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GEOSTATISTICAL MODELING OF TIMBER VOLUME SPATIAL VARIABILITY FOR *Tectona grandis* L. F. PRECISION FORESTRY

ABSTRACT: Considering the hypothesis that the wood volumes present spatial dependence, whose knowledge contributes for the precision forestry, the aim of this work was to estimate the volume spatial variability for timber assortments and identify their spatial patterns on *Tectona grandis* stands. A dataset of 1,038 trees was used to fit taper models and estimate the total stem, sawlog, and firewood volumes in 273 plots allocated on *T. grandis* stands at eight years old, which represents the second thinning that enables commercial volumes. Semivariograms models was applied to fit the spatial dependence, and punctual kriging was used to compose volume maps. Geostatistical modeling allowed us to estimate the *T. grandis* spatial variability and develop timber volume maps. Thus, silvicultural treatments, such as thinning and pruning, as well as for planning spatial interventions, are possible to be recommended for aimed wood products.

Keywords:
Taper model
Timber assortments
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MODELAGEM GEOESTATÍSTICA DA VARIABILIDADE ESPACIAL DO VOLUME DE MADEIRA PARA O MANEJO DE PRECISÃO DE *Tectona grandis* L. F.

RESUMO: Considerando a hipótese de que os volumes de madeira apresentam dependência espacial, cujo conhecimento contribui para o manejo de precisão, o objetivo deste trabalho foi estimar a variabilidade espacial do volume de sortimentos de madeira e identificar seus padrões espaciais em povoamentos de Tectona grandis. Utilizou-se um conjunto de dados de 1.038 árvores para ajustar funções de afilamento e estimar os volumes para fuste total, serraria e lenha em 273 parcelas alocadas em povoamentos de T. grandis ao oitavo ano de idade, o qual representa o segundo desbaste que possibilita volumes comerciais. Modelos de semivariogramas foram aplicados para ajustar a dependência espacial e a krigagem pontual foi utilizada para compor mapas de volume. A modelagem geoestatística permitiu estimar a variabilidade espacial de T. grandis e desenvolver mapas de volume de madeira. Assim, tratamentos silviculturais, como desbaste e poda, bem como planejamento de intervenções espaciais, podem ser recomendados para produtos de madeira almejados.

Palavras chave:
Função de afilamento
Sortimento de madeira
Dependência espacial
Interpolador de Krigagem

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INTRODUCTION

Tectona grandis L. f. (Lamiaceae) is an Asian tree species cultivated in Africa, and South and Central America (NOCETTI et al., 2011; PELISSARI et al., 2013). Its wood has high commercial value due to workability and durability features (MORA; HERNANDÉZ, 2007), intended mainly for furniture and shipbuilding industries (FIGUEIREDO et al., 2005). Moreover, the use of thinned wood is possible for many purposes, especially for sawlog and firewood on the second thinning in the forest stands.

Although the lack of information about specific management regimes for *T. grandis*, this species is an important income source and lucrative alternative for forest managers (ÂNGELO et al., 2009; NEWBY et al., 2012), due to the reduction of wood supply from natural forest and the increasing demand for timber products. Thus, the development of tools is needed to support sustainable forest management for assorted raw materials, such as methods to increase the accuracy of volume estimates and their spatial features in forest stands.

Taper functions are essential to measure tree stem forms, providing estimation of diameter at any height, height at any top diameter, and total and commercial tree volumes (BARRIO ANTA et al., 2007; TANG et al., 2016), in which equations have been proposed for quantifying and qualifying the *T. grandis* wood volume for timber assortments (FIGUEIREDO et al., 2006; LEITE et al., 2011; FAVALESSA et al., 2012). However, these studies did not report the timber volume spatial features, which are special important for forest management (AKHAVAN et al., 2015).

For this reason, geostatistical analysis stands out as a set of statistical techniques for spatial modeling and interpolate values in non-sampled areas (SUN et al., 2008; DAFONTE et al., 2010). Geostatistics is based on the Theory of Regionalized Variables (MATHERON, 1971; WEBSTER; OLIVER, 2007), which establishes the regionalized variable as a numerical function of spatial phenomenon, in which semivariance is a basic statistics to measure the spatial structure and relationships between plots.

