH^{\beta_3})} + e \quad \text{(Eq. 4)}$$

where H_T = total height (m); DBH = diameter at breast height (cm); β_0, β_1, β_2 and β_3 = regression coefficients in the respective models; and e is the residue of the respective models.

The criteria for selecting the best equation initially followed the highest adjusted coefficient of determination (r^2_{adj}) and lowest standard error of the estimate. To validate the proposed models, 500 trees were randomly resampled (DHB, H_T, and H_S) and assumed as a training population, and the remaining 80 trees were used as the validation population. To assess the quality of the models, the following were observed in the validation process: the predictability coefficient (ρ) (equation (5)) and the root mean square error (RMSE), a bias rate (equation (6)):

$$\rho = \frac{\mathrm{cov}(h, h_{pred})}{\sqrt{s_h^2 \, s_{h_{pred}}^2}} \quad \text{(Eq. 6)}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_i^n (h_i - h_{pred_i})^2} \quad \text{(Eq. 7)}$$

where cov = covariance, h = height, h_{pred} = height predicted in the validation scheme, and s_h^2 = the height variance.

3. Results

Descriptive analysis of the variables

Considering a coefficient of variation (CV) ≤ 15% as a high degree of homogeneity, 15<CV<30 average homogeneities, and a CV ≥ 30 as a high degree of heterogeneity, the data showed medium to high heterogeneity, mainly due to genetic diversity in the area. A CV above 15% was obtained for the variables in the two years, except for that of Cc, which had a high degree of homogeneity in the two years (Table 1).

In the first year of collection, average values of 0.08 m, 6.79 m, 3.17 m, 4.42 m², and 69.41% were obtained for DBH, H_T, H_S, Ac, and Cc, respectively. From the third to fourth year of planting, an average gain of 25.9% was obtained for each variable, with respective values of 11.2%, 29.3%, 37.1%, and 2.59%.

Table 1. Statistical results of diameter at breast height (DBH), total height (H_T), stem height (H_S), crown area (Ac) and canopy cover (Cc) of African mahogany trees (*Khaya grandifoliola*) grown in Fazenda Felicidade, municipality of Piracanjuba, GO.

	DBH (cm)		H_T (m)		H_S (m)		Ac (m²)		Cc (%)	
Year	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
N	581	580	581	580	581	580	581	580	20	20
Min	1,74	1,40	1,30	1,70	0,60	1,60	0,16	0,05	53,98	50,34
Mean	8,10	10,20	6,79	7,55	3,17	4,10	4,42	6,06	69,57	71,37
Max	12,40	15,00	17,80	17,10	9,80	9,90	14,47	30,02	84,92	87,52
SD	2,00	2,00	2,45	1,77	1,29	1,25	1,59	2,63	9,26	9,86
CV (%)	24,12	19,22	36,16	23,48	40,72	30,63	35,94	43,48	13,35	13,84

Max = maximum, min = minimum, SD = standard deviation, CV = coefficient of variation, N trees = number of trees measured.

A total of 580 trees were measured in 2018, and 8.62% of the trees reached the desired H_S (> 6 m). The largest classes of H_S, representing 37.59% of the total, varied from 3.1 m to 4.1 m. Regarding H_T, 46.22% of the trees occupied the largest classes, ranging from 6.7 m to 8.7 m. The largest classes of the Ac ranged from 2.78 to 8.23 m². The mortality rate was 3.17%. The H_S and H_T recorded in 2018 are shown in Figure 1.

