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Assessment of Multiproducts in *Schizolobium Parahyba* var. *Amazonicum* Plantations: Tapering Functions Application in Livestock-Forestry Integration Systems

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Abstract

Given the strategic importance of commercial forest plantations of native species, this study aimed to select a tapering model to estimate the multiple products of *Schizolobium parahyba* var. *amazonicum* planting in integrated livestock-forestry systems in the Amazon and to identify the management regime with the highest production. The research was conducted in the state of Pará, comparing production as a function of variations in spacing and planting age. The Hradetzky, Schöepfer, and Max & Burkhart tapering models were evaluated, considering goodness-of-fit statistics and scatter plots. The Schöepfer model provided the most accurate estimate of tree cross-sectional volume. The management regime with 3.5 × 3.5 m spacing and 60 months promoted the highest assortment production (164 m^3) and the lowest amount of residue (60 m^3), indicating the largest spacing with the highest plant utilization.

Keywords: Forest modeling, Management system, Planting spacing, Tree shape.

1. INTRODUCTION

Native vegetation is crucial for providing essential ecosystem services that sustain life on Earth (Covey & Megonigal, 2019; Felton et al., 2020). In this context, planted forests emerge as a strategic alternative to meet the demand for timber and reduce pressure on natural ecosystems, which must be preserved (Binkley et al., 2017; Marchi et al., 2018). Furthermore, the exploitation of production forests with native species generates both financial and ecological benefits (Tullus et al., 2025). Thus, research development is essential for improving productive management and aligning economic, environmental, and social interests (Ceretta et al., 2025).

Brazil has established itself as one of the world's largest forest producers (ITTO, 2025). In 2023, the country set a historic record, surpassing 10 million hectares of planted forest distributed among various species (IBÁ, 2024). In the Amazon region, *Schizolobium parahyba* var. *amazonicum* (paricá) stands out for its numerous qualities; its planted area increased from 85,473 ha in 2010 to 90,811 ha in 2018, demonstrating linear growth in the following years (IBÁ, 2019). These data reinforce the relevance of paricá and highlight the dynamism of the Brazilian forestry sector on a global scale.

Paricá plantations occur in different configurations. The species can be cultivated homogeneously (Delarmelina et al., 2023), used in the recovery of degraded areas (Schwartz et al., 2017), or integrated into Integrated Crop-Livestock-Forestry (ILPF) systems (Silva et al., 2020; Mascarenhas et al., 2021; Minini et al., 2024). ILPF crops have gained prominence by offering multiple benefits, such as the increased sustainability (Rodrigues et al., 2023), maximization of resources (Oliveira et al., 2024a), maintenance and reconstitution of forest cover (Ndjadi et al., 2021), nutrient cycling (Bessi et al., 2024), soil bioremediation (Matos et al., 2022) and increased carbon stocks (Leite et al., 2023), in addition to favoring economic viability (Costa et al., 2020) and the generation of carbon credits (Gebara & Agrawal, 2017). Thus, the diversity in planting arrangements highlights the potential of integrated systems to transform forest management.

Paricá has remarkable morphological and physiological characteristics. It is a species native to South America, with accelerated growth, which develops rapidly in height and diameter, with a density ranging from 0.32 to 0.40 g cm^{-3} (Melo et al., 2018). Classified as a heliophilous and large-sized pioneer, the species reaches heights of 15 to 40 m and diameters of 50 to 100 cm, presenting a straight, cylindrical stem with little tortuosity (Ucella-Filho et al., 2023). These attributes enable its use in various applications, including energy production, civil construction, the manufacturing of utensils, and, most notably, in the lamination industry to produce panels (Callegari et al., 2022; Dionisio et al., 2024). Thus, the intrinsic qualities of paricá qualify it as a valuable option for multiple applications in the timber sector.

Determining the multi-products from paricá wood is essential for the full use of the plantation. In addition to more accurately quantifying the production destined for the largest consumer market for paricá wood: the veneering industry. From a single stem, it is possible to segment the wood for different purposes, based on predetermined measurements that guide its destination (Fiorentin et al., 2019; Menezes et al., 2020). This strategy enables the acquisition of specific products intended for use in sawmills, the laminating industry, energy production, and pulp and paper manufacturing (Baselly-Villanueva et al., 2025). Furthermore, the application of mathematical tapering functions enables the estimation of diameter variation along the stem, thereby contributing to the accurate classification of the wood (Onilude et al., 2017; Souza et al., 2018; Mctague & Weiskittel, 2021; Saud et al., 2024). In this way, tapering modeling represents a powerful tool for optimizing the planning and harvesting of multi-products.

