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Spatial variability of the productive capacity of teak (*Tectona grandis* Linn F.) plantations in the eastern Amazonia

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Abstract

Application of geostatistics in mapping the productive capacity of forest stands is an important tool to guide decision making regarding precision silviculture. In this study, we investigated the productive capacity of teak clonal plantations and its spatial dependence, making the site mapping possible. We also investigated the influence of soil chemical attributes on productive potential. We used dominant height, age and geographic coordinates data from plots during five evaluations in clonal teak plantations of different ages. We performed the classification of the forest sites by the guide-curve method. The principal components analysis was used to group the forest stands according to soil chemical attributes (available P and exchangeable K, Na and Mg). The spatial variability analysis of productive capacity was carried out through geoestatistics. The results show that the productive capacity has spatial dependence. The exponential model has provided the best estimates of dominant height, revealing that 69.2% of the mapped area was from medium and 30.8% from high productive capacity. The multivariate analysis showed that soil fertility has influenced the productive capacity, discerning the most productive sites, in agreement with the soil quality. The geostatistical technique was efficient to estimate the productive capacity in unsampled areas, revealing sites with different productive potentials and their response to edaphic factors. This may assist in the efficient management of planting, when establishing silvicultural actions in specific locations, which are identified in the planted area maps, reducing the management costs.

Keywords: Dominant height; geostatistics; kriging; multivariate analysis; productivity; teak.

Abbreviations: A_age; APD average percentage deviation; R^2_{ad}%_the adjusted determination coefficient; S_{yx}%_standard error the estimate Ca_calcium; R^2_determination coefficient; DBH_diameter at 1.3 m from the ground; Dh_dominant height; H_total height; K_potassium; MC_main component; Mg_ magnesium; Na_sodium; PCA_principal component analysis; RA_reference age; RSS_residual sum of squares; SDI_spatial dependence index; SI_site index; WV_weighted value.

Introduction

Tectona grandis Linn F. (teak) is a tropical timber species of the Asian continent, which has adapted very well to the tropical and sub-tropical climate in Brazil. The species has an economic impact and great relevance in the country´s forest scenario, being widely used in plantation forestry due to the high value of its timber (Chaiyasen et al., 2017; Oliveira et al., 2019). Furthermore, teak has relevant industrial qualities that allow its use for several purposes such as shipbuilding and carpentry among others, in addition to its long durability, good dimensional stability, resistance, and aesthetic qualities (Tewari and Mariswamy, 2013).

Teak plantations have expanded significantly in Brazil due to the high demand and appreciation in the international commerce, mainly the Indian and Chinese markets (Quintero-Méndez and Jerez-Rico, 2017; Zhou et al., 2017). Some silvicultural studies have focused on increasing the productivity of *T. grandis* plantations. Among them we cite the initial planting spacing (Pachas et al., 2019), application of coppice techniques (Auykim et al., 2017), determination of optimal age for thinning and projection of growth and production (Bermejo et al., 2004; Berrocal et al., 2020).

Important advances in these aspects have been observed elsewhere but as far as the Amazon region is concerned there is a lack of studies concerning the productive capacity of teak plantations. Research on this subject is of great importance regarding the optimization of forestry practices to reduce silvicultural costs. This directly influences evaluation of the feasibility forest management and decision making about establishing *T. grandis* forests (Socha et al., 2017; Silva et al., 2018).

Determining the productive capacity of forest stands is essential for growth and yield projection (Socha et al., 2017; Silva et al., 2018; Wu et al., 2019). This requires information of forest inventories for projecting growth and yield by means of dominant height models (Weiskittel et al., 2009; Scolforo et al., 2019a, b). Productivity of forest plantations, in many cases, is carried out using traditional methods, which employ a measure of central tendency and dispersion to explain a given phenomenon, without assessing the possible correlations between neighboring observations and are therefore susceptible to errors (Pelissari et al., 2014).

In this context, modern management techniques can be used based on previous information about the genetic and spatial variability attributes of forest stands of interest to the forester (Pelissari et al., 2017; Mulyadiana et al., 2020). Such knowledge about the spatial variability of forest stands can be an important tool for managing silvicultural activities, providing specific and precise interventions through studies of spatial dependence of the interest variable (Pelissari et al., 2014).

Spatial dependence can be studied by geostatistics technique based on the geographic position of the interest variable (Raimundo et al., 2017). It allows the development of semivariograms and the subsequent construction of kriging maps and can reveal the limiting factors i.e. nutrients, water and light in each forest site (Carvalho et al., 2012). Therefore, the use of this tool may enable studies about the spatial variability of the dominant height for the productive capacity analysis of the forest site. This tool may allow the delimitation of homogeneous management sites for applying silvicultural practices in a more precise way along the crop rotation (Pelissari et al., 2014).