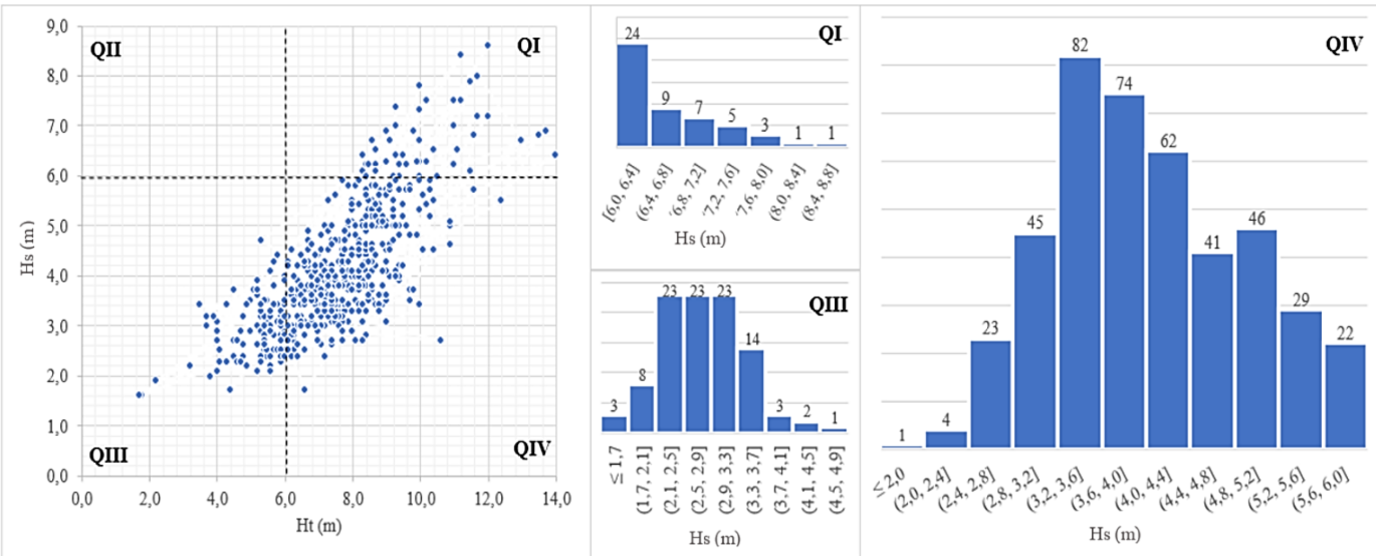

Figure 1. Variation of classes regarding stem height (H_S) and total height (H_T) in African mahogany trees (*Khaya grandifoliola*) cultivated at *Fazenda Felicidade*, municipality of Piracanjuba (GO State). The four quadrants are, QI: very suitable trees, with the first bifurcation greater than 6 meters above ground; QII: an infeasible combination of $H_T \times H_S$; QIII: trees that have not yet reached commercial height, some with still commercial potential and others that have already early bifurcated; and QIV: trees with bioenergetic potential, will be discarded for sawmill purposes.

Quadrant I (IQ) consisted of 50 trees that already reached an H_S greater than 6 m. The largest H_S class was found to range from 6 m to 6.4 m, representing 48% of the total trees in the quadrant. Quadrant II (QII) had no trees as it is impossible to obtain trees with an H_S greater than the H_T. Quadrant III (QIII) consisted of trees that had an H_T and consequently, H_S below 6 m (total, 100 trees), 69% of which were found in the largest classes ranging from 2.1 m to 3.3 m of H_S. Quadrant IV (QIV) consisted of 429 trees with an H_T greater than 6 m and an H_S less than 6 m. Of this total, 50.82% of the trees were distributed in classes ranging from 3.2 m to 4.4 m of H_S. The plants in quadrant IV should be analyzed with more criteria to identify any bifurcations, and collect new data to generate information regarding the bole, ultimately ensuring informed decisions.

In 2017, 2.75% of the total population had unwanted bifurcations, with a mean height of 3.8 m. In 2018, the number of bifurcations increased to 8.1%, with a mean height of 4.6 m. In the interval from the third to the fourth year of planting, the number of bifurcated trees increased from 16 to 47, which represents a very significant increase of 194.55%.

Adjusting the hypsometric (height-diameter) models

The variables with the highest correlation were H_T and H_S (r=0.77), followed by DBH and H_T (r = 0.74), DBH and H_S (r = 0.56), DBH and Ac (r = 0.43), and H_S and Ac (r = 0.30). All correlations were significant, with a p-value of <0.01. The Pearson's correlation coefficient (r > 0.9) was considered a strong indicator of collinearity.