Mathematical taper models are versatile and essential tools in forest management. These models are used to estimate yield, plan forest exploitation, and simulate and optimize timber production (Li et al., 2021). Taper equations can be used to estimate total trunk volume (Laly et al., 2025), marketable volume for different diameters, log volumes of various sizes (Nicoletti et al., 2019; Kärenlampi, 2022), and even biomass (López-López et al., 2017). Additionally, these equations facilitate the development of classification tables based on specific length and diameter limits (Węgiel et al., 2018; Wilms et al., 2024). Thus, taper models demonstrate their effectiveness as instruments that improve the management and sustainability of forest resources.

Improving research on native species planting is crucial to the success of forestry projects. Diversifying management regimes and optimizing production maximizes economic and environmental benefits, attracting new investments. Thus, the hypotheses guiding this work are that (i) among the models analyzed, at least one will indicate precise and accurate results for estimating the volume of assortments of paricá trees in consortium with livestock farming, and (ii) one of the management regimes under analysis stands out concerning the highest production of assortments. Therefore, this study aims to select and validate the most effective taper model and indicate the management regime with the highest production of assortments of *Schizolobium parahyba* var. *amazonicum* trees in consortium with livestock farming in the Brazilian Amazon.

2. MATERIAL AND METHODS

2.1. Study Area

The study took place at Cinco Águas Farm, a private property located at coordinates 05°21’42” S and 48°47’36” W, in the municipality of Abel Figueiredo, Pará (as illustrated in Figure 1). The farm has a total area of 254 ha, of which 120 ha are designated for planting *Eucalyptus grandis*, the result of a forestry company’s support, and approximately 46 ha are designated for planting *Schizolobium parahyba* var. *amazonicum* (paricá).

According to the Köppen-Geiger classification, the climate is classified as type Aw (Álvares et al., 2013). The predominant soils are Dystrophic Yellow Latosol, Yellow Argisol, Red Yellow Argisol, and Haplic Gleysol with gentle to undulating relief, with slopes ranging from 8% to 20% (Santos et al., 2018). The vegetation is characterized as Subperennial Equatorial and Hygrophilous Floodplain Equatorial Forest, with an average annual temperature of 26.6 °C, relative humidity of 82%, and average precipitation of 2,057 mm (Nascimento et al., 2022).

Seedlings produced on-site were used, sourced from seeds purchased in regional stores. The area received a fertilization at the time of planting, followed by a topdressing fertilization after 40 days. The pasture is formed with the forage species *Panicum maximum*, and the herd consists of 40 head of dairy cattle (undefined breed due to crossbreeding), with a stocking rate of 0.87 individuals per hectare. Although the implementation of the pasture varied in the paricá plantations, the cattle began to roam freely throughout the property as of 2022. Due to these differences, the paricá plantation was segmented into three management regimes (Table 1).

