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RESEARCH ARTICLE

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Forecasting production in thinned clonal stands of *Tectona grandis* in Eastern Amazonia

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Abstract

Aim of study: We investigated the most suitable thinning ages and intensities to maximize productivity and minimize the rotation age of *Tectona grandis* clonal plantations in the Brazilian Eastern Amazon.

Area of study: Capitão Poço, State of Pará, Eastern Amazonia, Brazil.

Materials and methods: We used diameter, height, and volume data from 72 permanent plots measured on nine occasions. We determined the classification of forest sites using the generalized algebraic difference approach (GADA). Clutter's segmented model was used to simulate different intensities of basal area reduction, determining the technical ages according to the projected increments.

Main results: The polymorphic site curves generated by the GADA method revealed that there were sites with different productive characteristics. The Clutter model produced compatible projections of basal area and volume that followed the behavior of the productivity classes. The final production was maximized when three thinning intensities (basal area reductions) were applied: 1st thinning (50%), between the ages of 3.5 to 4.2 years; 2nd thinning (50%), between the ages of 6.1 to 7.3 years; and 3rd thinning (25%), between the ages of 10.6 to 12.8 years. Projected rotation ages ranged from 13.9 to 16.6 years. The simulations increased the net volume by 8.3%, on average, compared to no thinning.

Research highlights: Simulations with three thinnings maximized production compared to the no thinning scenario. The time interval between thinnings was less than five years. The research results can help forest management decision-making and reveal production increases of *T. grandis* clonal stands in a shorter time.

Additional key words: modelling; GADA; silvicultural treatments; simulation; site index.

Abbreviations used: BA (basal area); CAI (current annual increment); dbh (diameter at 1.3 m from the ground)); Dh (dominant height); GADA (generalized algebraic difference approach); h (total height)); MAI (mean annual increment); RMSE (root mean square error); RMSPE (root mean square percentage error); SI (site index); TRA (technical rotation age); TTA (thinning technical age).

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Introduction

Forest plantations are the main way to meet the increasing demand for timber worldwide, replace products from natural forests, and prevent deforestation (Cuong *et al.*, 2019). Among the species with great expression for the establishment of planted forests, *Tectona grandis* Linn. F. (teak) stands out (Quintero-Méndez & Jerez-Rico, 2017; Orrego *et al.*, 2020). This is a Southeast Asian native species, widely used in shipbuilding and in the production of fine furniture and decks since it presents highly durable wood, good dimensional stability, high workability, and aesthetic quality (Upadhyay *et al.*, 2005). Due to these characteristics, commercial plantations of such species have expanded in several countries, such as Costa Rica, the Ivory Coast, India, Indonesia, Malaysia, Tanzania, Thailand, Laos, Myanmar, and Brazil (Tewari *et al.*, 2013; Kollert & Kleine, 2017).

Worldwide, commercial teak plantations cover an area of 6.9 million hectares, of which 88.2% are located in Asia, 7.8% in Africa, and 4% in Latin America (Midgley *et al.*, 2015; Graudal & Moestrup, 2017). Brazil has the largest area of teak plantations in Latin America, c. 94 thousand hectares (IBA, 2020), presenting a high productive potential, advanced technology for cultivation and management, favorable edaphoclimatic conditions, and extensive potential areas for reforestation, which makes it even more promising to expand plantations of this species in the country (Stape *et al.*, 2001; Gonçalves *et al.*, 2008).

The growing global demand for certified timber, as well as the concern about the extensive logging of natural forests, justifies the need for scientific and technological advances in the development and improvement of superior genetic materials of teak, whose plantations are mostly of seed origin. Therefore, genetic improvement supported by its wide genetic variation can assist in the selection of genotypes with better growth and production characteristics (Graudal & Moestrup, 2017; Mulyadiana *et al.*, 2020).

In this context, studies aimed at developing best management practices to increase the timber production of teak in clonal stands are necessary (Souza *et al.*, 2022). Regarding management practices in Brazil, there is a strong need to study productive capacity and to forecast the timing of technical thinning and rotation age (Medeiros *et al.*, 2017). Teak thinning and rotation technical ages are longer compared to other industrial plantations in Brazil of species, such as *Eucalyptus* sp., *Pinus* sp., *Acacia* sp., and *Schizolobium parahyba* var. amazonicum (Graudal & Moestrup, 2017; IBA, 2020), due to their growth rates, commercial products with large dimensions, and wood quality (Seta *et al.*, 2021). Silvicultural treatments, such as thinning, are important for boosting tree growth, especially in diameter, concentrating production on a smaller number of trees and improving the wood's technological properties and, consequently, its market value (Kanninen *et al.*, 2004; Pachas *et al.*, 2019).

Monitoring growth and yield along the rotation will help to develop models that include variables such as density and productive capacity, improving the stand´s thinning plan (Medeiros *et al.*, 2017). In Brazil, Clutter's model (Clutter *et al.*, 1983) is the most used by forest companies, which is part of the modeling at the total stand level, in which it estimates the average volume as a function of the plantation density, age, and site index. Several studies have been developed using Clutter's model for forecasting production in non-thinned stands (Valeriano *et al.*, 2020).