In the hypsometric adjustment using H_T, the linear, quadratic, and Weibull models showed a straighter curve behavior, whereas the Henricksen model displayed a downward concave behavior (Figure 2A). In the hypsometric adjustment using H_S, the quadratic and Weibull models displayed concavity upward, while the Henricksen model displayed concavity downward (Figure 2B). Accordingly, the first two models were identified to be more reliable for data regarding the age of the plants. This behavior can be attributed to the age at which the population was measured. The models showed a greater discrepancy between the estimated and observed values when a lower DBH was obtained.

For H_T, the linear, quadratic, and Weibull models were more consistent with reality. The Henricksen model underestimated the residue when DBH was <6 m (Figure 2C). For H_S, when the DBH was lower, the quadratic and Weibull models underestimated the residues, while the linear and Henricksen models overestimated the residues (Figure 2D).

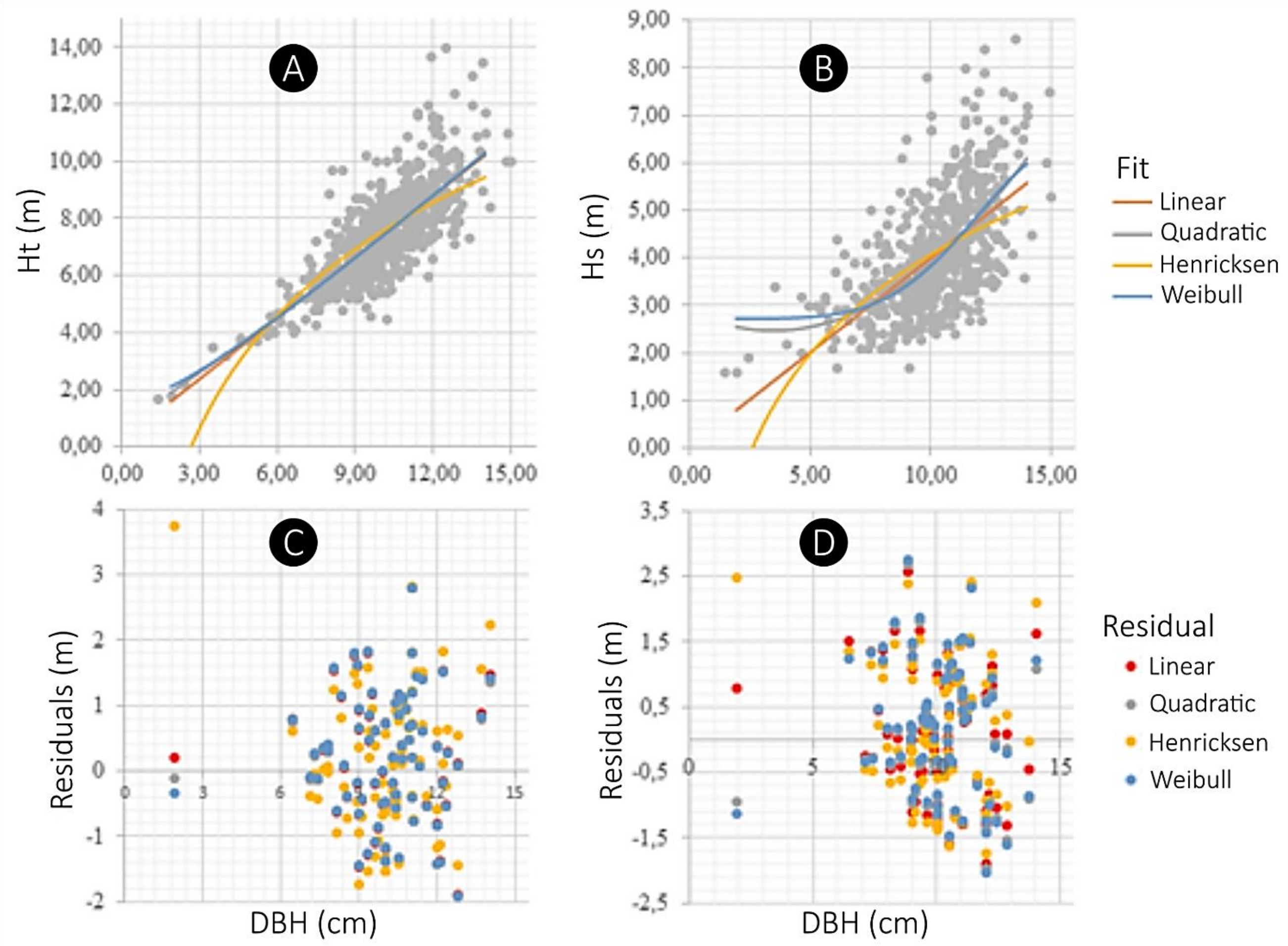

Figure 2. Hypsometric relationships charts using the training data set: A - total height (H_T) and diameter at breast height (DBH); B - stem height (H_S) and diameter at breast height (DBH). The straight lines are the 4 models: Linear, Quadratic, Henricksen and Weibull. Residual charts of the respective models, in this case, using the validation data set (80 observations), in which: C - total height (H_T) and D - stem height (Hs).

All estimated parameters for the four models and the adjustment statistics are listed in Table 2. The r_{adj}^2 values for H_T were higher in the linear, quadratic, and Weibull models, with 0.61 and 0.55 for the Henricksen model. Using the same models, the r_{adj}^2 values for H_S were higher for the quadratic and Weibull models, with a value of 0.39; this was followed by the Linear model (0.36), and the Henricksen model (0.30). The low r_{adj}^2 value is due to the high variability resulting from the use of seminal seedlings for the commercial planting of *K. grandifoliola*.