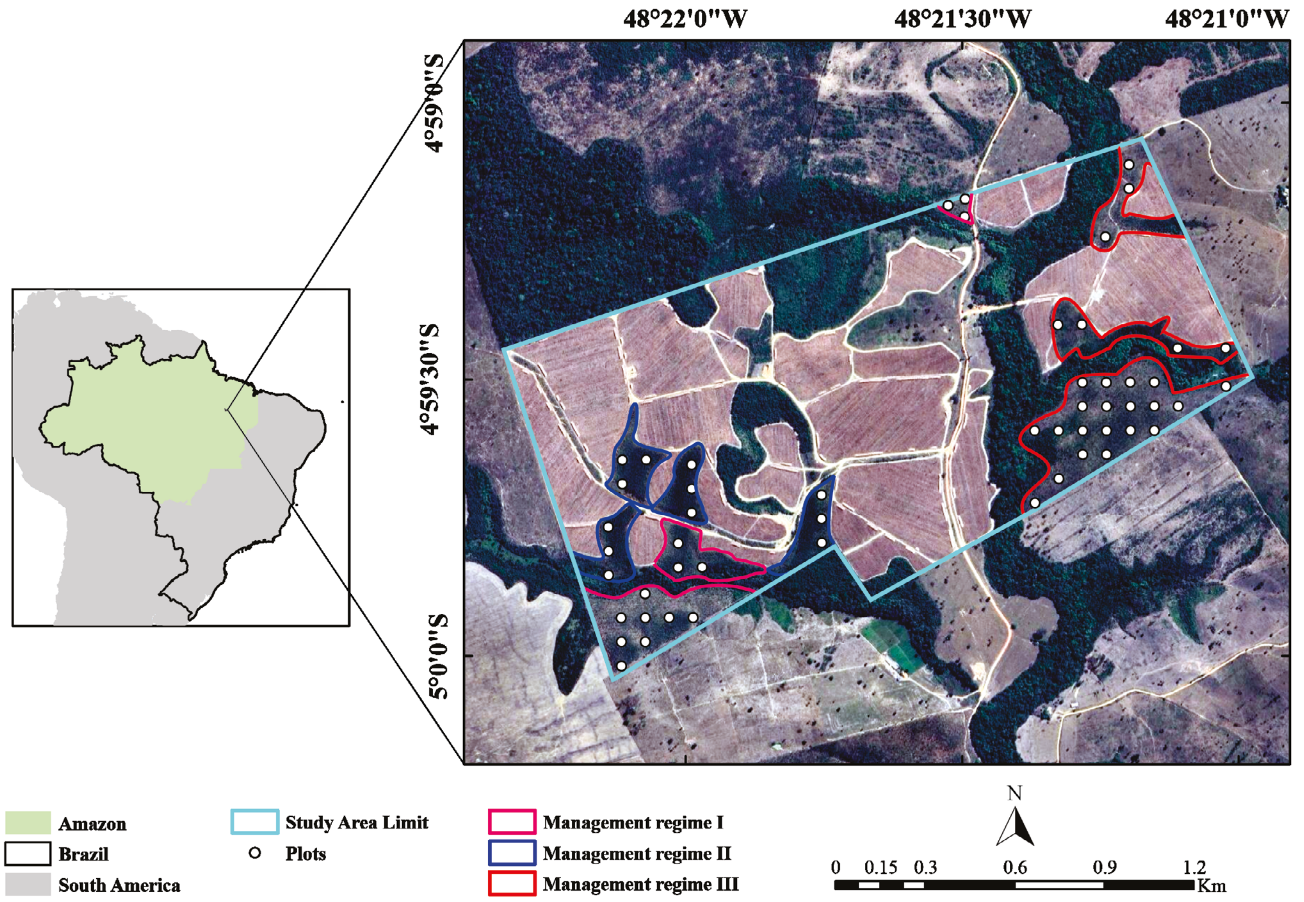

Figure 1. Location of the Cinco Águas farm in the Amazon (highlighted) in Brazil. Source: IBGE, SIRGAS (2000).

Table 1. Description of management regimes for paricá planting in an integrated livestock-forest system.

Features	Management regime		
	MR I	MR II	MR III
Planting age (months)	47	47	60
Presence of forage	Yes	No	Yes
Entry of cattle after planting (months)	24	-	12
Tree spacing (m)	4.0 x 2.0	4.0 x 2.0	3.5 x 3.5
Number of installments	14	12	27
MR area (ha)	12.32	9.09	23.82

MR is the management regime.

2.2. Data collection

The forest inventory, conducted in 2023, adopted a systematic sampling system, with circular plots of 500 m^2 installed at 80 m intervals and stratified according to the management regime area (see Table 1 and Figure 1). Diameter at breast height (DBH) was measured at 1.3 m above the ground using a Haglof Mantax Blue 50 cm equipment, and the average of two perpendicular measurements was used to increase the accuracy of the diameter data.

Cubic measurement was performed indirectly and non-destructively to preserve the integrity of the trees. A Criterion RD 1000 digital dendrometer, mounted on a Kingjoy SF048 tripod (Costa et al., 2022), was used to measure two trees per plot, totaling 106 trees in the entire plantation. Following the Smalian method (Simões et al., 2025), diameters were measured at specific heights 0.1 m, 0.7 m, 1.30 m, and then at 2 m intervals until the insertion of the first branch, corresponding to the commercial height (Biazatti et al., 2020). Additionally, the total height of each tree was recorded.

The trees for cubing were selected to represent the diameter distribution of management regimes and the whole forest, prioritizing individuals without apparent defects (straight trunks, without bifurcation) and with a healthy crown. Specifically, the following criteria were adopted: (i) systematic selection of trees closest to the center of the plot, located in the same spatial positions in relation to geographic north and tree spacing orientation; and (ii) selection of trees to capture the structural variability of the stand as a whole, collecting a sample size of at least 60 trees for the entire forest area and management regimes under inventory. This procedure follows classic recommendations for forest inventory studies, as well as being a routine activity in commercial inventories on the market, practices such as the systematization of plots and trees for collecting height and stem taper measurements (Campos & Leite, 2017).

