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Research Article

Modeling Growth and Yield of *Schizolobium amazonicum* under Different Spacings

Gilson Fernandes da Silva,[1] Salvador Alejandro Gezan,[2] Carlos Pedro Boechat Soares,[3] and Luciano Zumerle Zaneti[4]

[1] *Departamento de Ciências Florestais e da Madeira, Universidade Federal do Espírito Santo, Avenida Governador Lindemberg, No. 316 Centro, 29550-000 Jerônimo Monteiro, ES, Brazil*
[2] *School of Forest Resources and Conservation, University of Florida, 363 Newins-Ziegler Hall, P.O. Box 110410, Gainesville, FL 32611-0410, USA*
[3] *Departamento de Engenharia Florestal, Universidade Federal de Viçosa (UFV), 36570-000, MG, Brazil*
[4] *Centro de Pesquisa do Paricá (CPP), BR 010, Km 18, Caixa Postal 2549, 68633-000 Dom Eliseu, PA, Brazil*

Correspondence should be addressed to Gilson Fernandes da Silva; fernandes5012@gmail.com

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This study aimed to present an approach to model the growth and yield of the species *Schizolobium amazonicum* (Paricá) based on a study of different spacings located in Pará, Brazil. Whole-stand models were employed, and two modeling strategies (Strategies A and B) were tested. Moreover, the following three scenarios were evaluated to assess the accuracy of the model in estimating total and commercial volumes at five years of age: complete absence of data (S_1); available information about the variables basal area, site index, dominant height, and number of trees at two years of age (S_2); and this information available at five years of age (S_3). The results indicated that the 3×2 spacing has a higher mortality rate than normal, and, in general, greater spacing corresponds to larger diameter and average height and smaller basal area and volume per hectare. In estimating the total and commercial volumes for the three scenarios tested, Strategy B seems to be the most appropriate method to estimate the growth and yield of Paricá plantations in the study region, particularly because Strategy A showed a significant bias in its estimates.

1. Introduction

In the past, logging of high-grade trees in Brazilian natural forests occurred in an unplanned and predatory way. At present, the trend is toward increasingly rigorous environmental legislation to prevent illegal harvesting of natural forests. In Brazil, most wood still comes from native forests. Companies that produce pulpwood and fuelwood constitute a minor part of the total timber production and often fill their needs with their own supply. In contrast, companies that produce sawtimber and plywood correspond to a large proportion of the total production and usually require wood from native forests. The increasing difficulty removing wood from native forests due to legislation or supply has resulted in some companies beginning to produce high economic value species through commercial plantations. However, little is often known about the silviculture of some of these native species, and it is typically difficult to find improved genetic material for high yields and more homogeneous forests.

One attractive native species that has been planted in recent years due to its favorable characteristics is *Schizolobium amazonicum* Huber ex Ducke, known in Brazil as Paricá. This species has rapid growth, a straight bole, natural pruning, and highly valued wood in domestic and foreign markets [1, 2]. Paricá has been widely cultivated by timber companies in the northern and northeastern regions of Brazil, mainly in the states of Pará and Maranhão. In 2010, the total area planted with Paricá in Brazil reached 85,470 hectares, remaining practically unchanged from the previous year [3]. The main use of its wood is in the production of veneer and plywood, as it has a small amount of nodes and its stem shape is cylindrical. In addition, its straight

stem and timber with few defects favor high yields of quality veneer [4]. Although Paricá presents high economic value, desirable wood quality, and rapid growth, there is still limited knowledge of how to manage this species in plantations, including aspects such as silvicultural treatments, suitable genetic material, and rotation yields. In addition, knowledge of the growth of the species is very limited, with only a few references [1, 2, 5].

The availability of growth and yield models for productive systems of interest is a critical part of the decision-making process. They assist with planning and management of forest resources, as they describe the forest stand dynamics and predict yields over time [6]. The literature assessing and developing growth and yield forest models classifies them into whole-stand models, size-class models, and single-tree models. In Brazil, there are several applications of the use of all of these models, especially for *Eucalyptus spp.* and *Pinus spp*. However, there are very few models that estimate yield at the stand or tree level for native species in Brazil. Growth and yield models, or their components, for *Schizolobium amazonicum* have not been constructed yet. Similarly, there is still very little information about the ideal density for producing Paricá in planting. Understanding the effects of spacing and stocking on stand characteristics and parameters such as mortality, height, diameter, basal area, volume, tree form, and wood quality is important for building models of growth and yield and making better management decisions [7–11]. Thus, considering the little information available regarding Paricá, this study aims to present a system of equations at the whole-stand level for this species originating from a study that evaluated different plant spacings.

2. Materials and Methods

2.1. Data. This study was conducted with data collected from pure stands of unthinned *S. amazonicum*, situated between the cities of Dom Eliseu and Paragominas, PA, Brazil, belonging to a company called Laminit. The stands consisted of trees planted in spacings of $3 \times 2, 3 \times 3, 4 \times 3, 4 \times 4$, and 5×5 meters. In each of these spacings, 30 randomly located permanent plots were established, with areas ranging from 168 to 288 m^2. For each tree, the diameter at a height of 1.3 m (D, cm) and total tree height (H, m) were measured at 24, 36, 48, and 60 months after planting. The volume of each tree was calculated using the following fitted local equation: $\widehat{V} = 0.0164 + 0.3512(D^2H)$, where $\widehat{V}$ is the estimated total stem volume in m^3, and the variables D and H were defined earlier. The following equation was also used to estimate plywood volume [1]: $\widehat{V}c = 0.000003D^{2.723141}H^{0.877189}$, where $\widehat{V}c$ corresponds to the estimated volume of plywood in m^3. The data collected were divided in two groups of equal size: data to fit the models and data to validate the models.