Table 2. Coefficients of the adjusted models and precision statistics for the variables total height (H_T) and stem height (H_S).

	Model	b_0	b_1	b_2	b_3	r_{adj}^2	*Sxy*	Validation	
								ρ	RMSE
H_T	Linear	0,2401	0,7135	–	–	0,61	0,10 (14,64%)	79,70%	0,970
	Henricksen	-5,627	5,7147	–	–	0,55	0,17 (15,57%)	75,12%	1,073
	Quadratic (Trorey)	0,7393	0,6030	0,0058	–	0,61	0,10 (14,65%)	79,69%	0,971
	Weibull	28,4603	26,9727	0,0096	1,4057	0,61	0,10 (14,66%)	73,58%	0,972
H_S	Linear	0,0436	0,3949	–	–	0,36	1,00 (24,60%)	48,90%	0,996
	Henricksen	-2,8164	2,9943	–	–	0,30	1,05 (25,84%)	45,88%	1,022
	Quadratic (Trorey)	2,8516	-0,2269	0,0328	–	0,39	0,98 (24,11%)	47,23%	1,012
	Weibull	6,5862	3,8771	2,9E-6	5,0503	0,39	0,98 (24,86%)	46,44%	1,023

H_T: total height (m); H_S: stem height (m); Sxy: standard error (in meters and%); r_{adj}^2: coefficient of determination adjusted; ρ: predictability of the model (correlation between observed and estimated by the model); RMSE: square root of the mean of the deviations (in meters).

The lowest standard error of the estimate (Sxy) values for H_T were obtained with the linear, quadratic, and Weibull models, with a variation of 14.64 to 14.66%. The Henricksen model yielded an Sxy of 15.57%. For H_S, the lowest Sxy value was obtained with the quadratic model (24.11%); this was followed by the linear model (24.60%), Weibull model (24.86%), and Henricksen model (25.84%), which resulted in the worst value.

The standard error for H_T based on the models was close to 14%, while that for H_S was approximately 24%, which can be justified by the low correlation between the variables, H_S and DBH. The models that presented the highest coefficient of determination and the lowest standard error were the most efficient and had good precision. Therefore, for the variable, H_S, the linear and quadratic models had the best performance, while for H_S, the quadratic and Weibull models had the best performance.