Many gaps still exist in studies that seek to integrate different forest variables by means of geostatistics (Amparán et al., 2019) such as the productive capacity of forest stands (Pelissari et al., 2014). In this study, we assessed whether the productive potential of clonal teak stands has spatial dependence, making it possible to map the stand site through geostatistical analysis. We also investigated whether the soil chemical attributes have influence on the productive potential of these stands.

Results

Site index modelling of the teak stands

All models adjusted to the data from the *T. grandis* plantations presented highly significant values of F (p <0.05), highlighting the existence of regression (Table 2). The values of the adjusted determination coefficient (R^2_{ad}%) ranged from 78.7% to 94.8%, those of standard error the estimate (S_{yx}%) from 9.1% to 11.2%, while the average percentage deviation (APD%) ranged from -1.2% to -0.2%.

When applying the criteria used for selecting equations and considering the analysis of the weighted values, it was observed that the best estimate for the dominant height guide curve was obtained by Prodan´s equation (4). The adjusted coefficient of determination revealed that nearly 95% of the variation of Dh was explained by the stand age. The result of S_{xy}% showed that the values of Dh estimated by the equation oscillated, on average, 9.5%, when compared to real values. The APD% indicated that the selected equation overestimated Dh values by 0.2%. The coefficients were highly significant (p <0.01). The residues dispersion showed an amplitude error of ± 40% in the early ages of the plantations and was reduced to 20% from the third year onwards (Fig 2). However, this distribution of residuals does not prevent the use of this equation, considering the result for APD%, close to zero.

The results allowed to discriminate sites with different bio edaphoclimatic characteristics, showing a difference of productive potential in with site index classified as high (SI = 15.8 m), average (SI = 13.3 m), and low (SI = 10.8 m) productivities (Fig 3). The site index curves showed an unstable Dh behavior among the age classes up to the second year. On the other hand, older plantations showed a stability in the growth pattern (Dh) adequately represented by the generated curves.

The dominant height model was validated by the equivalence test (Table 3), confirming their accuracy for re-estimating their respective variable. This test (ε = 0.25 and α = 0.05, with 1000 bootstrappings) indicated that there was no statistical difference between the estimated and observed values. The dissimilarity hypothesis was rejected for the model, because the confidence intervals of the parameters of each model were found within the similarity region.

Geostatistics

The descriptive statistics of Dh revealed that the mean is higher than its respective variance, indicating a higher homogeneity of the data. Dh presented a coefficient of variation less than 10%, being considered low and characteristic of homogeneous data. As for skewness and kurtosis, the results were also considered low (between - 1 and 1) (Table 4).

The models showed a low variation in the quality of the adjustments, with low nugget in relation to their respective sill, causing a satisfactory spatial dependence to ensure a greater control of spatial variability over Dh variation. The exponential model generated better estimates of the Dh variable based on SDI analysis (1.35%), R^2 (82.3%), and residual sum of squares (RSS) (0.245). Thus, this model was selected for the construction of the Dh kriging map of the *T. grandis* plantation at the reference age (Table 5).

The determination coefficient (R^2) values of the evaluated models were considered suitable (> 79%) for estimating the spatial variability, since this criterion measures the ability of the model to estimate the response variable. The RSS was low (<0.5), with values close to zero and SDI indicating a strong degree of spatial dependence.

Based on the established site index classes, it was found that 30.8% (112.6 ha) and 69.2% (253 ha) are classified as high and medium productivity, respectively (Fig 4). Stands 11, 12 and 13 had medium production capacity, with a total area of 88.65 ha (24.3%) and Dh ranging from 12 to 14.4 m. Differentiated production units within the same stand (8, 9, 10 and 14) were also checked, adding up to an area of 223.46 ha (61.1%). Stands 15 and 16, whose total area was

53.27 ha (14.6%), showed high productive capacity, with values of Dh> 15 m.

The zones of least uncertainty (close to 0 m) are located exactly on the points where the measurement plots were installed, while the areas farthest from the sample plots showed higher error ranges, suggesting a centrifugal behavior of the variable estimate (Fig 4). In the most distant areas, higher errors (around 1m) of Dh estimate were observed, representing 7% in relation to the population average. This value is considered acceptable for individuals from 12 m in planted forests and is within the limit of the absolute error of 1.14 m, generated by the Prodan equation

Multivariate grouping of the stands

The principal components analysis (PCA) revealed that the first two components explain 85.9% (PC1 = 57.09% and PC2 = 28.86%) of the data variability of soil chemical attributes and dominant height (Fig 5.). The variables that most influenced the latent variables were Dh, Mg, Ca and K, for PC1; Na, K, and Mg, for PC2 (Table 6).

The dispersion of forest stands as a function of the scores and eigenvectors obtained in the PCA can be observed in Fig 5. Three distinct groups of stands with similar soil chemical characteristics and similar Dh were formed. Notoriously, group 1, formed by stand 16, was more distinct in comparison to the others, with more divergent soil and planting characteristics, such as the values of K (11.00 $\mathrm{cmol_c\ dm^{-3}}$), Ca (2.50 $\mathrm{cmol_c\ dm^{-3}}$), and Mg (1.41 $\mathrm{cmol_c\ dm^{-3}}$) (Table 7).