2.2. Whole-Stands Model. To develop the whole-stand model, the following stand parameters were calculated for each combination of age and spacing: maximum diameter (DM, cm); quadratic diameter (Dq, cm); dominant height (HD, m), defined as the average height of the tallest 100 trees per ha; site index (SI, m), defined as the dominant height at 5 years; density (NHA, trees/ha); basal area (GHA, m^2/ha); and total and commercial volume ($TVHA$ and $MVHA$, m^3/ha).

Two modeling strategies were studied (Strategies A and B), and to evaluate the performance of these strategies for estimating total and commercial volume at 5 years (i.e., 60 moths) of age, three scenarios (scenarios 1, 2, and 3) were used. Here, scenario 1 (S_1) considered no information on the stand as is the case when a stand is started by a new plantation. Scenario 2 (S_2) considered the case in which information about the variables GHA, SI, HD, and NHA is available at an age of 2 years and thus could be used for projections to year 5. Finally, scenario 3 (S_3) assumed the case in which the same information available in S_2 is available at 5 years, that is, the latest inventory.

Using Strategy A based on S_1 to estimate the total and commercial volumes at age 5, the following system of equations was used:

$$HD_i = \frac{\beta_0}{1 + \exp\left(\left(\beta_1 - A_i\right)/\beta_2\right)}, \tag{1}$$

$$SI = \frac{HD_i\left(1 + \exp\left(\left(\beta_1 - A_i\right)/\beta_2\right)\right)}{1 + \exp\left(\left(\beta_1 - A_{\text{ind}}\right)/\beta_2\right)}, \tag{2}$$

$$NHA_1 = NHA_0 - \left(\left(\frac{\text{AREA}}{HD_1}\right)^{\beta_0}\left(A_1^{\beta_1}\right)\right), \tag{3}$$

$$GHA = \beta_0 HD^{\beta_1} NHA^{\beta_2}, \tag{4}$$

$$GHA_2 = \exp\left(\ln\left(GHA_1\right)\left(\frac{A_1}{A_2}\right) + \alpha_0\left(1 - \frac{A_1}{A_2}\right) + \alpha_1\left(1 - \frac{A_1}{A_2}\right)SI\right), \tag{5}$$

$$VHA_2 = \exp\left(\beta_0 + \beta_1\left(\frac{1}{A_2}\right) + \beta_2 SI + \beta_3 \ln\left(GHA_2\right)\right). \tag{6}$$

In these equations, NHA_0 is equal to the number of trees at age zero (i.e., initial planting density); NHA_1 is equal to the number of trees at age 1; HD_i is equal to dominant height in the age i; A_i and A_{ind} are equal to the ith age ($i = 2, 3, 4, 5$) and index age, respectively; and AREA is equal to the average area occupied by each plant at planting. Here, the spacings evaluated were 3×2, 3×3, 4×3, 4×4, and 5×5, corresponding to AREA values of 6, 9, 12, 16, and 25 m^2, respectively. GHA_1 and GHA_2 are equal to the current and future basal areas per hectare, respectively; A_1 and A_2 are equal to the current and future ages, respectively; and VHA_2 is equal to the total or commercial volume per hectare in the future. The other variables were previously defined. In addition, αs and βs are estimated parameters that were obtained by fitting the above models using the statistical package R [12]. Equation (1) was based on the work of Calegario et al. [13], and (2) is derived from (1) [14].