2.3. Data analysis

Three tapering models were tested to quantify multi-products (Table 2). Among the models evaluated, one was segmented (Max & Burkhart) and two were non-segmented (Hradetzky and Schöepfer). The data were divided into two sets, adjustment and validation, each containing 50% of the records. This equal division facilitates the identification of possible errors in extrapolating the models to the total population, an issue that is especially crucial considering the high variability of individuals in a seed plantation. The equal partition minimizes the bias that could occur in smaller samples (Raj, 1968).

The Hradetzky and Schöepfer models were adjusted in R software (version 4.3.1) using the least squares method. The determination of the optimal combination of integer and fractional powers of the Hradetzky model was performed using the stepwise method (Scolforo et al., 2018). The Max & Burkhart model was adjusted with the “rp.nls” function of the “rpanel” package (Crawford & Bowman, 2021), which implements weighted nonlinear least squares estimates using the Gauss-Newton algorithm (R Core Team, 2023). The significance of the coefficients was evaluated using robust Newey-West standard errors to handle autocorrelation between adjacent sections along the shaft and possible heteroscedasticity patterns (Pinheiro & Bates, 2000), using the Newey-West and coeftest functions from the sandwich package in R.

The selection of the most appropriate model was based on robust quantitative criteria widely used in forestry science. For the response variable (di/d), the Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC), the estimated efficiency (EE), and the mean percentage error (MPE%) were considered (Table 3). The AIC and BIC criteria combine the error of the estimates with the number of parameters, allowing the comparison of models with different methods and complexities (Dziak et al., 2020), while the EE, similar to the adjusted coefficient of determination (R^2_{aj}), is applied for adjustments via least squares (Nascimento et al., 2020).

Table 2. Tapering models for quantifying multi-products from paricá planting in an integrated livestock-forest system.

Author	Model	Equation
Hradetzky	$\frac{d_i}{d} = \beta_0 + \beta_1 \left(\frac{h_i}{h}\right)^{p1} + \beta_i \ldots \beta_i \left(\frac{h_i}{h}\right)^{pn} + \varepsilon$	(1)
Schöepfer	$\frac{d_i}{d} = \beta_0 + \beta_1 \left(\frac{h_i}{h}\right) + \cdots + \beta_5 \left(\frac{h_i}{h}\right)^{5} + \varepsilon$	(2)
Max & Burkhart	$\frac{d_i}{d} = [\beta_1(X-1) + \beta_2(X^2-1) + \beta_3(\alpha_1 - X)^2 I_1 + \beta_4(\alpha_2 - X)^2 I_2]^{0,5} + \varepsilon$	(3)

d_i is the diameter corresponding to the height hi (cm), d is the diameter at 1.3 m from the ground (cm), h_i is the measured height of the stem sections (m), h is the individual height of the tree (m), β_i are the parameters of the equations, pn are the selected powers, X is h_i/h, α_i are the connection points of the polynomials and $I = 1$ if $\alpha_i \geq X$, otherwise: $I_i = 0$

Table 3. Selection criteria for tapering models to quantify multi-products from paricá planting in an integrated livestock-forest system

Selection criteria	Formula	Equation
AIC	$\log\left(\frac{rss}{n}\right) + \left(2\frac{p}{n}\right)$	(4)
BIC	$\log\left(\frac{rss}{n}\right) + \left(\log(n)\frac{p}{n}\right)$	(5)
EE	$1 - \left\{\left[\frac{\sum(y - \hat{y})^2}{\sum(y - \bar{Y})^2}\right]\left[\frac{(n-1)}{(n-p)}\right]\right\}$	(6)
MPE%	$\frac{\sqrt{\sum_{i=1}^{n}\frac{(y_i - \hat{y}_i)^2}{n}}}{\bar{Y}}100$	(7)

AIC is the Akaike information criterion, BIC is the Bayesian information criterion, EE is the estimate efficiency, MPE% is the mean percentage error, rss is the sum of residual squares, n is the number of observations, p is the number of coefficients in the equation, y is the observed value, Ȳ is the arithmetic mean of the observed value, and ŷ is the estimated value.

The EE and MPE% evaluation criteria were applied to the validation data and variables derived from the models, such as the diameter along the stem (di), the volume of the sections (vi), and the total volume of the tree (tv). Additionally, scatter plots were prepared to compare the observed and estimated values using the "latticeExtra" package (Sarkar & Andrews, 2022) within the R software (R Core Team, 2023). This graphical analysis was essential for identifying trends, confirming the consistency of the models, and verifying possible biases.