Groups 2 and 3 were formed by intermediate stands. Group 3, composed by stands 10, 11 and 15, it was more latent of the chemical attributes, especially K and Na soil contents, evidencing the influence of these basic cations in these stands. Group 2 showed greater proximity to the other chemical attributes and to Dh values, when compared to the stands belonging to group 3, which had virtually no influence of the variables analyzed. The order of the best groups of stands is the following: 1 > 3 > 2.

Discussion

The Prodan model that applied in this work performed better considering the values of R²aj and Syx%, when compared to the results reported by Conceição et al. (2012) who reported different values on *T. grandis* seminal plantations at the age of 26 years (R^2_{ad}= 0.69 and S_{yx}%= 14.27%) in Monte Dourado region, eastern Amazon. Regarding the analysis of dispersion of residues, an unstable distribution was observed in the early ages of plantations. However, this distribution does not preclude the use of Prodan´s equation, since the result for APD% was slightly close to zero. There is a tendency towards the homogenization of Dh and, consequently, stabilization, within their respective site curves, as the biological rotation age approaches (Machado et al., 1997).

In addition, this study corroborates the fact that the 2.5 m interval is not sufficient to encompass all data in the early ages. This fact was also observed in young plantations of T. grandis in the state of Mato Grosso - Brazil, where the observed results of Dh were outside the curves (Ziech et al., 2016; Vendruscolo et al., 2019). An alternative to keep Dh values within the limits of the curves, is the use of intervals between larger classes and/or increase the number of classes. Adopting an interval greater than 4 or 5 m is recommended, since the adoption of smaller intervals would be inconsistent with the actual behavior of *T. grandis*, as it does not have accelerated growth in height at the early ages, which could confuse the understanding biological (Pachas et al., 2019).

The results of adjustments of all semivariogram models were satisfactory, allowing interpolation of data by kriging, with low SDI values. High values of this parameter would represent a local distribution with low symmetry; and therefore, with small influence on space variation (Grego et al., 2006). When analyzing the spatial variability of total timber volume of *T. grandis* stands, Pelissari et al. (2017) reported similar results to this study regarding the strong spatial dependence of that variable. Our results also demonstrated the efficiency of using geostatistics as a silvicultural planning tool, especially when based on the site index. Parresol et al. (2017) observed the existence of correlation between the site index and other variables with spatial variability mapped through kriging, as also obtained by the present research.

The spherical, Gaussian, and exponential models presented different range values (α). This attribute indicates the maximum distance in which the influence of space on the variability of Dh occurs. It is necessary that the α is not greater than the distance between the two most distant sample points. Thus, α values that are not very high are a desirable characteristic in semivariogram models, in order to avoid estimation errors (Yamamoto and Landim, 2013). SDI% is a fundamental criterion to predict Dh in the non-sampled areas (Yamamoto and Landim, 2013). This criterion consists of the categorization of spatial dependence by calculating the proportion between the nugget effect and its respective sill. It therefore consists of one of the most efficient ways of inferring about the degree of regionalization of variables (such as Dh), through the theoretical semivariogram (Cambardella et al., 1994).

In summary, all fit quality criteria (R², RSS and SDI%) indicated that the exponential model proved to be efficient in Dh spatialization. This result corroborates the observations of Kingsley et al. (2019) on the exponential model as one of the best semivariogram adjustments. The exponential model is suitable to fit volume and basal area data, thus being indicated to estimate the spatial variability of these dendrometric parameters (Pelissari et al., 2014). Despite this, spherical and Gaussian models generate good adjustments to estimate the spatial variability of the volume in of *T. grandis* stands (Santos et al., 2017). The results of the productive capacity demonstrate that external factors still occurred to the point of differentiating local productive units in the population, despite using improved genetic material in the plantations, applying the same management system and having a topography without significant variation. As mentioned by Vaides-López et al. (2019), edaphoclimatic factors directly influence the quality of a forest site, affecting its productivity.

The analysis of the eigenvector signals revealed the type of association between the variables and the main components. Thus, the best Dh were found when the CP1 values were high and CP2 low. Elevated CP1 values indicated plots with a high K, Na, Ca content. In contrast, reduced CP2 values resulted in more fertile soils and elevated Dh in the *T. grandis* plantations.

In the plots that formed group 2, we observed the importance of the complementary fertilization to improve the chemical properties of the soil and increase the production potential of the sites.

Table 1. Selected growth models for fitting the dominant height of the *T. grandis* clonal planting in eastern Amazonia, Brazil.