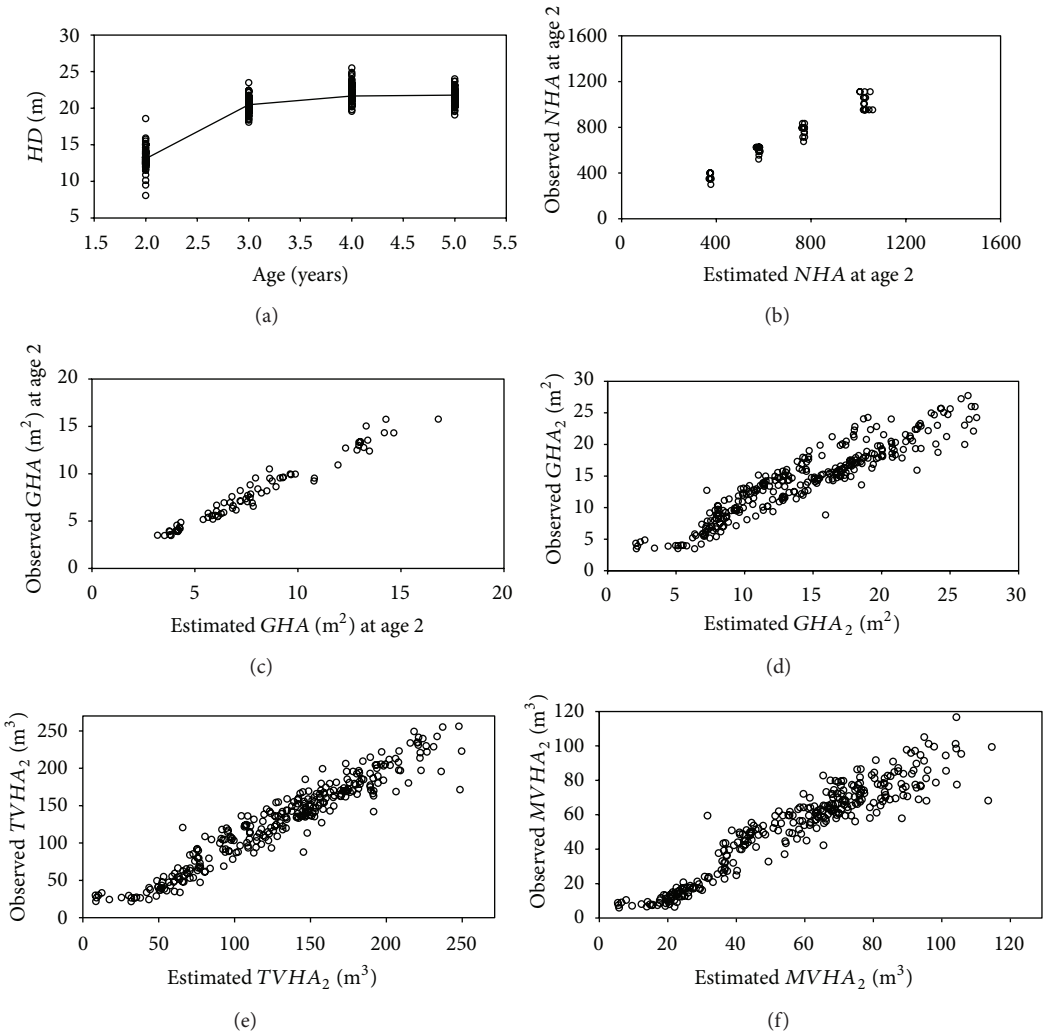


Figure 1: Graphical analysis of residues of Strategy A according to the models presented in Table 2.

Equation (3) was adapted from Pieenar et al. [15], and (4) was based on the work of Spurr [16]. Equations (5) and (6) were originally described by Clutter [17].

For scenario 1, the first step consisted of fitting the dominant height equation (1) to obtain a site index equation (2). The *SI* values, obtained at an index age of 5 years, ranged from 16 to 24 meters for each of the plots. Here, the following three productivity sites can be identified according to their *SI*: high (21–24 m), medium (19–21 m), and low (16–19 m). For S_1, where no prior stand parameter information is available, it was assumed that each stand could be classified as low, medium, or high productivity based solely on soil analysis. Therefore, their *SI* value corresponded to the midrange value of these classes (i.e., 17.5, 19.5, and 22.5, resp.). With this information and using (2), it was possible to estimate *HD* at 2 years. The next step for this scenario consisted of predicting the *NHA* at 2 years based on the density at planting (i.e., NHA_0) by using (3). It was then possible to estimate GHA_1 using (4) fit to data at 2 years. Then, (5) was used to project the basal area and to estimate the basal area per hectare at 5 years (GHA_2) for each plot using GHA_1 calculated (4) and the productive capacity (*SI*) for each plot. Finally, the last step was to evaluate (6) in order to estimate the total and commercial volumes at 5 years (VHA_2) using GHA_2 and *SI* calculated for each plot.

To use Strategy A in S_2, it was assumed that information about the variable GHA_1 at 2 years was already available from an inventory. It was thus not necessary to estimate NHA_1 or GHA_1 at 2 years. Here, the variable *SI* was determined according to productivity classes (as defined in S_1) and later using (5) and (6) to estimate $TVHA_2$ and $MVHA_2$ at 5 years. Finally, for Strategy A in S_3, it was assumed that the value of the variable GHA_2 at 5 years was available. Here, *SI* could be estimated more accurately according to the known *HD* at age 5 and using (1) or (2) and finally using (6) to estimate the total and commercial volumes per hectare at 5 years (VHA_2).

To estimate the total and commercial volumes employing Strategy B for S_1, a system of models containing the previously defined (1), (2), (3), and (4) was fit together with the following two expressions:

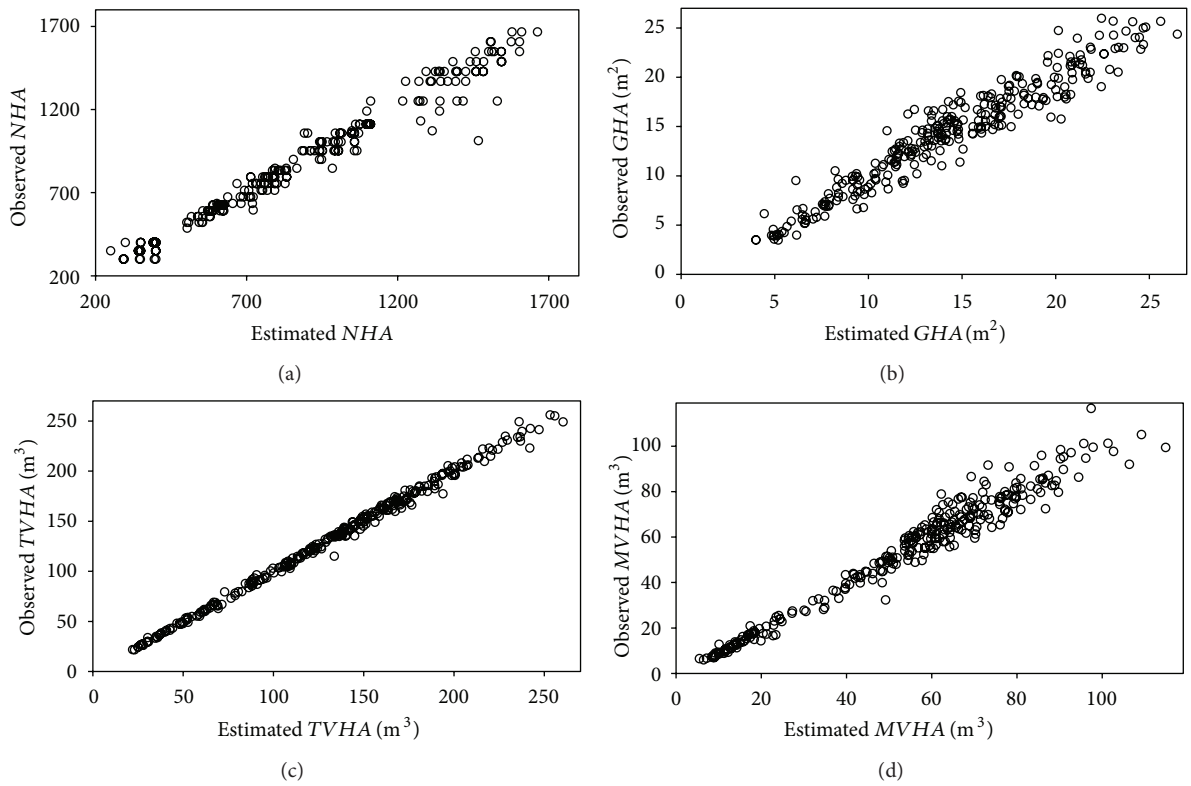


Figure 2: Graphical analysis of residues of Strategy B according to the models presented in Table 2.