For the validations, the results of the linear and quadratic models revealed greater predictability of the model (ρ) for H_T, with values of 79.70% and 79.69%, respectively. The values from the Henricksen and Weibull models were 75.12% and 73.58%, respectively. Considering H_S, the highest ρ was 48.90% (Linear), followed by 47.23% (Quadratic) and 46.44% (Weibull). The worst ρ was obtained with the Henricksen model (45.88%). Superior validation using the RMSE for H_T was obtained with the linear, quadratic, and Weibull models, with values of 0.970, 0.971, and 0.972 m, respectively. A value of 1.073 m was obtained with the Henricksen model. For H_S, the best RMSE was obtained with the linear model (0.996 m). The quadratic model yielded an RMSE of 1.012 m, while the Henricksen and Weibull models yielded the worst RMSE of 1.022 and 1.023 m, respectively.

4. Discussion

The growth and development of trees, whether commercial or not, are affected by several factors, such as water deficit, genetic differences, insect attack, thinning, and infestation by invasive plants (Rolim and Piotto 2018). The plantation in this study is cultivated to produce high-quality and highly commercial noble wood, and has an H_S and DBH greater than 6 m and 50 cm, with the expectation of a 21-year cutting cycle. As planting was performed with seedlings of seminal origin, heterogeneity in growth and development was expected (Table 1). Even when small, a genetic variability was found between individuals of the same species in terms of the shape of the bole; however, this format is usually more dependent on the environment yielding heritability and the presence of competition (Sebbenn et al. 2009; Weber et al. 2009; Araújo et al. 2014).

Forest breeding can positively influence the growth of tree species planted without genetic selection (Rolim and Piotto 2018). A great variation in growth exists among different sources of various forest species, with a high potential for productivity gain (Sebbenn et al. 2000). Clonal production of African mahogany has already been obtained by some companies in Brazil; however, the results are still in the preliminary stage. No material has been obtained based on the advantages and disadvantages of using clonal seedlings compared to seminal seedlings for *K. grandifoliola*.

The occurrence of bifurcation in plants, in an early form, was related to the attack of pests, and the difference in genetic material within the population added to competition for production resources. The commercial planting of *K. grandifoliola* led to 6.14% of trees displaying regrowth, with the plots closest to the bee nest were the most attacked, resulting in 38% of trees subjected to attack and regrowth. Pruning was performed to ensure a single, straight stem (Souza et al. 2017).

The plantation under study was attacked by "*arapuá*" bees (*Trigona spinipes*) and ants saúvas (genus *Atta*) and quenquéns (genus *Acromyrmex*). According to Klein et al. (2016), attack by the arapuá bee causes atrophy and super shoots in the plant, leading to unwanted ramifications. Proper management minimizes the loss of stem quality. Early sprouts must be removed at the right time, guaranteeing straighter wood, free of knots, and a stem with superior physical and mechanical qualities. In planted Eucalyptus and Pinus forests, leaf-cutting ants stand out as one of the main pests, especially during pre-cut, budding, or immediately after planting. Leaf-cutting ants can cause reduced growth and even plant collapse after establishing stability in the area. A preventive start must thus be adopted before the planting of commercial culture (Boaretto and Forti 1997).

Care must be exercised in forest stands, as certain species can produce several trunks. The straightest and most developed stem must also be selected, and the others eliminated. Pruning should also be carried out as some defects in the wood can be caused by its absence, such as knots, among others. These defects reduce the physical resistance of wooden pieces and damage their appearance (Resende et al., 2018, Reis et al. 2019). The sooner the performance of management, the faster the development of the remaining stem.

Trees can be dominated by the limited availability of growth resources resulting from competition with dominant trees, causing changes in the shape of the stem, among others (Campoe et al. 2013). Trees at a competitive disadvantage can rarely resume growth rates to keep pace with the dominant trees. Thus, thinning is not only essential to select the desired dominant trees but also increase planting stability, wood quality, and stem shape (Cameron 2002). Therefore, the evaluation of the canopy area and Cc variables is important to understand the behavior of the forest, as photosynthetically active energy is absorbed through the leaves, which is directly linked to tree development. By assessing the ecophysiological behavior of tropical tree species, such as mahogany, Marenco et al. (2001) found that different light intensities in the environment alter the variables of gas exchange and concentration of carbohydrates. Further, leaves exposed to the sun were found to have higher rates of stomatal conductance, photosynthesis, and transpiration.