Most teak silvicultural research has been carried out in stands established from seedlings. A gap exists in mode-

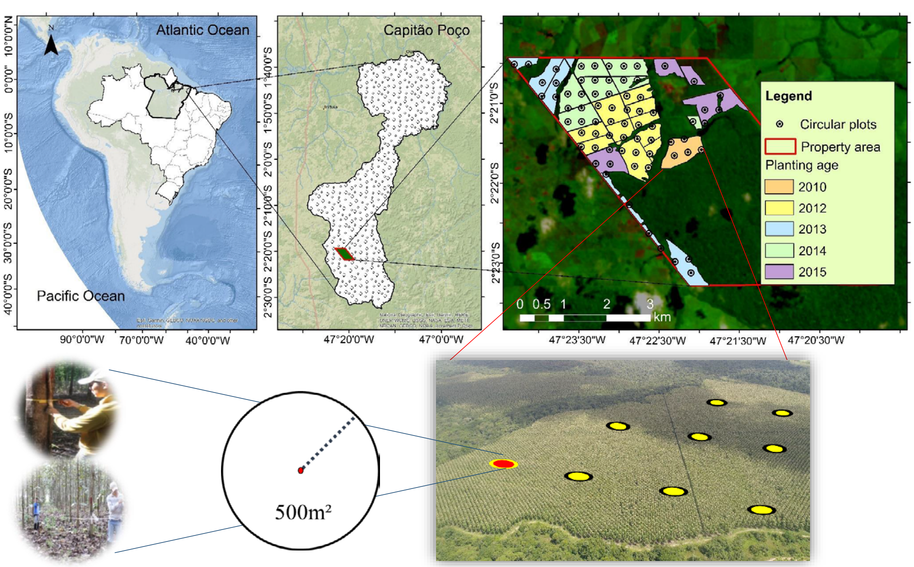

Figure 1. Study area location and spatial arrangement and separation of sampling plots by age in teak clonal plantations in Eastern Amazonia, Brazil.

Table 1. Descriptive statistics for the variables of clonal teak plantations in Eastern Amazon, Brazil.

Variables[1]	Fit data				Validation data			
	Min.	Max.	Mean	SD[2]	Min.	Max.	Mean	SD[2]
A	2.00	9.00	4.23	1.69	2.00	9.00	4.16	1.72
Dh	7.28	19.39	13.27	2.53	6.04	17.93	12.80	2.84
BA	2.27	34.73	14.68	5.95	2.37	25.58	14.69	5.91
V	8.67	231.30	82.12	40.15	8.33	159.38	81.28	39.89
dbh	7.50	31.57	16.52	4.43	6.04	29.01	16.25	4.68

[1] A: age (years); Dh: dominant height (m); BA: basal area (m^2 ha^{-1}); V: volume (m^3 ha^{-1}); dbh: diameter at breast height (cm). [2] SD: standard deviation.

ling thinned stands and forecasting yields in clonal plantations at different ages and thinning intensities, as well as in determining the best technical rotation age (Adu-Bredu *et al.*, 2008; Novaes *et al.*, 2017). This is important in the process of species forest management planning since models that disregard silvicultural treatments cannot be used (Souza *et al.*, 2022).

Our research addresses the following scientific question: What is the technical age, thinning intensity, and rotation age of clonal teak plantations that maximize volume production? We tested the hypothesis that three thinning interventions over a period of less than 20-years rotation would give the best response to the timber yield of the species in clonal stands in the Brazilian Eastern Amazonia.

Material and methods

Study area and silvicultural practices

This study was carried out in teak clonal plantations located in the municipality of Capitão Poço, State of Pará, Eastern Amazonia, Brazil (2°30’00” S; 47°20’00” W and 2°20’0” S; 47°30’0” W) (Fig. 1). In this region, Dense Ombrophilous Forest is the main forest type, and reliefs range from flat to smoothly undulating (IBGE, 2012). The main soil types occurring in the region are Petroplintic Dystrophic Yellow Latosol, Typical Dystrophic Yellow Latosol, and Petric Concretionary Plintosoil (EMBRAPA, 2013). The climate is *Am* according to Köppen´s classification and is characterized as warm and humid, with a short dry season (Alvares *et al.*, 2013). The total annual rainfall and temperature are 2256 mm and 26.1ºC, respectively (INMET, 2020).

The area (745.4 ha) was divided into 19 monoclonal stands planted manually at spacings of 3.5 × 3.5 m, 3.75 × 3.75 m, and 4 × 4 m. The stands were 4, 5, 6, 7, and 9 years old during the study period. Silvicultural practices consisted of controlling leaf-cutting ants with ant killers; liming with dolomitic limestone (3 tons ha^{-1}); fertilization (200 g $plant^{-1}$ of NPK 8-28-16 and 100 g $plant^{-1}$ of KCl); controlling invasive plants through hoe crowning, mechanized brushing; pruning; and fertilizing with the application of boron (7 g $plant^{-1}$) and KCl (100 g $plant^{-1}$). Thinnings were carried out at 4.5 and 8.5 years, reducing the basal area by 50% (Souza *et al.*, 2022).