Nº	Model	References
1	$Dh = \beta_0 + \beta 1\ A + \beta 2\ A^2 + \beta 3\ A^3 + \varepsilon_i$	Machado (1980)
2	$Dh = \beta_0\ A^{\beta 1} + \varepsilon_i$	Campos e Leite (2017)
3	$Dh = \beta_0\ e^{\beta 1\ A} + \varepsilon_i$	Scolforo (2006)
4	$Dh = A^2/(\beta_0 + \beta_1 A + \beta_2 A^2) + \varepsilon_i$	Prodan (1968)
5	$Dh = e^{(\beta 0 + \beta 1\ 1/A)} + \varepsilon_i$	Machado (1980)
6	$Dh = \beta_0\ e^{(\beta 1\ Ln\ A\ +\ \beta 2\ (Ln\ A)^2)} + \varepsilon_i$	Scolforo (2006)

Dh= dominant height; β_i= regression parameters; A= age; ε_i= random error.

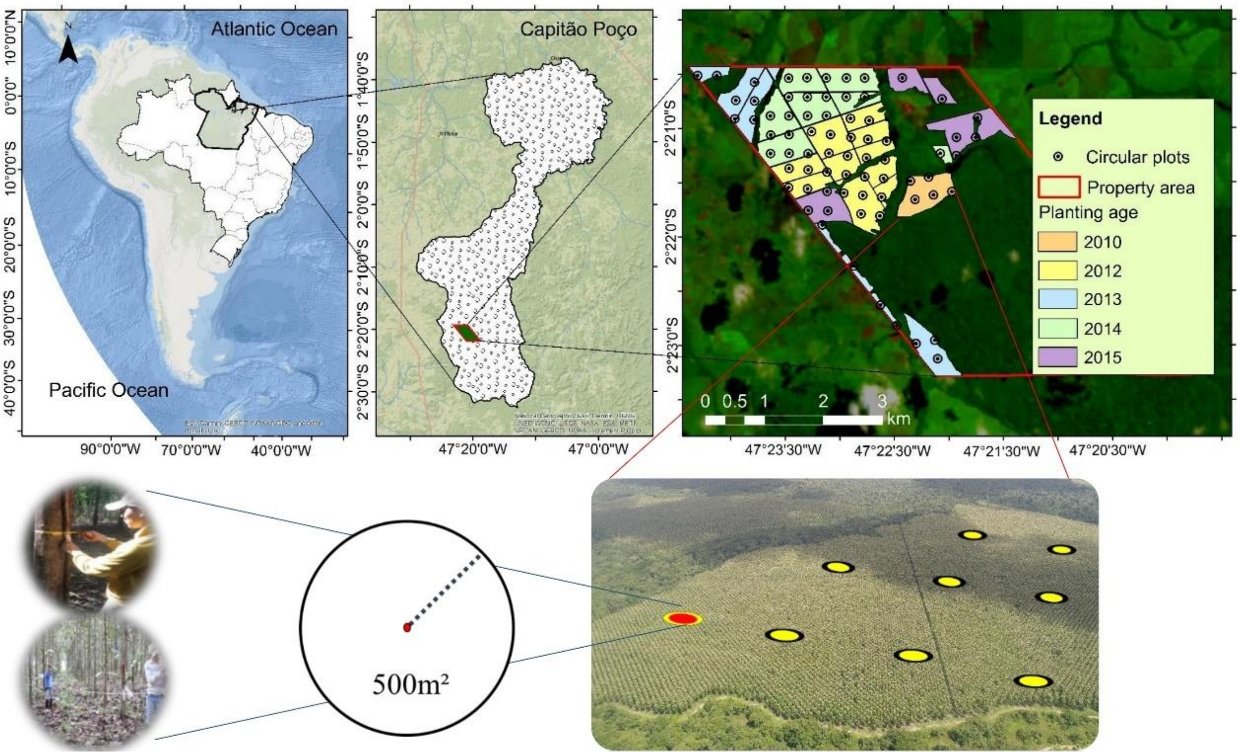

Fig 1. Study area location, spatial arrangement, separation and size of sampling plots by age and other measurement procedures in *T. grandis* clonal plantations, in eastern Amazonia, Brazil.

Table 2. Results of regression analysis and selection criteria for the best model for dominant height of *T. grandis* clonal plantations in the eastern Amazonia, Brazil.

Model number	Coefficient	t Test	$R^2_{ad}\%$	$S_{yx}\%$	APD	F	WV
1	$b_0 = 4.69569$	< 0.001	85.03	9.5	-1.2	332.2 *	9
	$b_1 = 3.57858$	0.0032					
	$b_2 = -0.40368$	0.3678					
	$b_3 = 0.02656$	0.5949					
2	$b_0 = 2.04336$	< 0.001	83.05	9.1(1)	-0.6	858.6 *	6
	$b_1 = 0.44048$	< 0.001					
3	$b_0 = 1.93479$	< 0.001	79.38	10.8(1)	-0.8	674.8 *	13
	$b_1 = 0.17863$	< 0.001					
4	$b_0 = -0.06875$	0.0003	94.84	9.5(1)	-0.2	7429.8 *	5
	$b_1 = 0.16376$	< 0.001					
	$b_2 = 0.03348$	< 0.001					
5	$b_0 = 2.83391$	< 0.001	78.68	11.2(1)	-0.8	646.7 *	16
	$b_1 = -0.82089$	< 0.001					
6	$b_0 = 2.04802$	< 0.001	82.99	9.56(1)	-0.6	427.9 *	10
	$b_1 = 0.41186$	< 0.001					
	$b_2 = 0.01876$	0.5621					

$R^2_{ad}\%$= adjusted coefficient of determination; $S_{yx}\%$= standard error of the estimate in percentage; APD%= average deviation in percentage; F= calculated value of the F test; WP= weighted value, (1)=recalculated estimation error; *= significant at 5% level ($p \leq 0.05$).