$$NHA_2 = NHA_1 - \left(\left(\frac{\text{AREA}}{HD_1}\right)^{\beta_0}\left(A_2^{\beta_1} - A_1^{\beta_1}\right)\right), \quad (7)$$

$$VHA = \beta_0 GHA^{\beta_1} HD^{\beta_2}, \quad (8)$$

where NHA_2 was equal to the number of trees at age 2, and the other variables were defined earlier. Equations (7) and (8) were based on [15, 16], respectively.

The differences between Strategy B and Strategy A, considering S_1, were as follows: *HD* and NHA_1 were estimated at 2 years using (1), (2), and (3), as done previously. Then, (7) was used to estimate survival from ages 2 to 5 and to project the number of trees at age 5 (NHA_2) using the number of trees at age 2 (NHA_1) estimated previously. Later, a basal area equation was fitted (4) considering available data from all ages, which was followed by fitting the total and commercial volumes equations using (8). But to use (8) to estimate *TVHA* and *MVHA* at age 5, it is necessary to know *GHA* and *HD* at age 5. In contrast, to estimate *GHA* at age 5, it is necessary to know *NHA* and *HD* at age 5. Then to obtain *HD* at age 5 (2) was used and to obtain the *NHA* (NHA_2) at age 5 (7) was used. Knowing *NHA* and *HD* at age 5, it is possible to estimate *GHA* and thus *TVHA* and *MVHA* for each plot at age 5.

For S_2 under Strategy B, it was assumed that information about the variables *HD* and NHA_1 at 2 years is available. Then, (7) was used to estimate survival from age 2 to 5 and to project number of trees at age 5 (NHA_2) using the number of trees at age 2 (NHA_1) available from an inventory. Later, a basal area equation was fitted (4) considering the available data from all ages, which was followed by fitting the total and commercial volumes equations using (8). After estimating *GHA* at age 5 based on the *HD* and NHA_2 at age 5, *TVHA* and *MVHA* for each plot at 5 years were estimated.

In S_3, information about the variables *GHA* and *HD* at age 5 was available, and it was possible to estimate *TVHA* and *MVHA* for age 5 for each plot using (8). As before, to fit the equations for all models and scenarios evaluated, the software R [12] was used.

2.3. Evaluation of Model Accuracy. The residuals from the different fitted models were examined to detect any departures from normality or systematic patterns. To evaluate the accuracy of model predictions for each of the strategies and scenarios, the absolute and relative bias (Bias, Bias%) and root mean square error (RMSE, RMSE%) were calculated together with an empirical R^2 (or model efficiency) [18] using the following expressions:

$$\text{Bias} = \frac{\sum(y_i - \hat{y}_i)}{n}; \qquad \text{Bias\%} = \frac{\text{Bias}}{\overline{y}}100,$$

$$\text{RMSE} = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n}}; \quad (9)$$

$$\text{RMSE\%} = \frac{\text{RMSE}}{\overline{y}}100, \qquad R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \overline{y})^2}.$$