Forest inventory

Nine assessments were carried out in 72 permanent sample plots of 500 m^2 laid out systematically over the plantation area in a regular grid of 320 × 320 m. In each plot, we measured the diameter at breast height (dbh), and the total height (h) with a Vertex IV hypsometer (Haglöf, 2007). In each plot, height measurements were performed in five dominant and five randomly selected trees. We estimated the total height and the volume over bark for the rest of the trees in each plot using the Gompertz hypsometric (Eq. 1) and Schumacher–Hall volume equations (Eq. 2), respectively. The dominant height (Dh) was determined according to the criterion established by Assmann (1970), which considers that the Dh is the average height of the 100 trees with the largest diameters in one hectare. The dataset was divided into two random groups covering all ages and site classes (Table 1): a database to develop the models (58 plots—80%) and a database to validate the models (14 plots—20%).

$$h = 24.392345\ e^{e^{(0.45230779 + 0.05900041\ dbh)}} \quad (1)$$

$$v = 0.000106486\ dbh^{1.9671}\ h^{0.5918} \quad (2)$$

where h is the total height (m); dbh is the diameter at breast height (cm); and v is the volume (m^3).

Site, growth, and yield modeling

We obtained site indexes using the generalized algebraic difference approach (GADA), focusing on three dynamic equations as candidates for determining the plantations’ productive capacity. We used the dynamic equations of Lundqvist–Korf, Cieszewski, and Schumacher (Table S1 [suppl]) (Cieszewski, 2001; Cieszewski & Strub, 2008; Tewari *et al.*, 2014). These equations allow polymorphic solutions since this behavior represents the growth of the main forest variables (Tewari *et al.*, 2014). The GADA methodology is based on changing certain parameters of the base model by explicit functions of X and may be adapted to account for the temporal correlation expected for longitudinal data of dominant height evolution. This is an unobservable independent variable that makes it possible to describe the productive capacity of the site (bioedaphoclimatic factors) (Souza *et al.*, 2022). The applied reference age (RA) was 9 years, as it is the most advanced and the closest to the rotation age (Campos & Leite, 2017).

The segmented Clutter model was used to model the thinned stands. It consists of a system of simultaneous equations in which the prediction of the parameters is performed using the ordinary least squares method in two stages. This model is the most indicated when there is simultaneity between the models (Gujarati & Porter, 2008), which allows the prediction of the basal area (Eq. 3) and volume (Eq. 4), and to simulate different thinning regimes (Clutter, 1963).

$$\mathrm{Ln}(BA_2) = \mathrm{Ln}BA_1\left(\frac{A_1}{A_2}\right) + \alpha_0\left(1-\frac{A_1}{A_2}\right) + \alpha_1\left(1-\frac{A_1}{A_2}\right)\mathrm{SI} + \mathrm{Ln}\varepsilon_i \quad (3)$$

$$\mathrm{Ln}(V_2) = \alpha + \beta A_2^{-1} + \gamma\,\mathrm{SI} + \sigma\,\mathrm{Ln}BA_2 + \mathrm{Ln}\varepsilon_i \quad (4)$$

where Ln is the natural logarithm; A_1 and A_2 are the current and future age (months), respectively; BA_1 and BA_2 are the basal areas in ages A_1 and A_2 ($m^2\ ha^{-1}$), respectively; V_1 and V_2 are the volumes in ages A_1 and A_2 ($m^3\ ha^{-1}$), respectively; SI is the site index (m); α_0, α_1,…, α_n, α, β, γ, and σ are model adjusted parameters; and ε_i is the random error.

To use the prognosis models, we verified the compatibility (path invariance) of the projections (Clutter, 1963; Campos & Leite, 2017), considering that the result of the projection from state t_0 to state t_1, and from t_1 to t_2 should be the same as the projection from t_0 to t_2. We obtained the initial basal area (BA_i) (input for the projection of the future basal area) from the corresponding model for each site class at 2 years, notably, $\mathrm{Ln}(BA_i) = 13.7850 + \left(\frac{-69.7777}{Dh_i}\right)$ simulating from 2 to 3 years, from 2 to 4 years, and from 3 to 4 years.

We considered the hypothesis that thinning technical age (TTA) and technical rotation age (TRA) occur when the maximum annual mean increment (MAI) of the projected volume ($m^3\ ha^{-1}$) is reached divided by the age of the stand at age (Leuschner, 1990). We carried out thinning simulations with different BA reductions (25, 30, 35, 40, 45, and 50%) by site classes over time to simulate stand growth until TRA. Using Clutter's equations, we determined the production of variable density, the graphic projection of growth, and the production of thinned stands. Using this information, we evaluated the consistency of the estimates over the effects of the initial basal area and site index on the TTA and TRA.

Selection and validation of the models

To evaluate the goodness of fit and verify the occurrence of bias, we used the following statistical criteria as a basis: the highest adjusted coefficient of determination ($R^2_{adj.}$) for the linear models (Clutter models for basal area and volume); the highest Pearson´s coefficient of correlation ($r_{\hat{y}y}$) for nonlinear models; the smallest root mean square error (RMSE) and root mean square percentage error (RMSPE); the smallest Bayesian information criterion (BIC); graphical analysis of the distribution of residuals in percentage; analysis of observed and predicted values; frequency histogram of the relative error test; significance of the regression parameters; and the normality of residuals verified by the Shapiro–Wilk test (Shapiro & Wilk, 1965).