The determination of multi-products was based on research carried out in sawmills in the region. Two types of logs were defined for the laminating industry, based on the minimum diameter limits (Table 4). The volume of each multiproduct was calculated based on the diametric distribution of the plantations and segmented by management regime, facilitating the visualization and comparison of data, as demonstrated by Costa et al. (2020).

Table 4. Dimensions of multi-products according to the rolling industry

Category	Smallest diameter (cm)	Length (m)
Multiproduct I	≥20	2.30
Multiproduct II	≥12	1.30
Residue	<12	1.30

3. RESULTS

3.1. Model adjustments and selection

The procedure indicated that, for the Hradetzky model, the best combination was obtained with two powers (0.9 and 20). In contrast, while all the parameters of the Hradetzky and Schöepfer models presented statistical significance, the Max & Burkhart model revealed two non-significant parameters (Table 5). Although the models were fitted via ordinary linear regression, the assessment of the significance of the coefficients considered the possible presence of autocorrelation and heteroscedasticity in the residuals, common characteristics in sequential measurements along the shaft. Thus, the standard errors were recalculated using the Newey–West correction, which provides robust estimators under these conditions. The estimated coefficients remained stable, reinforcing the consistency of the models for functional comparison purposes.

In general, the selection criteria presented similar values, except the Max & Burkhart model for the variable volume of the stem sections (Table 6). The AIC and BIC of the di/d variable indicated the Max & Burkhart model as the best model for the adjustment data. However, since this model presented non-significant parameters, it could not be selected for estimating the multi-products. Thus, the selection criteria for the adjustment data (AIC and BIC) of the di/d indicated the Schöepfer model as the best. The Hradetzky model presented the best result for the selection criteria EE and MEP% of the di/d variable and for the di variable. The Schöepfer model also indicated the best result for the variables vi and tv.

Table 5. Adjusted parameters of tapering models.

Parameters	Models		
	Hradetzky	Schöepfer	Max & Burkhart
α_1	-	-	0.67619 *
α_2	-	-	0.09153 ns
β_0	1.05733 *	1.09658 *	-
β_1	-0.33717 *	-1.81789 *	9.35487 *
β_2	-0,71876 *	11.10859 *	-6.98988 *
β_3	-	-34.32642 *	7.56011 *
β_4	-	46.01280 *	13.64878 ns
β_5	-	-22.06749 *	-

ns is not significant, and * is significant at the 5% probability level.

Table 6. Selection criteria for tapering models for variables of interest estimated with the fitting data.

Models	Selection criteria			
	AIC	BIC	EE	MPE%
Model response variable (di/d)				
Hradetzky	-1.5967	-1.5924	0.7846	18.99%
Schöepfer	-1.5798	-1.5713	0.7822	19.15%
Max & Burkhart	-1.5772	-1.5688	0.7771	19.20%
Diameters along the trunk (di)				
Hradetzky	-	-	0.8331	18.45%
Schöepfer	-	-	0.8305	18.59%
Max & Burkhart	-	-	0.8263	18.82%
Volume of trunk sections (vi)				
Hradetzky	-	-	0.5457	46.95%
Schöepfer	-	-	0.5756	45.38%
Max & Burkhart	-	-	0.0920	90.61%
Total tree volume (tv)				
Hradetzky	-	-	0.6595	32.68%
Schöepfer	-	-	0.6744	31.96%
Max & Burkhart	-	-	0.6686	32.24%

AIC is the Akaike information criterion, BIC is the Bayesian information criterion, EE is the estimated efficiency, and MPE% is the mean percentage error.

The evaluation criteria demonstrate consistent results between the adjustment data and the validation data (Table 7). In both sets, the EE and MPE% criteria were similar for most variables. Specifically, the Hradetzky model performed best for di/d, di, and tv, while the Schöepfer model stood out, particularly for the variable vi. Therefore, the validation data reinforce the selection of the Schöepfer model for the final application in the determination of multi-products.

Table 7. Selection criteria for tapering models for variables of interest estimated with validation data.

Models	Selection criteria	
	EE	MEP%
Model response variable (di/d)		
Hradetzky	0.7796	19.09%
Schöepfer	0.7736	19.41%
Max & Burkhart	0.7724	19.29%
Diameters along the trunk (di)		
Hradetzky	0.8397	18.26%
Schöepfer	0.8337	18.61%
Max & Burkhart	0.8346	18.56%
Volume of trunk sections (vi)		
Hradetzky	0.6815	45.51%
Schöepfer	0.6892	44.91%
Max & Burkhart	0.1225	85.35%
Total tree volume (tv)		
Hradetzky	0.7540	31.72%
Schöepfer	0.7536	31.74%
Max & Burkhart	0.7097	34.46%

EE is the estimate efficiency, and MPE% is the mean percentage error.