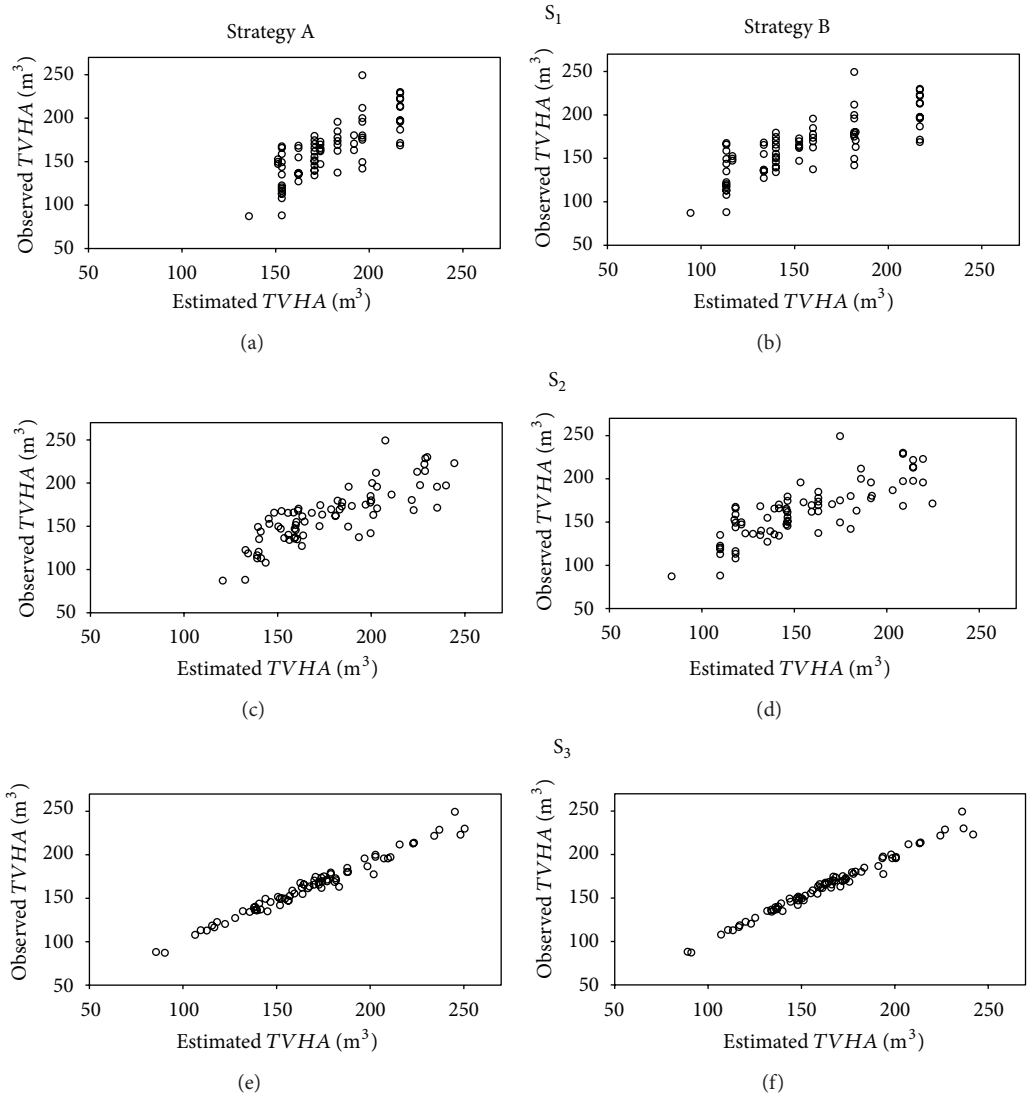


Figure 3: Scenarios for the estimates of the total volume at five years of age by Strategies A and B.

Here, y_i, $\hat{y}_i$, and $\overline{y}$, are the observed, estimated, and average values, respectively. The above goodness-of-fit statistics were evaluated for the variables *HD*, NHA_1, NHA_2, *GHA*, GHA_2, *TVHA*, *MVHA*, $TVHA_2$, and $TVHA_2$.

3. Results

The summary data presented in Table 1 show the development patterns that are expected for most forest species. Considering the maximum and quadratic diameters (*DMax* and *Dq*), an increase in these diameters occurred over time, and different spacings had a clear effect on diameter growth; that is, greater spacings yielded larger diameters. In the case of basal area and volume (*GHA* and *VHA*), the spacing had the opposite effect; that is, the greater the spacing was, the lower the values for these stand parameters were. This is clearly a result of the subutilization of the available space. It should be noted that the 3 × 2 spacing was the only case that exhibited a reduction in the basal area and volume between the fourth and the fifth years, which was much more pronounced than other spacings.

The fitted parameters from the nonlinear models together with the goodness-of-fit statistics are presented in Table 2 for Strategies A and B. In the case of Strategy A, it is important to note the fact that the variable *SI* presented by (5) had no significant effect ($P = 0.143$) on the equation of the projection of the basal area; in addition, the model of *TVHA* had the unexpected result of a significant but positive coefficient associated with of the inverse of age. For the *MVHA*, the *SI* of the model presented by (6) also had no significant effect ($P = 0.134$). The normality of residuals and homoscedasticity of variance were verified using the Shapiro-Wilk and White tests, respectively. Serious problems were not detected.

When evaluating measures of accuracy, although the equations showed high values of R^2 and lower values of bias, the RMSE% values were moderate, especially for the equations predicting *MVHA*, *TVHA,* and GHA_2. The equations fitted for Strategy B showed better results, especially