The algorithm of the Levenberg–Marquardt function "nlsLM" from the software R package 'minpack.Im' (Elzhov *et al.*, 2016) was used to fit the Clutter models, applying instrumental variables (*proxy*). For GADA modeling, the nonlinear generalized least squares method, the "gnls" method, was used as a function of the 'nlme' package of R® software (R Core Team, 2022). We assumed an autoregressive structure of residuals, whose models were adjusted separately (García *et al.*, 2011). To account for this possible autocorrelation, we modeled the error term using a first-order continuous autoregressive error structure method that allowed the models to be applied to irregularly spaced and unbalanced data (Gregoire *et al.*, 1995).

The equivalence TOST test (two one-sided test) based on regression using bootstrap was used to validate the models using 20% of the total measured plots, randomly selected. This aimed to assess the equivalence between the predicted and observed values (Robinson *et al.*, 2005). The dissimilarity hypothesis was rejected or accepted according to the equivalence regions for the regression parameters (intercept and slope, with 25% at the 95% probability level and 1000 bootstraps). Linear regression was estimated between the observed and predicted values to calculate two confidence limits for the parameters and their respective comparisons with the estimated equivalence region.

Results

Site classification

Based on the selection criteria, we chose the Lundqvist–Korf model, which generated accurate estimates of the Dh (Table 2). The model presented the lowest values of BIC criteria, the highest r-value, and the lowest values for RMSE and RMSPE when compared to the other models, showing significance for regression coefficients ($p < 0.05$).

The distribution of the residuals (%) for this model did not show any bias in the Dh estimate, with a residual amplitude of less than ± 20% (Fig. 2a), presenting a high correlation between observed and predicted values (Fig. 2b),

Table 2. Results of growth models to estimate the dominant height of teak clonal plantations in Eastern Amazonia, Brazil.

Model	Parameters[1]	SE[2]	Precision indicators[3]			
			$r_{\hat{y}y}$	RMSE	RMSPE	BIC
Lundqvist-Korf	α = -36951.60	4751.499	0.962	0.678	4.719	764.975
	β = 117641.31	15168.286				
	γ = 0.630000	0.042				
Cieszewski	α = 22.741305	7.780661	0.959	0.719	5.005	806.873
	β = 3.302115	0.697304				
	γ = 0.814998	0.048407				
Schumacher	α = -4.315373	0.07790798	0.952	0.851	5.924	911.165

[1] α, β and γ: model parameters. [2] SE: standard error. [3] $r_{\hat{y}y}$: correlation coefficient; RMSE: root mean square error; RMSPE: root mean square percentage error; BIC: Bayesian information criterion.

and with residuals concentrated in the error central classes (Fig. 2c).

The curves generated by the Lundqvist–Korf model revealed that there were locations with distinct productive characteristics, resulting in a difference in productive potential, represented by the site indexes (SI) at 15, 17, and 19 m. As this model had a low error (0.678 m), the 2 m amplitude among the polymorphic curves was the one that represented all Dh values in all ages, with three site classes (Fig. 3). We observed that 18.1% (n = 13), 65.3% (n = 47), and 16.7% (n = 12) of the sampling plots from the inventory belonged to the classes of low, medium, and high productivity, respectively.

Modeling growth and yield

Clutter

The Clutter model produced good fitting indicators (R^2_{adj}, RMSE and RMSPE) with accurate and consistent projections of basal area and volume (Table 3). In the volume equation, the negative sign of the *β* coefficient (−6.906879) and the low value of the α coefficient (1.087015) corroborate the consistency for future volume projections. In addition, the behavior of these coefficients denotes an increase of a smaller magnitude for volume estimation. All estimated coefficients were significant (p < 0.05), demonstrating the relationship between the SI and both basal area and volume.

The distribution of residuals in percentage for basal area and volume was within ± 30% (Figs. 4a1 and 4a2), with high correlations between the values observed and predicted by the models (Figs. 4b1 and 4b2). Most errors were concentrated in residual classes of ± 10% (Figs. 4c1 and 4c2). The volume model showed no trends in estimates, while the basal area model showed slight trends to underestimate the basal area from 0 to 10 m^2 ha^{-1} and overestimate it from 25 to 35 m^2 ha^{-1}. However, these slight trends did not impact the models' prognostic power for basal area and volume.