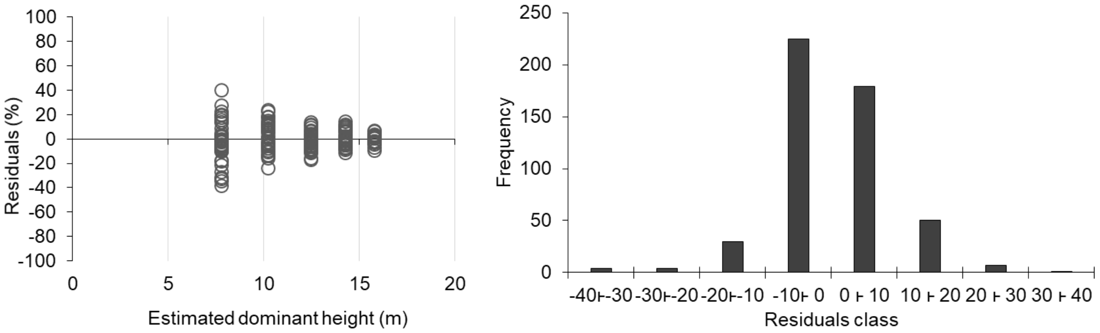

Fig 2. Distribution of estimation errors in percentage and histogram of frequency of the absolute error, generated by the Prodan model for the estimate of dominant height of *T. grandis* clonal plantation in the eastern Amazonia, Brazil.

Table 3. Validation of the dominant height model in clonal planting of *T. grandis* in eastern Amazonia, Brazil.

Parameters	Confidence interval	Similarity region	Dissimilarity
Intercept	11.56899 ± 12.107	9.177 ± 15.295	Reject
Slope	0.750 ± 0.945	0.749 ± 1.250	Reject

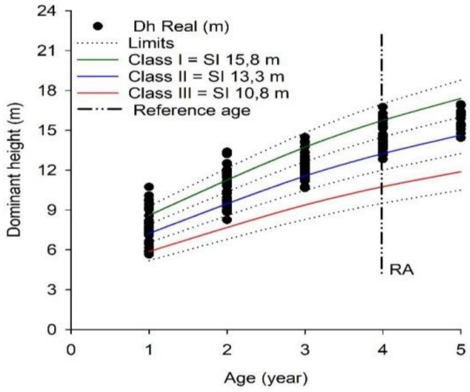

Fig 3. Site Index curves for *T. grandis* clonal plantations in the eastern Amazon. The points represent the observations at different ages of the dominant height. The dashed lines represent the class boundaries. The lines in green, blue and red represent classes III, II and I. Vertical dashed line represents the reference age.

Table 4. Descriptive statistics of dominant height (Dh) of *T. grandis* clonal plantations in eastern Amazonia, Brazil.

Variable	Average (m)	s (m)	Variance	CV (%)	Asymmetry	Kurtosis	Normality
Dh	14.36	0.93	0.87	6.5	0.73	-0.24	$p > 0.05$

s= standard deviation; CV%= variation coefficient; Dh= dominant height.

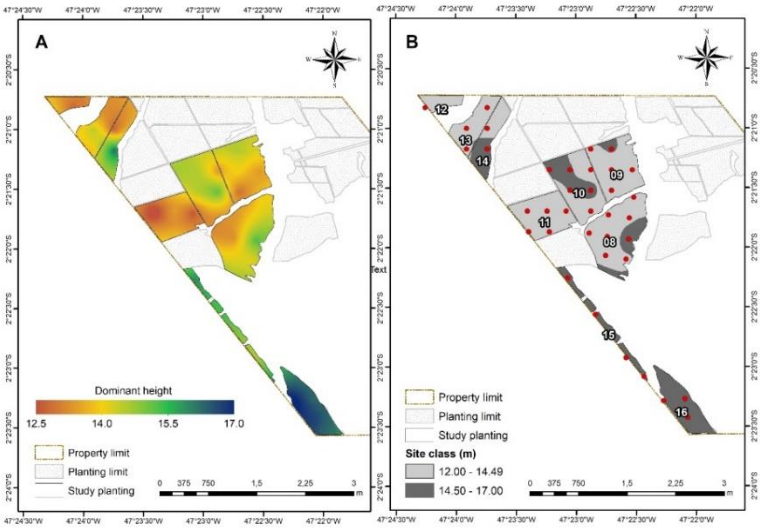

Fig 4. Kriging map and uncertainty map showing the gradient of dominant height from red (least productive) to blue (most productive) (A) and classes of productive capacity (B) in *T. grandis* clonal plantations in the eastern Amazonia, Brazil.