The graphical analysis of the estimated values for the di/d variable reveals specific trends in the behavior of the models. The estimated values were concentrated around 1 cm (Figure 2). In the adjustment data, the Hradetzky and Schöepfer models did not present evident biases, while the Max & Burkhart model showed a tendency to overestimate by up to 1 cm and, thereafter, to underestimate the results. In the validation data, the underestimation bias of this same model remained slight. Consequently, the graphical analysis corroborates the quantitative criteria, reinforcing the choice of the Hradetzky and Schöepfer models for estimating the di/d variable.

The graphs of diameters along the stem (di) demonstrated good dispersion and consistency in the estimates (Figure 2). The models tested, both in the adjustment and validation data, exhibited similar dispersion patterns. A slight tendency of overestimation was observed for diameters below 15 cm, followed by an underestimation for larger diameters, especially noticeable in the Max & Burkhart model in the adjustment data.

The evaluation of the section volumes (vi) confirms the expectations regarding the smaller magnitude of the stem volumes, whose results were concentrated in values up to 0.05 m^3 (Figure 2). In both data sets, the models tended to overestimate the volumes, with this tendency being less pronounced in the Schöepfer model for the validation data.

The results for the total tree volume (tv) showed a distribution quite consistent with the 1:1 line (Figure 2). The estimated tv values are close to the observed values, although all models show a slight tendency to overestimate. This tendency was smaller in the Schöepfer and Hradetzky models in the validation data. The proximity of the estimated values to the observed values is crucial for the quality of the tv estimates, a variable directly related to the evaluation of multi-products. Thus, the tv analysis reinforces the choice of the Schöepfer model in practical application. Therefore, the Schöepfer model was adopted as the best option for estimating the multiproducts of *Schizolobium parahyba* var. *amazonicum* planting.