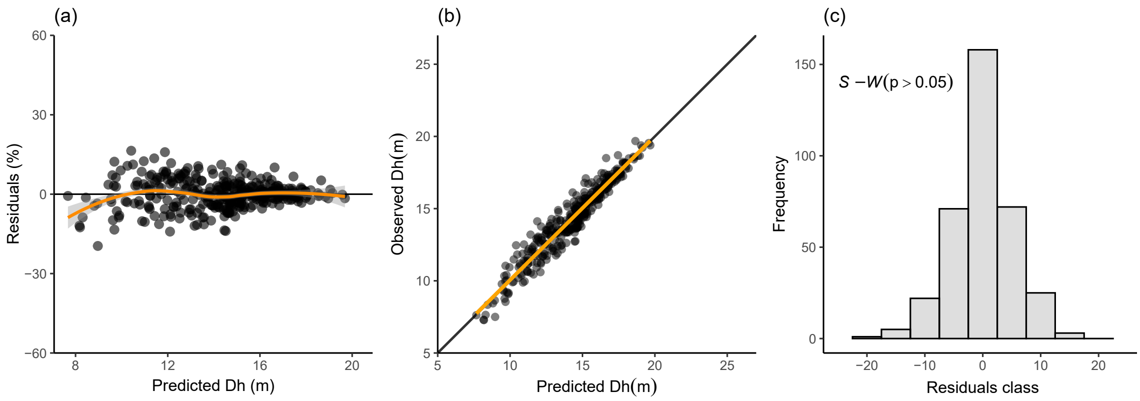

Figure 2. Distribution of residuals in percentage of the dominant height (Dh) growth model (a), correlation between observed and predicted values (b), and frequency histogram of the relative error generated by the Lundqvist–Korf model fitted to Dh (c) in teak clonal plantations in Eastern Amazonia, Brazil. The red and orange lines (LOESS and linear regression, respectively) represent the data tendency lines.

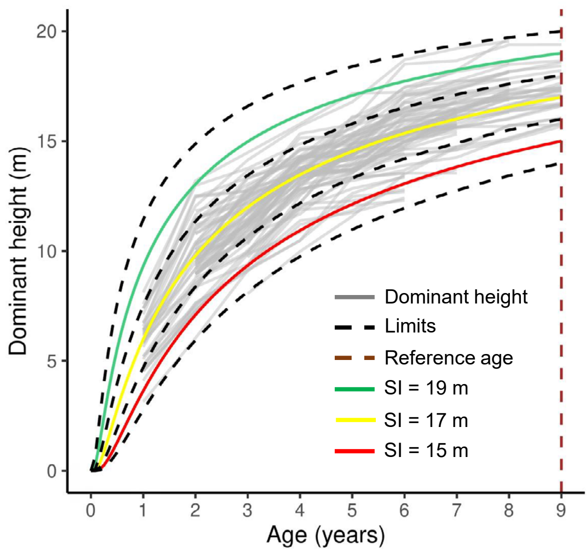

Figure 3. Site index (SI) curves for clonal plantations of teak in Eastern Amazonia, Brazil.

Validation of the models and compatibility of growth and yield

The Dh, basal area, and volume models were validated by the equivalence test (Table 4), confirming their accuracy in re-estimating their respective variables. This test ($\varepsilon = 0.25$ and $\alpha = 0.05$, with 1000 bootstraps) did not detect any statistical difference between the estimated and observed values. The dissimilarity hypothesis was rejected because the confidence intervals of the parameters of each model were found within the similarity region. Therefore, the Lundqvist–Korf (site) and Clutter (basal area and volume) models can be used to predict teak stands in the present study.

The compatibility test of the Clutter models for basal area and volume showed that both models were compatible, projecting the same value for basal area (16.96 $m^2 ha^{-1}$) and volume (88.51 $m^3 ha^{-1}$), at ages of 2 to 4 years and 3 to 4 years. This result allows the adoption of the Clutter model for projecting the growth and yield of teak stands.

Growth and yield of thinned stands

The theoretical stagnation of stand growth occurred when the mean monthly increment (MAI) reached its peak and coincided with its current annual increment (CAI) values in volume. The combination of BA reductions with three thinnings generated 56 different possibilities for silvicultural interventions. BA reductions of 50% (1st thinning), 50% (2nd thinning), and 25% (3rd thinning) were found to be the best combinations. This scheme resulted in higher growth and production in each site class; therefore, this was the thinning regime selected for projecting the volume production of plantations with and without thinning.

Simulations of several BA reductions showed that the thinning technical age varied according to the site class and was anticipated in the most productive sites. When projecting the stands without thinning, growth stagnation occurred at 3.5, 3.8, and 4.2 years for SI 19, 17, and 15 m, respectively, with a basal area reduction of 50%, as presented in Fig. 5 (c1, b1 and a1). The simulations of BA reductions generated the following TTAs:

- 1st thinning—50% of BA reduction in site indexes 15, 17, and 19 m: TTA at 4.2, 3.8, and 3.5 years, respectively.
- 2nd thinning—50% of BA reduction in site indexes 15, 17, and 19 m: TTA at 7.3, 6.5, and 6.1 years, respectively.
- 3rd thinning—25% of BA reduction in site indexes 15, 17, and 19 m: TRA at 12.8, 11.3, and 10.6 years, respectively.

The simulations projected TRAs of 13.9, 14.9, and 16.6 years for the high, medium, and low productivity capacity classes, respectively. The least productive site corresponded to 28.5% (73.50 $m^3 ha^{-1}$) of the final average production in the rotation age. However, the medium (86.58 $m^3 ha^{-1}$) and high (100.99 $m^3 ha^{-1}$) productivity sites corresponded to 33.16 and 38.68% of the final average production, respectively. The net production estimation increased by 8.12% (13.83 $m^3 ha^{-1}$), 8.37% (16.68

Table 3. Clutter model results for projecting basal area and volume of teak clonal plantations in Eastern Amazonia, Brazil.