Table 5. Characteristics of the semivariogram models selected to predict the dominant height of *T. grandis* clonal plantations in the eastern Amazonia, Brazil.

Model	C_0	$C_0 + C_1$	SDI (%)	α (m)	DSD	R^2 (%)	RSS
Spherical	0.0150	0.7363	2.04	1818.00	Strong	80.9	0.320
Gaussian	0.0190	0.7364	2.58	1183.16	Strong	79.9	0.425
Exponential	0.0010	0.7383	1.35	2260.8	Strong	82.3	0.245

C_0= nugget; $C_0 + C_1$= sill; SDI= spatial dependence index; α= range; DSD= degree of spatial dependence; R^2= coefficient of determination; RSS= residual sum of squares.

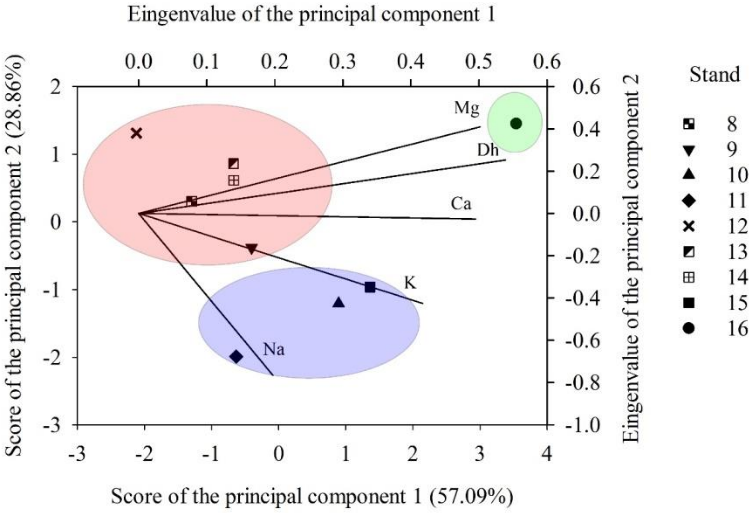

Fig 5. Multivariate grouping of forest stands of *T. grandis* clonal plantations in eastern Amazonia, Brazil. Shapes in pink, blue, and green represent the three groups formed.

Table 6. Eigenvectors of the first two principal components of the soil chemical attributes and dominant height of *T. grandis* clonal plantations in the eastern Amazon, Brazil.

Variable	PC1	PC2
K ($cmol_c$ dm^{-3})	0.4172*	-0.4257*
Na ($cmol_c$ dm^{-3})	0.1972	-0.7657*
Ca ($cmol_c$ dm^{-3})	0.4950*	-0.0267
Mg ($cmol_c$ dm^{-3})	0.5015*	0.4096*
Dh (m)	0.5391*	0.2530

PC1 and PC2= principal component 1 and 2; K= potassium; Na= sodium; Ca= calcium; Mg= Magnesium; Dh= dominant height; *= Variables with significant contribution to the principal components.

Table 7. Average values of soil chemical attributes and growth of *T. grandis* clonal stands, in the eastern Amazon, Brazil.

Group	K ($cmol_c.dm^{-3}$)	Na ($cmol_c.dm^{-3}$)	Ca ($cmol_c.dm^{-3}$)	Mg ($cmol_c.dm^{-3}$)	Dh (m)
1	11.00 ± 0.00	3.64 ± 0.00	2.50 ± 0.00	1.41 ± 0.00	16.33 ± 0.00
2	6.27 ± 0.72	3.59 ± 0.77	0.99 ± 0.46	0.35 ± 0.13	14.08 ± 0.33
3	10.83 ± 1.61	5.21 ± 0.11	1.42 ± 0.78	0.36 ± 0.90	14.43 ± 0.90

K= potassium; Na= sodium; Ca= calcium; Mg= Magnesium; Dh= dominant height.

This was confirmed by the values of the dominant height (Dh). In plots belonging to group 3, there is a need for a more rigid fertilization program to increase planting productivity. The better response of this stand to cationic nutrients should have provided higher Dh values (16.33 m), evidencing their influence on the growth in height of individuals. The elaboration of fertilization programs for T. *grandis* must be constant, since the species has specific nutritional requirements, which if not meet, compromises the productivity of the plantations, and consequently, the crop rotation (Chanan et al., 2019).

Plants with levels considered adequate for cationic nutrients (Ca, Mg, and K) and beneficial elements such as Na, present better photosynthetic performance, biomass production and accumulation and, consequently, better growth (Fernandes et al., 2019). Mg has a vital function in the vegetative growth of species, since it participates in several reactions in photosynthesis, also as a central component of chlorophyll molecules (Lima et al., 2016; Silva et al., 2017).