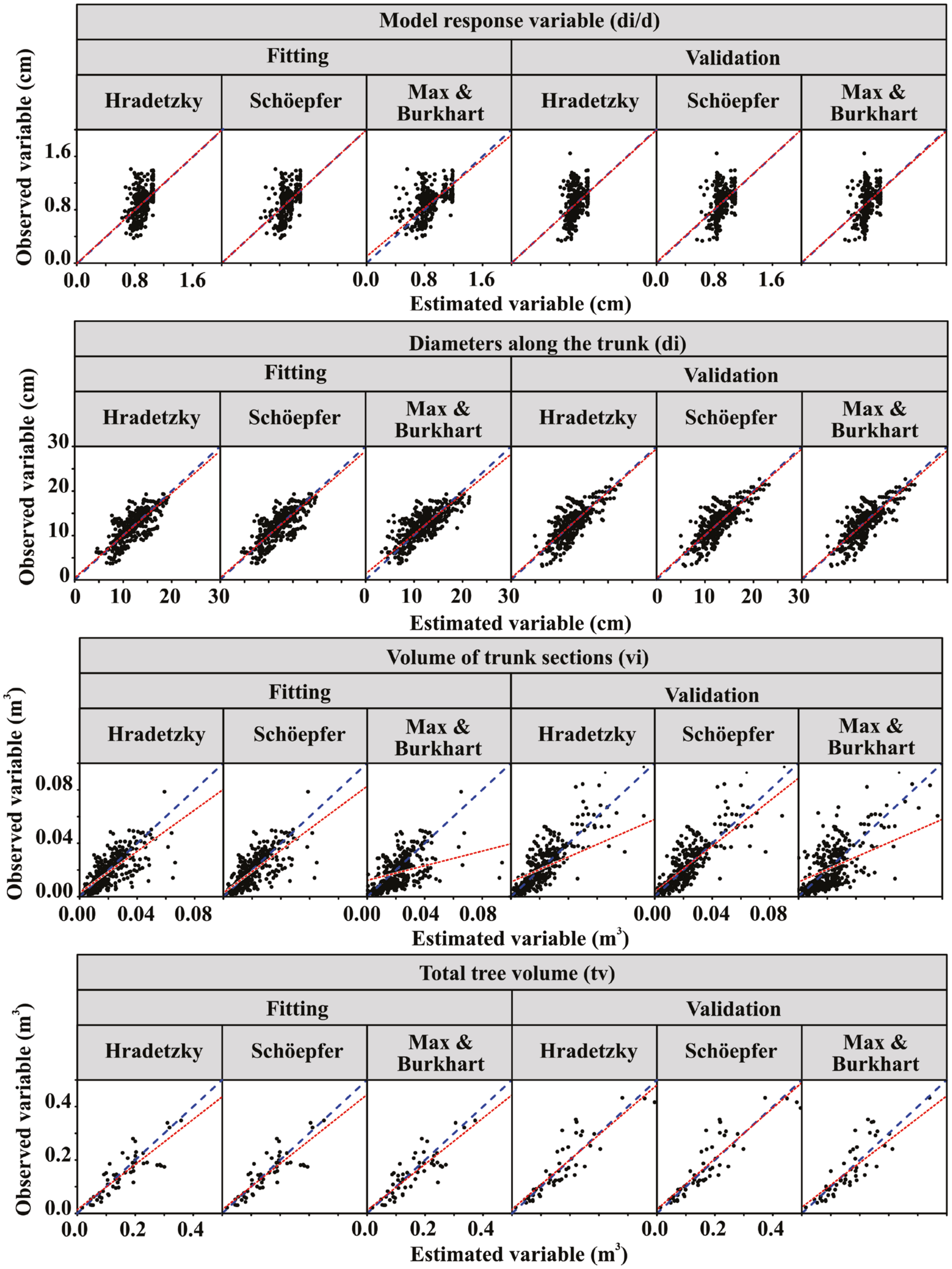

Figure 2. Scatterplots of estimated and observed variables by the tapering models. Where: the black dots represent the estimated values on the X axis and the observed values on the Y axis of the tested variables; The blue lines represent the perfect 1:1 direct relationship line, and the red lines are the trend lines of the estimates.

3.2. Determination of multiproducts

The MR I and MR II regimes, both with 4 × 2 m spacing and 47 months of age, presented similar results, although MR II (without forage) demonstrated 9.02% more wood in the smaller diameter assortment and a greater volume of larger diameter logs, in addition to a higher total volume (Table 8). In contrast, the MR III regime, with 3.5 × 3.5 m spacing and 60 months of age, presented a considerably higher total volume of both assortments, with the smaller diameter assortment being 64.91% higher than that of MR II.

Table 8. Estimate of multi-products each management regime per hectare of paricá plantation in an integrated livestock-forest system.

MR	Nt	Nl Ass. I	Ass. I (m3)	Nl Ass. II	Ass. II (m3)	tv Sor. (m3)	Residue (m3)	tv MR (m3)
I	1,091	-	-	2,621	49.9784	49.9784	101.1600	151.1354
II	1,158	5	0.3918	2,848	54.9313	55.3231	111.9735	167.2966
III	742	94	8.1358	6,670	156.5605	164.6963	60.6962	225.3925

Nt is the number of trees, Nl is the number of logs, Ass. I is the assortment with logs ≥ 20 cm in diameter; Ass. II is the assortment with logs ≥ 12 cm in diameter, tv is the total volume, and MR is the management regime.

Regarding residues, MR II presented significantly higher amounts (9.66% more than MR I and 84.48% more than MR III). These quantitative differences demonstrate that spacing and age significantly influence the productivity and quality of multi-products, indicating that regimes with greater spacing and age favor the production of more usable wood. Therefore, the analysis of the management regimes reveals that MR III exhibits the best productive potential, contributing to the definition of management strategies that optimize the exploitation of multiple products.

4. DISCUSSION

4.1. Model selection and adjustment

The behavior of tapering models varies according to the region and species, which makes it essential to adjust and select the most appropriate model for each planting condition (Salekin et al., 2021). In this context, trunks can be divided into solids of revolution, exemplified by a neiloid shape at the base, followed by a paraboloid in the center, and a cone at the top (Pukkala et al., 2019). Although segmented models generally present greater accuracy (Rocha et al., 2022), their adjustment is more complex, as it requires the precise identification of the inflection points that delineate each solid in the stem (Zhang et al., 2021). In the present study, the lack of significance in some parameters of the Max & Burkhart model suggests that the inflection points may not have been accurately determined, compromising its performance (Oliveira et al., 2024b).