Stand parameter	Parameter[1]	SE[2]	Precision indicators[3]		
			R^2_{adj}	RMSE	RMSPE%
Basal area	$\alpha_0 = 2.79492$	0.29292 ($p < 0.05$)	0.99	0.97	5.88
	$\alpha_1 = 0.04367$	0.01725 ($p < 0.05$)			
Volume	$\alpha = 1.087015$	0.091401 ($p < 0.05$)	0.97	5.71	6.06
	$\beta = -6.906879$	1.530770 ($p < 0.05$)			
	$\gamma = 0.029434$	0.006069 ($p < 0.05$)			
	$\sigma = 1.094510$	0.031195 ($p < 0.05$)			

[1] α, α_i, β, γ and σ: model parameters. [2] SE: standard error. [3] R^2_{adj}: adjusted coefficient of determination; RMSE: root mean square error; RMSPE: root mean square percentage error.

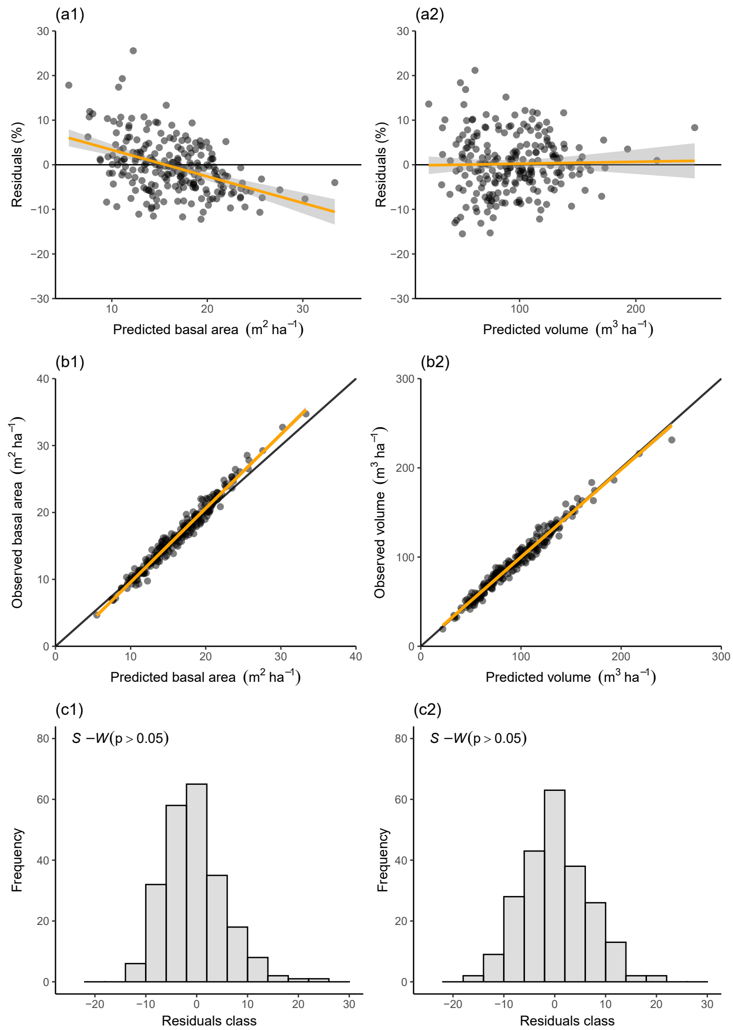

Figure 4. Distribution of residues (%) of the Clutter model in basal area (a1) and volume (a2), correlation between observed and predicted values for basal area (b1) and volume (b2), and frequency histogram of residues for basal area (c1) and volume (c2) in clonal plantations of teak in Eastern Amazonia, Brazil. The orange lines (LOESS and linear regression) represent the data tendency lines.

m^3 ha^{-1}), and 8.35% (19.43 m^3 ha^{-1}) for the low, medium, and high productivity of the site, respectively, compared to no thinning (Table 5).

Discussion

Site classification

The Lundqvist–Korf model has provided a precise and realistic adjustment of the Dh as a function of age, with an error of less than 5%. The SI polymorphic curves showed consistency in height prediction with the use of GADA. Tewari *et al.* (2014) also reported similar findings when performing SI modeling for teak stands in India. Tewari *et al.* (2014) and Cañadas-López *et al.* (2018) also pointed out that this method can be used in stands of this species to determine their productive capacity. This is justified by the possibility of explaining GADA according to the growth rate and the asymptote in such a way that one more parameter of the model depends on the productive capacity, generating more flexible curves with polymorphism and multiple asymptotes (Cieszewski & Bailey, 2000).

The polymorphic curves reflected the evolution line trend for the observed values of Dh, suggesting that the approach of the algebraic difference is efficient in determining the site indexes, even in stands that have not yet reached the rotation age (Tewari *et al.*, 2014; Cañadas-López *et al.*, 2018; Souza *et al.*, 2022) (Fig. 3). The SI curves showed that the study area presented suitable conditions for the establishment of clonal teak plantations, with two meters of amplitude and three productivity classes (SI = 15, 17, and 19 m), as also observed by Souza *et al.* (2022), when assessing the same fertilized teak stands as in the present

Table 4. Validation of dominant height, basal area, and volume models of teak clonal plantations in Eastern Amazonia, Brazil.