Calcium, in turn, is essential for cell development and division, processes that are also essential for vegetative growth, in addition to being particularly important in flowering and fruiting plants. In trees, Ca is a nutrient commonly found in the bark due to its low mobility, with structural function in the cell membrane. It gives rigidity to the cell and tissues and controls the selective permeability of the membranes (Fernandes et al., 2019).

In addition to their availability for absorption by the root system of trees, the increase in the exchangeable levels of Ca and Mg in the soil can provide a decrease in soil acidity. This is due to the increased occupation of negative colloidal charges in the soil by these nutrients, decreasing the occupation by acid cations, such as exchangeable aluminum, which give acidity to the soil, a limiting factor for the growth of plant species. The limestone reacts with the soil solution, forming OH-ions, which will be responsible for neutralizing the acidic ions, while the cationic nutrients occupy the negative charges of colloid (Zhou et al., 2017).

Thus, the PCA demonstrated the importance of soil fertility management in the development of forest stands, discriminating more productive sites due to the greater availability of the basic cations analyzed. Such information was essential to verify whether the fertilization regime adopted was adequate, which is, neither too much nor incipient. Silva et al. (2013) also observed the influence of mineral fertilization regimes on Eucalyptus plantations in sandy soils. These authors found the need to reduce the NPK fertilization adopted in the plantations to guarantee efficiency in the productive potential of the stands.

Materials and methods

Study area, characteristics and silvicultural practices

The study was carried out in teak plantations located in the municipality of Capitão Poço, Pará State, Brazil (2°30’00”S; 47°20’00”W and 2°20’0”S; 47°30’0”W) (Fig 1.). The main soil types occurring in the region are the Petroplintic Dystrophic Yellow Latosol, Typical Dystrophic Yellow Latosol, and Petric Concretionary Plintosoil (Embrapa, 2013). Climate is Am according to Köppen´s classification, characterized as warm and humid, with a short dry season (Alvares et al., 2013). The total annual rainfall and temperature are 2,256 mm and 26.1 ºC, respectively (INMET, 2020).

The clonal stands of teak were established in 2012 and 2013 using spacings of 3.75 x 3.75 m (14.06 m^2 per plant), covering a total area of 365.6 ha, divided into nine stands. The stands were four and five years old, respectively, at the period of assessment from the present study. The stands were formed through cuttings from teak clonal orchards. The cultural practices consisted of combating leaf-cutter ants with formicide baits, area cleaning with crawler tractor, manual planting, liming with dolomitic limestone (3 t ha^{-1}), soil fertilization (NPK 2-28-16: 200 g $plant^{-1}$ and KCl: 100 g $plant^{-1}$), controlling invasive plants by means of manual weeding, semi-mechanized and mechanized mowing with hydraulic tractor, maintenance fertilization with application of Boron (7 g $plant^{-1}$) and KCl (100 g $plant^{-1}$), and artificial pruning (saw and mechanized pruner) (Souza et al., 2022).

Monitoring the plantation

A continuous forest inventory was performed in the stands aged between four and five years, in 38 circular plots systematically distributed in a grid of 320 x 320 m. Each plot had a radius of 12.61 m, covering an area of approximately 500 m² (Fig 1.). The following dendrometric variables were measured: total height (H), diameter measured at 1.30 m of ground (DBH), and age (A). With the DBH data, the dominant individuals and their respective dominant heights (Dh) were identified according to methodology proposed by Assmann (1970), which consists of the arithmetic mean of the heights of the 100 individuals with the largest DBH per hectare. Tree Height was measured with a Vertex IV Hypsometer and DBH was measured with a diametric tape.

In addition to the inventory, soil sampling was performed for fertility analysis. Soil samples were collected at 20 points, distributed in the stands, with the aid of a Dutch auger. At each soil sampling point, four single samples were collected, which were mixed and homogenized to form a composite sample, collected at depth of 0-30 cm. Subsequently, chemical analysis was carried out to assess some soil fertility attributes, obtaining the following edaphic variables: exchangeable potassium, sodium, calcium and magnesium (K, Na, Ca and Mg, respectively), in $cmol_c$ dm^{-3}. Such analyzes were performed according to the methodology described by Embrapa (2017).

Testing of growth models

Six growth models were tested - a linear one (1) and five non-linear (2-6), correlating dominant height (Dh) as dependent variable and stand age (A) and its mathematical transformations as independent variables (Table 1). The site indexes were obtained using the curve guide method, generating anamorphic curves. The reference age (RA) considered was four years. We determined three classes of productive capacity with an amplitude of 2.5 m in order to facilitate the stratification of the stand into low productivity (class III), average productivity (class II), and high productivity (class I).

The regression models were adjusted either using the ordinary least squares method. The best model was selected considering the following statistical criteria: the highest adjusted coefficient of determination (R^2_{ad} %); the smallest standard error of estimate in percentage (S_{yx}%) and recalculated standard error (S_{yxr}%) for the linearized models; diagnosis of the error distribution in percentage (ei%) by trendless graphical analysis; and the average percentage deviation (APD) being the closest to zero (Schneider et al., 2009).