On the other hand, non-segmented models have the advantage of describing the shape of the stem through a single equation, which facilitates their adjustment and integration, providing reliable accuracy (Stefanello et al., 2021). Specifically, the Hradetzky model can reproduce the stem profile when using multiple fractional powers, with the highest powers representing the base and the lowest the upper part (Pelissari et al., 2017). In the present study, the Hradetzky and Schöepfer models showed similar efficiency, probably due to the similarity in their configurations (Sanquetta et al., 2018), and these results are supported by studies carried out with species such as *Pinus taeda* (Téo et al., 2018), *Araucaria angustifolia* (Martins et al., 2017), *Eucalyptus grandis* (Farias et al., 2019) and *Xylopia brasiliensis* (Miranda et al., 2020).

4.2. Assortment and waste

Studies on forest plantations spacing are essential, as tree density directly influences growth, yield, and stem shape, in addition to impacting harvesting operations and rotation periods (Tun et al., 2018). In integrated systems, where components are strongly interrelated (Hammarstrom & Bianchi, 2019; Sales et al., 2021), the MR I (with forage) and MR II (without forage) regimes, both with 4 × 2 m spacing and 47 months of age, presented similar assortment volumes.

However, in intercropping systems, spacing becomes even more decisive, as competition between forage and tree species for light, water, and nutrients can significantly affect production (Sarto et al., 2020). Another factor that may have contributed to the lower production observed in MR I is the early entry of cattle, starting in the 36th month after planting (Behling et al., 2021), which, combined with the fact that individuals are thinner due to shorter spacing and age (Marziliano et al., 2015), caused more pronounced mechanical shocks (Gonçalves et al., 2022).

The MR III regime stood out for presenting the highest production. With greater spacing (3.5 × 3.5 m) and an older age (60 months), the trees were more robust (West & Smith, 2020), resulting in stems that were better suited for obtaining multiple products (Barbosa et al., 2019). Furthermore, the greater spacing in MR III reduced the impact of animals on the trees, since the entry of cattle occurred only 12 months after planting. An alternative strategy to increase use in the MR I and MR II regimes would be the application of thinning, which, in addition to increasing the diameter of the remaining trees, offers economic benefits to the integration system (Viana et al., 2021; Grigoreva et al., 2022).

Although studies indicate that plantings with smaller spacing produce trees with smaller diameters, the increase in the number of individuals usually compensates for this difference (Zahabu et al., 2015; Zhang et al., 2020). However, this pattern was not evident in the present study, possibly due to the difference in planting age (Eloy et al., 2018) or the additional benefits of the integration system in MR III, such as natural fertilization promoted by the presence of livestock (Gil et al., 2015).

Finally, the greater volume of waste observed in the MR I and MR II regimes can be attributed to the lower use of the trunks of trees with reduced diameter (Ferraz Filho et al., 2018). A viable solution would be to convert this waste into bioenergy (López-Hortas et al., 2021), considering that, for this purpose, the minimum diameter must be 4 cm; smaller trunks can still be used as firewood (Okello et al., 2001).

The greater spacing, in addition to indicating greater production in cubic meters of assortment, also demonstrated optimized utilization of trunks with a lower volume of residue. The reduction in planting density, in addition to its impact on production, which can be related to reduced competition and greater space for development, also affects the economic aspect. With fewer trees, planting costs are reduced. Thus, the advantage of maximizing production is evident, in addition to production diversification, another economic advantage of integrated production systems.

5. CONCLUSION

The Schöepfer model demonstrated the best performance in estimating the volumes of *Schizolobium parahyba* var. *amazonicum* (Huber ex. Ducke) Barneby assortments in an integrated livestock-forestry system.

The management regime with 3.5 × 3.5 m spacing and 60 months of age, integrated with livestock, presented the highest total production volume for both the assortment $\geq$ 20 cm and $\geq$ 12 cm. The regime with 4 × 2 m spacing and 47 months of age, without integration with livestock, generated the largest volume of waste, and its allocation to bioenergy is recommended.

To complement this research, we recommend monitoring the planting for further studies at older ages, in addition to obtaining data from other paricá planting areas with different edaphoclimatic conditions and management regimes as a means of validating and consolidating the species for commercial forest plantations.

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CORRESPONDENCE TO

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DATA AVAILABILITY

The entire dataset supporting the results of this study is available upon request to the corresponding author, Quinny Soares Rocha. The dataset is not publicly available because the raw data includes georeferenced records of permanent plots, the unrestricted disclosure of which could compromise the security of the sites and violate cooperation agreements with the institutions managing the data. Therefore, this is in accordance with established legal and ethical terms.

SUPPLEMENTARY MATERIAL

The following online material is available for this article:

Additional file 1. Estimate of multi-products of each diameter class per hectare of paricá plantation in an integrated livestock-forest system.

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