Model	Parameter	Confidence interval	Similarity region	Dissimilarity
Dominant height	Intercept	13.727 ± 14.109	13.632 ± 14.132	Reject
	Slope	0.913 ± 1.070	0.750 ± 1.250	Reject
Basal area	Intercept	2.756 ± 2.797	2.502 ± 3.002	Reject
	Slope	0.916 ± 1.071	0.750 ± 1.250	Reject
Volume	Intercept	4.460 ± 4.506	4.206 ± 4.706	Reject
	Slope	0.923 ± 1.067	0.750 ± 1.250	Reject

study. According to Bermejo *et al.* (2004), the variability of the sites highlights the importance of using the SI for modeling and forecasting growth and productivity in cases where most sites are in the intermediate yield class and a smaller number of sites belong to high and low production potential. This is in accordance with the findings of the present study.

The SIs determined in this research for non-clonal teak stands proved to be better than those found in similar studies carried out in Bangladesh (Upadhyay *et al.*, 2005), and

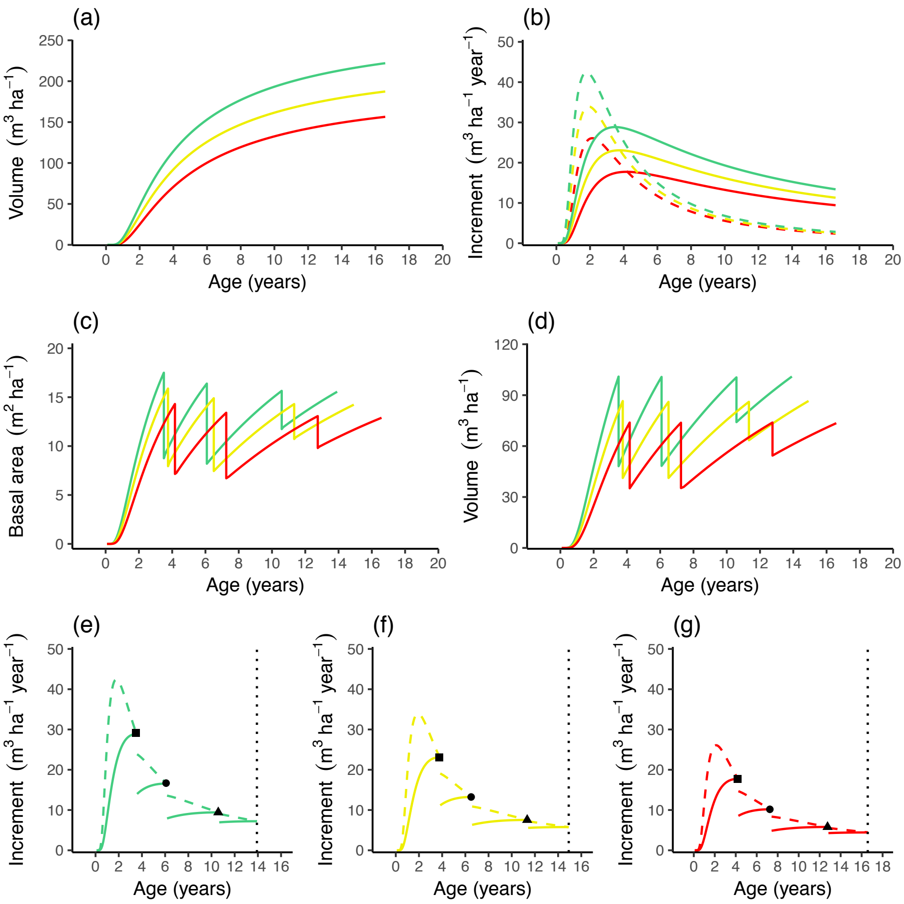

Figure 5. Growth and production curves by productivity class. Dashed lines represent the current annual increment (CAI) and the continuous average annual increment (MAI) (graphs: b, e, f, and g). Green lines indicate the 19 m site class; yellow lines represent the 17 m site class; and red lines represent the 15 m site class. The vertical dashed lines and black dots represent the moment when the MAI reaches its maximum (graphs: e, f, and g). (a) represents production and (b) volume increments in the scenario without thinning; (c) represents the projections for basal area and (d) volume in the thinning scenario in clonal teak plantations in Eastern Amazonia, Brazil.

Table 5. Volume production with and without thinning in clonal plantations of teak in Eastern Amazonia, Brazil.

	TTA[1]			TRA[2]	Total (m^3 ha^{-1})	Difference (m^3 ha^{-1})	Gain (%)
	1st	2nd	3rd				
Low productive capacity (SI = 15 m)							
Age	4.2	7.3	12.8	16.6			
With thinning	38.75	38.54	19.50	73.50	170.29	13.83	8.12
No thinning	-	-	-	156.45	156.45		
Medium productive capacity (SI = 17 m)							
Age	3.8	6.5	11.3	14.9			
With thinning	45.33	44.85	22.65	86.58	199.42	16.68	8.37
No thinning	-	-	-	182.74	182.74		
High productive capacity (SI = 19 m)							
Age	3.5	6.1	10.6	13.9			
With thinning	52.82	52.44	26.39	100.99	232.65	19.43	8.35
No thinning	-	-	-	213.22	213.22		

[1] TTA: thinning technical age; 1st, 2nd and 3rd: first, second and third thinning, respectively. [2] TRA: technical rotation age. Reference age: 9 years.