Carmona et al. (2018) found an average canopy projection value of 24.3 m² for *K. ivorensis*, with an average age of 13 years in the agroforestry systems. In the present study, a tree with a crown of up to 30.02 m² (mean of 6.06 m²) was observed in the fourth year.

Previously, Stolle et al. (2018) evaluated H_T and DBH using different models, including linear, quadratic, and Henricksen. Based on their findings, the graphic distribution of residues was similar for all proposed equations, with no trend in the height estimates and homogeneous dispersion of the residues.

Stolle et al. (2018) found a coefficient of determination of 0.46 for the H_T/DBH ratio based on the linear, Henricksen, and Quadratic models for a commercial plantation of *K. ivorensis*, at the age of three.

According to Campos and Leite (2006), a coefficient of determination less than 0.8 is common when the H_T/DBH ratio is used; this is due to the lack of a relatively strong relationship between the variables.

In a study performed with *Khaya ivorensis* (age, between 30 and 47 months), Silva et al (2016) found r_{adj}^2 values close to 0.7. According to the researchers, due to the planting of African mahogany originating from seedlings of seminal origin, high variability was generated in the data, causing a low coefficient of determination.

For the Linear and Henricksen models, Sousa et al. (2013) found a similar r_{adj}^2, ranging from 0.40 to 0.43, in an assessment of the hypsometric relationships for *Eucalyptus urophylla*. Low values were also obtained by Schikowski et al. (2014), who defined a hypsometric relationship for *Japanese Cryptomeria*; Nicoletti et al. (2016) for *Pinus taeda*; and Sanquetta et al. (2014) for *Acacia mearnsii*. Notably, Sanquetta et al. (2015) obtained an r_{adj}^2 of 0.89.

By assessing *K. ivorensis* at three years, Stolle et al. (2018) obtained Sxy value of 11.2% using the quadratic and linear models and 11.3% using the Henricksen model. According to the researchers, good precision was obtained given the low correlation between the variables and the low coefficient of determination of the equations. In studies of hypsometric relationships, Sxy values above 10% were found for *Eucalyptus* (Retslaff et al. 2015), Acácia (Sanquetta et al. 2014), and Teca (Sanquetta et al. 2015). Other studies revealed an Sxy of less than 10%, such as a study by Nicoletti et al. (2016) with Pinus. Using *K. ivorensis*, Silva et al. (2016) found errors of approximately 2 m for height estimation using hypsometric relationships.

5. Conclusions

Four years after planting, 8.35% of the population had already reached the desired H_S (≥ 6 m). Most trees achieved an H_T of over 6 m but did not achieve the desired H_S. The DBH of the trees did not reach the commercially desired value of 50 cm owing to the youthfulness of the planting.

Injuries potentially caused by bees and ants considerably increased the number of bifurcated plants, affecting stem formation. These changes influence the estimates as the bole could not grow as expected, causing models overestimation of the heights. The significant increase in bifurcations from the third to the fourth year suggests the need for cultural procedures to guarantee high-quality rods.

For the four-year-old studied population, the hypsometric relationships revealed some robustness, with a coefficient of determination between 0.4 and 0.6. The linear model proved to be superior for estimating H_T. For the H_S estimates, the most consistent models were the quadratic and Weibull models. Validation of the models revealed the reliability of their estimates.

Authors' Contributions: MATIAS, R.K.: acquisition of data, analysis and interpretation of data, drafting the article and critical review of important intellectual content; BRITO, C.N.: acquisition of data, analysis and interpretation of data, drafting the article and critical review of important intellectual content; RESENDE, R.T.: conception and design, analysis and interpretation of data, drafting the article and critical review of important intellectual content; RIOS, J.M.: acquisition of data, analysis and interpretation of data and critical review of important intellectual content; SANTANA, G.M.: acquisition of data and critical review of important intellectual content; DE OLIVEIRA, G.M.: conception and design, acquisition of data and critical review of important intellectual content; VENTUROLI, F.: conception and design, acquisition of data, drafting the article and critical review of important intellectual content. All authors have read and approved the final version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Ethics Approval: Not applicable.