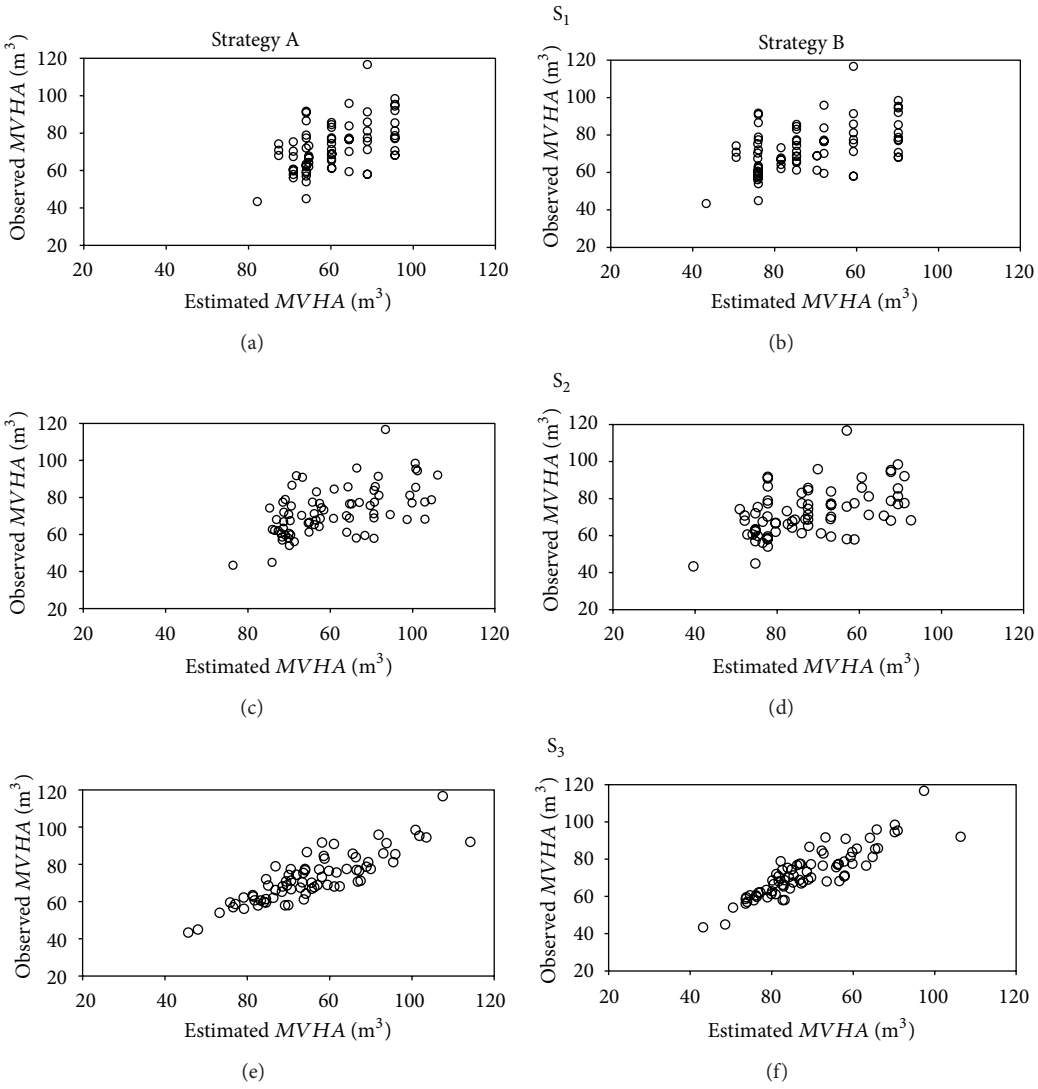


Figure 4: Scenarios for the estimates of the commercial volume at five years of age by Strategies A and B.

for commercial volume, presenting lower values of Bias and RMSE.

Figures 1 and 2 confirm some of the results presented in Table 2. In Figure 1, it is possible to see that the height growth was well characterized and is in accordance with what is expected for most forest species. Figures 1 and 2 show that there is no significant bias present in the fitted models, but they present low accuracy, particularly for the projection models in the basal area and volume of Strategy A. The *MVHA* estimates presented less accurate results compared to *TVHA* in both strategies.

Table 3 presents the results of evaluating the three scenarios proposed to estimate yield at 5 years for Strategies A and B. As expected, the availability of more and current (i.e., closer to 5 years) information led to more accurate model predictions. The lowest accuracy was found when there was little information about the stand; however, this information is still helpful in the absence of any other reference, for example, when new stands are established. Table 3 also shows the statistical validation of the use of Strategies A and B. It should be noted that the statistical validation was closer to the statistical adjustment for Strategy B.

Strategies A and B showed different results in predicting the volume at 5 years (Table 3). The exception is S_3. Strategy A showed more favorable R^2 and RMSE results but appeared slightly more biased in comparison to Strategy B. Based on Table 3 and Figures 3 and 4, Strategy A tended to overestimate the largest volumes, a trend that was more pronounced for *MVHA*.

4. Discussion

The results presented here indicate a trend in which both the basal area and volume asymptotically approaches the maximum value as the age increases to 5 years. This maximum is reached earlier for narrow spacings (see Table 1). The drop in *GHA* and *VHA* from age 4 to 5 in the 3×2 spacing is related to the decrease in *NHA*, that is, due to a higher level of mortality.

Table 1: Average and standard error (in parentheses) for selected stand variables at different combinations of spacing and age.