India (Sajjaduzzaman *et al.*, 2005). Investigating SIs for the same clonal teak stands, Souza *et al.* (2022) used the algebraic difference approach and found site indices close to those reported in this study at a reference age of 10 years (SI = 15.5, 17.5, and 19.5 m). This comparison reaffirmed that the approach, number of classes, class range, and site indices were consistent with the reality of the stand under study. Such results indicate that planting the species in locations in Brazilian Amazonia can be successful when submitted to soil fertilization. Thus, annual monitoring is essential to obtain reliable information about the variables of interest, to calibrate the models, and to make them more accurate (Upadhyay *et al.*, 2005).

Production of thinned stands

Clutter's segmented model was efficient in predicting the basal area and volume projection. In the study by Novaes *et al.* (2017), the Clutter model was used to estimate the growth and yield of teak in non-thinned plantations in the state of Mato Grosso, Brazil. The authors reported accurate projections, with estimated errors below 10%. Similar results were also observed in the present study, even in the non-thinning scenario. These results highlight the efficiency of the Clutter model for estimating teak behavior.

The use of the Clutter model for estimating basal area and volume showed consistent behavior for forecasting basal area and volume, as confirmed by the compatibility test. This is an important condition for obtaining good estimates of these variables in forest stands (Roveda *et al.*, 2016; Campos & Leite, 2017). Other studies predicting future volumes with the same model in *Eucalyptus* sp. plantations, *e.g.,* Azevedo *et al.* (2016), Pereira *et al.* (2016), and Roveda *et al.* (2016), also obtained suitable fitting quality and validation, corroborating the results of our study. In addition, our results showed the efficiency of this model in predicting the future volume of thinned stands at different ages and spacings.

Growth and yield behaviors were compatible with yield classes, technical thinning, and rotation ages. The technical ages were expected earlier in high-productivity sites, corroborating the results reported by Leite *et al.* (2011) and Souza *et al.* (2022) in Brazil and Bermejo *et al.* (2004) in Costa Rica. In our study, the thinning age intervals were not greater than four years, which is different from what was found by Bermejo *et al.* (2004), in which the simulated thinning intervals were five years. Projections of growth and yield of clonal plantations of the species at each site helped decision-making about the timing for silvicultural interventions, especially thinning.

Simulations projected growth stagnation earlier in highly productive sites, corroborating studies conducted elsewhere (*e.g.*, Nunifu & Murchison, 1999; Bermejo *et al.*, 2004). The growth of teak increased rapidly until it coincided with the inflection point of the accumulated growth curve, where the MAI and CAI values coincided (Fig. 5). This behavior is characteristic of homogeneous and even-aged stands, occurring earlier in denser plantations and more productive sites (Bermejo *et al.*, 2004; Medeiros *et al.*, 2017; Pachas *et al.*, 2019).

In Brazil, in teak plantations originating from seeds, rotations of 20–25 years are usual, with three or four thinnings applied at intervals of four to six years, whose intensity varies according to the region and silvicultural objective (Bezerra *et al.*, 2011). In other studies, such as those by Bermejo *et al.* (2004) and Cañadas-López *et al.* (2018), four thinnings were applied in rotations ranging from 15–25 years, according to the site potential. In our study, the simulations projected rotation ages varying from 13.9 to 16.5 years, reducing by 1.1 and 8.5 years relative to the ages reported by those authors.

This study revealed the superiority of clonal stands compared to seed stands since rotations of 20–25 years are usually expected in plantations of seed origin, as reported by Bezerra *et al.* (2011). Our results showed no evidence to reject the hypothesis formulated for the silvicultural prescriptions, *i.e.,* three thinning interventions with a basal area reduction of 50% (1st thinning), 50% (2nd thinning), and 25% (3rd thinning), with intervals of less than five years and rotation of less than 20 years. In addition, thinning produced larger diameters and volumes per tree, which would add more value to the wood in future harvests (Fig. 5), as also suggested by Seta *et al.* (2021) studying clonal teak plantations.

Several studies demonstrate that genetic breeding and silvicultural treatments can reduce rotation; however, they do not necessarily improve wood quality (*e.g.,* Hidayati *et al.*, 2013; Seta *et al.*, 2021) or the amount of heartwood, which is the portion of the stem that aggregates a higher value (*e.g.,* Moya *et al.*, 2020). For Hidayati *et al.* (2013), wood properties can be enhanced through genetic improvement programs aimed at this purpose, aligning the yield increase with the wood quality of this species.

Therefore, the present study focused on the yield of clonal teak stands, trying to determine suitable technical conditions for thinning interventions. Thus, we found that the interval between thinning ages was less than five years. We also found that the simulations with three thinnings aiming at the basal area reduction of 50%, 50%, and 25% maximized an average of 8.3% of the production, in comparison to the scenario with the absence of thinning. The productive gain of the remaining trees can be even greater with the recommended thinning system, as this technique is responsive in diametric growth, and this variable is responsible for the commercial value of teakwood, together with the proportion of heartwood. Furthermore, technical rotation ages were anticipated in comparison to plantings from seeds. This study is aligned with Brazilian and international initiatives of genetic improvement and better teak management, aiming to increase the gains of production in less time.

Authors' contributions

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