Acknowledgments: The authors would like to thank to Dr. José Humberto Barbosa e Silva, the owner of the studied area, for the availability; to ProFloresta (EA/UFG) for the resources availability; and the Coordination for the Improvement of Higher Education Personnel - CAPES, for the financial support.

References

ALVARES, C.A., et al. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*. 2013, **22**(6), 711-728. https://doi.org/10.1127/0941-2948/2013/0507

ARAÚJO, D., et al. Variação genética para caracteres silviculturais em progênies de polinização aberta de *Astronium graveolens* Jacq. (Anacardiaceae). *Cerne*. 2014, **20**(1), 61-68. https://doi.org/10.1590/S0104-77602014000100008

BOARETTO, M.A.C. and FORTI L.C. *Perspectiva no controle de formigas cortadeiras. Serie Técnica IPEF Piracicaba*. 1997, **11**(30), 31-46. Available from: https://www.ipef.br/publicacoes/stecnica/nr30/cap3.pdf

BOLFE, E.L., SANO E.E. and CAMPOS, S.K. Dinâmica Agrícola no Cerrado: Análises e projeções. Brasília-DF: Embrapa Cerrados, 2020.

CAMERON, A.D. Importance of early selective thinning in the development of long-term stand stability and improved log quality: a review. *Forestry*. 2002, **75**(1), 25-35. https://doi.org/10.1093/forestry/75.1.25

CAMPOE, O.C., et al. Stem production, light absorption and light use efficiency between dominant and non-dominant trees of *Eucalyptus grandis* across a productivity gradient in Brazil. *Forest Ecology and Management*. 2013, **288**(15), 14-20. https://doi.org/10.1016/j.foreco.2012.07.035

CAMPOS, J.C.C. and LEITE, H.G. Mensuração Florestal: Perguntas e Respostas. 2 ed. Viçosa: UFV, 2006.

CARMONA, I.N., et al. Variáveis morfométricas de três espécies florestais em sistema agroflorestal. *Revista Agroecossistemas*. 2018, **10**, 131. http://doi.org/10.18542/ragros.v10i1.5158

DA SILVA, M.G., et al. Indolbutyric Acid (IBA) in the African Mahogany (*Khaya grandifoliola* C. DC.) cuttings and mini-cuttings development. *Advances in Forestry Science*. 2020, **7**(2), 1009-1016. https://doi.org/10.34062/afs.v7i2.9793

KLEIN, D.R., et al. General and silvicultura aspects of *Cordia americana*, *Aspidosperma polyneuron*, *Toona ciliata* e *Khaya* spp. *Journal of Agroveterinary Sciences*. 2016, **15**, 155-164. https://doi.org/10.5965/223811711522016155

MARENCO, R.A., GONÇALVES, J.F.C. and VIEIRA, G. Leaf gas exchange and carbohydrates in tropical trees differing in successional status in two light environments in central Amazonia. *Tree Physiology*, Oxford. 2001, **21**, 1311–1318. https://doi.org/10.1093/treephys/21.18.1311

NICOLETTI, M.F., et al. Relação hipsométrica para Pinus taeda L. em diferentes fases do ciclo de corte. *Floresta e Ambiente*. 2016, **23**(1), 80-89. https://doi.org/10.1590/2179-8087.051513

OLIVEIRA, R.D.S. and FRANCA, T.M. Climate zoning for the cultivation of african mahogany species in Brazil. *Cerne*. 2020, **26**, 369-380. https://doi.org/10.1590/01047760202026032748

PELLICO-NETTO, S. and BRENA, D.A. Inventário Florestal. Curitiba: Editorado pelos autores, 1997.

PENNINGTON, T.D. and CHEEK, M. Khaya grandifoliola C. DC. 2015. Available from: http://floradobrasil.jbrj.gov.br/reflora/herbarioVirtual/ConsultaPublicoHVUC/ConsultaPublicoHVUC.do?idTestemunho=4658185

REIS, C.A.F., DE OLIVEIRA, E.B. and SANTOS, A.M. Mogno Africado (Khaya spp.): atualidades e perspectivas do cultivo no Brasil. Brasília-DF: Embrapa,2019.