Spacing	*DMax*				*Dq*				*DA*			
	2	3	4	5	2	3	4	5	2	3	4	5
3 × 2	12.64	17.33	18.64	19.38	9.87	13.13	14.00	14.40	9.72	12.88	13.72	14.11
	(1.43)	(1.32)	(1.51)	(1.76)	(1.39)	(0.88)	(0.88)	(0.88)	(1.44)	(0.91)	(0.89)	(0.87)
3 × 3	12.38	17.68	19.53	20.65	9.91	14.13	15.34	15.72	9.75	13.94	15.10	15.44
	(1.42)	(1.29)	(1.29)	(1.70)	(1.64)	(0.89)	(0.82)	(0.85)	(1.72)	(0.88)	(0.81)	(0.83)
4 × 3	12.78	18.44	20.16	21.40	10.48	15.09	16.22	17.03	10.35	14.93	16.02	16.82
	(1.29)	(1.12)	(1.10)	(1.32)	(1.30)	(0.89)	(0.91)	(0.82)	(1.35)	(0.91)	(0.94)	(0.84)
4 × 4	13.91	19.14	21.14	22.68	10.72	15.84	17.48	18.35	10.43	15.67	17.30	18.11
	(6.27)	(1.26)	(1.31)	(1.39)	(1.40)	(1.06)	(1.03)	(0.98)	(1.23)	(1.10)	(1.06)	(1.01)
5 × 5	13.17	20.18	22.42	24.28	10.79	17.22	19.41	20.69	10.60	17.05	19.26	20.47
	(3.15)	(1.93)	(1.78)	(1.88)	(1.89)	(1.39)	(1.29)	(1.46)	(1.93)	(1.41)	(1.32)	(1.54)
Spacing	*HD*				*HA*				*NHA*			
	2	3	4	5	2	3	4	5	2	3	4	5
3 × 2	13.39	19.81	21.27	21.03	10.48	15.85	17.13	16.73	1529.8	1488.1	1444.4	1277.8
	(2.02)	(1.50)	(1.47)	(1.20)	(1.84)	(1.29)	(1.28)	(0.94)	(99.1)	(120.1)	(160.1)	(200.6)
3 × 3	11.41	20.03	21.61	21.38	9.16	16.99	18.18	17.86	1001.8	993.0	978.8	945.3
	(2.35)	(1.96)	(1.62)	(1.05)	(2.31)	(1.73)	(1.40)	(1.23)	(79.74)	(96.95)	(93.98)	(89.76)
4 × 3	12.37	18.76	21.13	21.20	10.23	16.37	18.46	18.69	756.6	751.3	735.5	689.2
	(1.38)	(2.49)	(1.12)	(1.09)	(1.65)	(2.48)	(1.25)	(1.05)	(62.47)	(57.96)	(64.86)	(94.65)
4 × 4	12.45	19.42	20.88	21.30	10.31	17.38	18.90	19.31	577.6	572.9	563.7	554.4
	(1.37)	(1.28)	(1.27)	(1.29)	(1.48)	(1.41)	(1.23)	(1.32)	(51.16)	(50.56)	(57.44)	(65.43)
5 × 5	11.33	19.42	21.73	21.83	10.09	17.87	20.12	20.31	367.2	355.0	355.0	353.3
	(2.24)	(1.72)	(1.81)	(1.36)	(2.19)	(1.71)	(1.59)	(1.37)	(40.70)	(44.24)	(44.24)	(45.36)
Spacing	*GHA*				*MVHA*				*TVHA*			
	2	3	4	5	2	3	4	5	2	3	4	5
3 × 2	11.88	20.18	22.29	20.78	21.25	62.09	77.15	71.81	85.43	176.30	204.92	185.74
	(2.95)	(2.64)	(3.37)	(3.43)	(8.0)	(13.1)	(17.0)	(15.3)	(20.7)	(28.4)	(36.1)	(32.7)
3 × 3	8.03	15.74	18.21	18.44	13.30	53.44	69.69	70.78	53.13	142.33	171.99	170.13
	(2.53)	(2.85)	(2.93)	(2.83)	(6.2)	(14.5)	(16.6)	(16.2)	(17.0)	(32.6)	(34.4)	(31.6)
4 × 3	6.67	13.53	15.31	15.79	11.99	45.65	60.27	64.89	45.20	115.52	142.70	147.25
	(1.68)	(1.99)	(2.37)	(2.79)	(4.4)	(11.8)	(12.4)	(14.0)	(11.7)	(26.6)	(25.1)	(27.8)
4 × 4	5.33	11.41	13.66	14.79	11.64	41.80	57.60	66.00	37.39	101.19	128.28	140.63
	(1.44)	(2.10)	(2.43)	(2.66)	(11.9)	(10.4)	(13.4)	(14.9)	(13.8)	(21.4)	(26.1)	(28.6)
5 × 5	3.52	8.40	10.63	12.04	7.07	33.51	51.02	61.06	24.02	75.19	104.55	118.18
	(1.28)	(1.98)	(2.33)	(2.79)	(4.84)	(11.1)	(15.7)	(18.8)	(9.8)	(21.0)	(27.7)	(31.2)

DMax: maximum diameter, *Dq*: quadratic diameter, *DA*: average diameter at breast height, *HD*: dominant height, *HA*: average total height, *NHA*: number of trees, *GHA*: basal area, *MVHA*: commercial volume and *TVHA*: total volume.

It may also be noted that for the 3 × 2 spacing, mortality was most pronounced between the fourth and fifth seasons. One possible explanation for this result may be the fact that Paricá is a species with little genetic improvement; therefore, it is still not selected to perform well under high densities. In addition, little is known about its behavior under high competition. Hence, the 3 × 2 spacing, by providing a more intense competition, may have caused the death of individuals not adapted to competition. This process has been studied by many researchers and is known as self-thinning [9, 11, 19–26]. The principle of self-thinning is most easily described by the temporal changes that occur in the numbers of trees in undisturbed even-aged stands. According to Reineke [19] and Yoda et al. [22], there is a maximum density above which mortality of individuals begins, which is identified as the time when the full yield capacity is reached. Overpopulation tolerance varies among species and, although the quality of the site and fertilization should provide higher growth rates, they do not change the maximum density supported for a given average size of individuals [19, 22, 25]. These results reinforce the need for further research on the growth of the species, as well as advances in genetic improvement to favor higher competition.

Furthermore, when evaluating the commercial volume (*MVHA*), the differences found in the production at year five do not appear to be as great as those encountered in the total volume. One explanation for this may be the fact that, for the production of plywood, as shown by Hoffmann [1],

Table 2: Statistics obtained for the equations fitted for Strategies A and B.

Equation	b_0	b_1	b_2	b_3	R^2	Bias	Bias%	RMSE	RMSE%
				Strategy A					
GHA	0.00833*	0.49123*	0.83234*	—	96.22	−0.00	−0.04	0.65	8.12
HD	21.8048*	1.82404*	0.43105*	—	90.29	0.00	0.00	1.17	6.11
NHA_1	−1.17060*	5.84740*	—	—	97.47	1.35	0.15	61.33	7.19
GHA_2	2.49066*	0.04539ns	—	—	84.29	−0.09	−0.62	2.19	15.24
$TVHA_2$	1.89341*	0.03478*	1.91035*	0.7381*	92.15	−0.11	−0.09	15.94	12.29
$MVHA_2$	1.36699*	0.06832*	−0.29629ns	0.5456*	89.12	−0.41	−0.78	8.59	16.20
				Strategy B					
NHA_2	−2.0848*	2.0356*	—	—	97.46	1.81	0.21	58.42	7.07
GHA	0.00523*	1.45720*	0.53967*	—	92.57	−0.02	−0.19	1.51	10.47
TVHA	1.22839*	0.93941*	0.71858*	—	99.58	−0.06	−0.04	3.68	2.84
MVHA	0.03388*	0.69131*	1.83907*	—	96.29	−0.15	−0.28	5.01	9.46

*Significant at the 1% probability level by the *t*-test.
nsNot significant at the 5% probability level by the *t*-test.

Table 3: Statistics obtained for the scenarios evaluated by considering results of estimation and validation for Strategies A and B.