The hierarchical selection criterion or Weighted Value (WV) criterion was used to help the selection of the best model, considering all previously mentioned statistical criteria. The weighting of the values was determined by assigning values or weights to the statistical criteria. The statistics were classified according to their efficiency, with weight 1 assigned to the best statistic, 2 to the second best, and so on. In the end, the sum of the scores were performed for each mathematical model and the equation that received the lowest sum was chosen as most suitable for use (Schneider et al., 2009).

The dissimilarity hypothesis was accepted or rejected according to regions of equivalence for the regression parameters (intercept and slope, with 25% at the 95% of probability level, with 1000 bootstrapping). A linear regression was estimated between the observed and predicted values to calculate two confidence limits for the parameters and their respective comparison with the estimated equivalence region.

Geostatistics analysis

A descriptive statistical analysis was performed as an initial prerequisite for the geostatistics analysis. Subsequently, the average, standard deviation, variance, coefficient of variation, asymmetry, kurtosis, and the normality test of Kolmogorov-Smirnov at a 5% significance level were determined. Spatial variability was performed using geostatistics. For this, we used coordinates in UTM form, Datum WGS 84, previously obtained in the field, through the use of a GPS instrument, Etrex Model from the Garmin Interface. The coordinate points correspond to the epicenter of each circular plots. Based on the positioning of the plots and their relationship to the determination of the Dh variable for each plot, the following semivariogram models were adjusted: Spherical (Eq.1), Gaussian (Eq.2), and Exponential (Eq.3).

$$\gamma(h) = C_{0+}£* \left[\frac{3}{2} * \frac{h}{\alpha} - \frac{1}{2} * \left(\frac{h}{\alpha}\right)^3 \right] < 0 \quad \text{Eq.1}$$

$< h < \alpha$

$$\gamma(h) = C_{0+}£* \left[1 - \exp\left(-3* \left(\frac{h}{\alpha}\right)^2\right)\right] \quad \text{Eq.2}$$

$0 < h < d$

$$\gamma(h) = C_{0+}£* \left[1 - \exp\left(-3* \left(\frac{h}{\alpha}\right)\right)\right] \quad \text{Eq.3}$$

$=> 0 < h < d$

Where, C_0= nugget effect; £= threshold; h= distance between the points; α= range; exp= exponential.

The parameters nugget effect (C_0), sill (C1) and range (α), of the three models, were compared to verify the equation that best fitted the data. The following criteria were used: lower nugget (C_0), higher spatial dependence index (SDI %) of the variable, determined by the ratio C_0 / (C_0 + C_1), higher coefficient of determination (R^2) and lower sum of squares of the residues. To classify the spatial dependence index (SDI), we used the methodology described by Cambardella et al., (1994), which determines how much of the spatial variation is present in the total sample variation. These authors consider strong spatial dependence if SDI <0.25, moderate dependence if 0.25 ≤ SDI ≤ 0.75 and weak dependence if SDI> 0.75.

For each semivariogram generated, the following parameters were obtained: Range (α), in order to verify how far the analyzed variable has spatial dependence (regionalized variable); Sill ($C_{0} + C_1$), which indicates the spatial variability level of the variable, and the nugget effect (C_0) to ascertain the existence of irregularities at the origin of the semivariogram (Yamamoto and Landim, 2013). The spatial phenomenon of the Dh variable showed an anisotropic behavior, in which the semivariogram function ranged from 90º to 135º of directions. For this reason, the average direction of 112º was used to adjust the models, aiming to improve the estimate and ensure a suitable spatialization of the variable.

After determining the semivariogram and obtaining the most efficient model to estimate spatial variability, a prediction (interpolation) of the variable Dh was performed to estimate non-sampled areas. For this, ordinary kriging was used, assuming a linear association between the samples, because it is systematic sampling. From this estimate, an interpolation map was drawn up for the plantations. Adjustments of semivariograms and preparation of kriging maps were made with the aid of the statistical software Surfer, version 11.0.64 (Golden Software, 2012) and QGIS 3.24.0.

Multivariate grouping of forest stands

Aiming to assess the influence of edaphic attributes on the productive capacity of teak stands, multivariate grouping was performed by means of principal component analysis (PCA). The mean values of the soil chemical attributes (Ca, K, Na and Mg) and the values of dominant height of the plots were used in this analysis. Multivariate analysis was performed using software R, version 4.0.2 (R Development Core Team, 2021).

Conclusion

The productive capacity of the *T. grandis* plantation was influenced by the variation of the space in the study area. Soil chemistry strongly influenced the spatial variability of production in stands with similar genetic material, management system and topography. Geostatistics has proven to be an effective tool to diagnose the productivity of areas planted with the species. This can help the efficient management of plantations by establishing silvicultural actions in specific places identified in the maps of the planted area, thus reducing management costs.

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