RESENDE, R.T., et al. Air-drying of eucalypts logs: genetic variations along time and stem profile. *Industrial Crops and Products*. 2018, **124**, 316-324. https://doi.org/10.1016/j.indcrop.2018.08.002

RETSLAFF, F.A.Z., et al. Curvas de sítio e relações hipsométricas para *Eucalyptus grandis* na região dos Campos Gerais, Paraná. *Cerne*. 2015, **21**(2), 219-225. https://doi.org/10.1590/01047760201521021349

RIBEIRO, A., FERRAZ FILHO, A.C. and SCOLFORO, J.R.S. O Cultivo do Mogno Africano (*Khaya* spp.) e o Crescimento da Atividade no Brasil. *Floresta e Ambiente*. 2017, **24**, 1-11. https://doi.org/10.1590/2179-8087.076814

RIBEIRO, A., FERRAZ FILHO, A.C. and SCOLFORO, J.R.S. Tree height prediction in Brazilian *Khaya ivorensis* stands. *Bosque.* 2018, **39**(1), 15-26. http://dx.doi.org/10.4067/S0717-92002018000100015

ROLIM, S.G. and PIOTTO, D. Silvicultura e Tecnologia de Espécies da Mata Atlântica. Belo Horizonte: Editora Rona, 2018.

SANQUETA, C.R., et al. Inventários florestais: planejamento e execução. 4.ed. Curitiba: Multi-Graphic, 2014.

SANQUETA, M.N.I., et al. Ajuste de equações hipsométricas para estimação de altura total de indivíduos jovens de teca. Científica. 2015, **43**(4), 400-406. http://dx.doi.org/10.15361/1984-5529.2015v43n4p400-406

SCHIKOWSKI, A.B., et al. Ajustes de modelos hipsométricos para povoamento de *Cryptomeria japonica* (Thunb. Ex L. f). D. Don no Paraná. *Enciclopédia Biosfera*. 2014, **10**(19), 70-77.

SEBBENN, A.M., et al. Variabilidade genética e interação genótipo x locais em jequitibá-rosa – *Cariniana legalis* (Mart.) O. Ktze. *Revista do Instituto Florestal*. 2000, **12**(1), 13-23.

SEBBENN, A.M., et al. Comportamento da variação genética entre e dentro de procedimento e progênies de *Gallesia integrifólia* Vell. Moq. Para caracteres quantitativos. *Revista do Instituto Florestal*. 2009, **21**(2), 151-163.

SILVA, L.F., et al. Equações hipsométricas, volumétricas e de crescimento para *Khaya ivorensis* plantada em Pirapora. *Floresta e Ambiente*. 2016, **23**(3), 362-368. https://doi.org/10.1590/2179-8087.130715

SOARES, S.D., et al. Genetic diversity in populations of African mahogany (Khaya grandioliola C. DC.) introduced in Brazil. *Genetics and Molecular Biology*. 2020, **43**, 19. https://doi.org/10.1590/1678-4685-GMB-2018-0162

SOUSA, G.T.O., et al. Relações hipsométricas para *Eucalyptus urophylla* conduzidos sob regime de alto fuste e talhadia no Sudoeste da Bahia. *Scientia Plena*. 2013, **9**(4), 1-7.

SOUZA, K.R., et al. Danos em *Khaya ivorensis* provocado por *Trigona spinipes* na savana brasileira. *Acta Brasiliensis. 2017,* **1**(1), 40–42. https://doi.org/10.22571/Actabra11201715

STOLLE, L., et al. Modelos hipsométricos para um povoamento jovem de *Khaya ivorensis* A. Chev. *BIOFIX Scientific Journal*. 2018, **2**(2), 231–236. http://dx.doi.org/10.5380/biofix.v3i2.58799

WEBER, J.C., et al. Phenotypic selection of *Calycophyllum spruceanum* on farms in the Peruvian amazon: evaluating a low-intensity selection strategy. *Silvae Genetica*. 2009, **58**(4), 172-179. https://doi.org/10.1515/sg-2009-0023

Received: 30 August 2021 | **Accepted:** 19 October 2022 | **Published:** 03 February 2023

This is an Open Access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.