Scenario	Strategy A					Strategy B				
	R^2	Bias	Bias%	RMSE	RMSE%	R^2	Bias	Bias%	RMSE	RMSE%
					Estimation					
					Total volume					
S_1	38.32	−15.24	−9.36	25.35	15.58	45.28	8.00	4.91	23.88	14.67
S_2	43.84	−14.89	−9.15	24.19	14.86	49.97	7.80	4.79	22.83	14.03
S_3	95.32	−4.80	−3.15	8.22	5.39	93.80	−4.64	−2.85	8.03	4.93
					Commercial volume					
S_1	8.56	−8.11	−11.16	13.93	19.17	7.03	4.74	6.53	13.84	19.05
S_2	26.79	−8.12	−11.18	14.40	19.83	11.31	4.66	6.41	13.49	18.58
S_3	62.82	−3.09	−4.26	7.80	10.73	67.24	3.83	5.28	7.32	10.08
					Validation					
					Total volume					
S_1	36.97	−10.05	−7.08	32.10	22.61	36.24	−7.30	−5.14	32.29	22.74
S_2	42.73	−16.61	−11.70	30.60	21.54	47.50	−5.03	−3.54	29.30	20.63
S_3	90.55	−9.86	−6.94	12.42	8.74	98.64	−1.32	−0.93	4.71	3.31
					Commercial volume					
S_1	2.32	−16.77	−27.42	22.25	36.37	6.31	−3.46	−5.66	16.54	27.04
S_2	3.00	−11.74	−19.19	17.19	28.10	15.90	−2.74	−4.48	15.67	25.61
S_3	60.75	−8.30	−13.58	10.70	17.50	86.15	−0.15	−0.25	6.35	10.39

a larger diameter results in greater yield of plywood. Because wider spacings tend to produce larger diameters, there is an increase in the plywood yield, thus increasing commercial volume production. This result should be investigated further to find the optimum level of spacing to maximize commercial volume.

As expected, spacing does not exert much influence on *HD* [7, 27]. However, this is not true of *HA*, which exhibited a clear response as spacing changed, similar to that found for diameter, as previously discussed [14]. The reported results [28, 29] of diameter and height for Paricá plantations at 5 and 6 years of age in Mato Grosso, Brazil, are similar to those found in this study at 5 years. It was also suggested that the most suitable spacings for Paricá plantations are 4 × 4 and 4.5 × 4.5 m because they produce larger trees with lower production costs [30]. Moreover, there would be a greater risk of tree breakage by wind in narrower spacings because the diameters of trees are smaller, and the wood of the species has a low density and therefore lower mechanical strength, as indicated by studies with Paricá in plantations located in various regions of Brazil and in countries such as Bolivia and Costa Rica [31]. It was reported that the most satisfactory results were obtained for wider spacings [31], particularly 5 × 5 m and 4 × 4 m; the latter spacing resulted in a production of 228 m^3/ha at 6 years of age in Dom Eliseu (PA, Brazil).

In a diagnosis of reforestation projects in PA, Brazil [32], the total volume of Paricá plantations planted at spacings of 4 × 4 m in Dom Eliseu, Brazil, resulted in a total volume ranging from 85 m^3 at 3 years to 138 m^3 at 5 years. These results are similar to the values reported in this study (see Table 1).

Unfortunately, there are few studies with information on the growth, commercial volume, and plywood yield of Paricá.

The regression coefficient associated with the *SI* was not significant (Table 2). One potential explanation is that the area under study does not represent a wide range of site qualities. In terms of *MVHA*, this response is subject to additional uncontrolled sources of variations due to the nature of the wood quality characteristics. This means that, although there was a greater total volume, if the quality of the wood is not suitable, the commercial production volume may not be proportional total production. Several other factors can affect the production volume of plywood, such as spacing, forest management, harvest method, and production process.

As mentioned earlier, Strategies A and B showed different results in predicting the volume at 5 years of age. The exception is S_3, where Strategy A showed more favorable R^2 and RMSE results but had a larger bias than Strategy B. Little understanding of the silvicultural treatments and genetic material of Paricá when cultivated in plantations is likely to result in heterogeneous stands, which increases the difficulty in capturing all sources of variation in the model and reduces its accuracy.

However, what is most clear in both strategies is the fact that the more information one has, the more reliable the results are. Again, although this is an expected result, it is important to note how the estimates are affected by the lack of information. In the case of Paricá, because it is a species for which there is limited knowledge that is produced without much technology, the information is relevant to developing appropriate modeling techniques, improving the yield process and studying the management of its stands. Therefore, any new information that could guide the producers of the species and assist in making decisions and guide planning is relevant.

5. Conclusions

According to the results presented in this study, it is possible to conclude the following: (1) with the exception of *HD*, the variables *DM*, *Dq*, *DA*, *GHA*, *TVHA*, and *MVHA* were affected by spacing. Thus, the wider the spacing was, the larger *Dq* and *DA* and smaller the *GHA* and *VHA* were at the same age; (2) the fitted equations for the two strategies showed no significant bias and presented good accuracy. However, this was not as good in Strategy A for *GHA*, *TVHA* and *MVHA*; and (3) comparisons of Strategies A and B in relation to the three scenarios evaluated indicated that Strategy A presented some bias, especially in the complete absence of data (scenario 1). Strategy B showed a smaller bias and RMSE% in estimating volumes than those of Strategy A. Therefore, Strategy B seems to be the most appropriate method to estimate the growth and yield of plantations of Paricá in the region under study.

Disclosure

Three of the authors are researchers and university professors whose main interest is to produce information about a new species. One of the authors provided data from a company and valuable information about the species with the intent that the information produced should be useful for the commercial production of this species.

Conflict of Interests

There is no financial arrangement or any other agreement that may create a conflict of interests in relation to this research.

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