Aiming to provide information for the precision forestry, we considering the hypothesis that the stand volumes of different timber assortments present spatial dependence, whose knowledge contributes for planning thinning, harvesting prescriptions, specific silvicultural treatments, and commercial demands for wood products. Thus, the aim of this work was to estimate the volume spatial variability for timber assortments and identify their spatial patterns on *T. grandis* stands.

MATERIAL AND METHODS

This study was carried out in 1,260 ha of forest stands with *T. grandis* species, on the spacing 3 m x 3 m, and located in Mato Grosso State, Central-West Region of Brazil, on the coordinates 16°09'00" S at 16°13'50" S and 56°21'00" W at 56°24'20" W. The region's climate was classified as Aw (Köppen), with mean rainfall and annual temperature equal to 1,300 mm year^{-1} and 25 °C, respectively (ALVARES et al., 2013), while Haplic Planosol soil was identified in sandy-clay-loam texture and gently undulating topography.

A sample with 273 georeferenced plots (15 m x 30 m) was allocated covering five *T. grandis* stands at eight years old (Figure 1), named A to E, in which this age represents the second thinning that enables commercial volumes for sawlog and firewood. In addition, 1,038 trees were scaling by the Smalian's method, measuring diameters over-bark on the heights: 0.1 m, 0.5 m, 1.0 m, 1.3 m, 2.0 m, and 1.0 m intervals along the total height.

Stem taper modeling and timber volume estimation

Max and Burkhart (1976) and Parresol et al. (1987) segmented taper models were fitted by Marquardt algorithm to estimate stem diameters, while

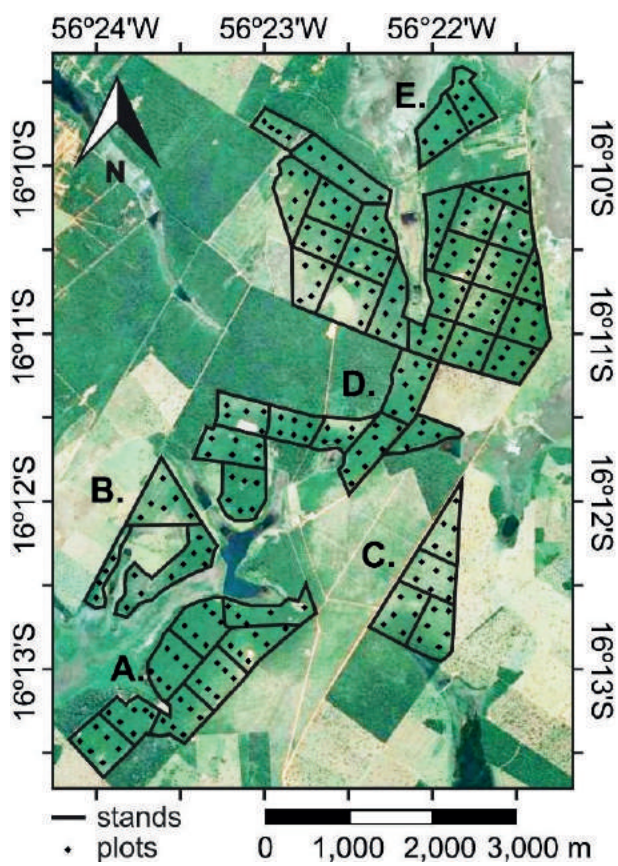

FIGURE 1 Position of the plots allocated on the *Tectona grandis* stands.

the powers (p_n) of Hradetzky (1976) non-segmented taper model were obtained through stepwise process described by Lanssanova et al. (2013). For evaluating the performance of these models, we considering the highest adjusted coefficient of determination ($R^2_{adj.}$), lowest relative standard error of the estimate (*SEE*%), regression coefficients (β_i) at 0.05 significance level, and graphical analysis of the stem profile (d_i/d - h_i/h). Where: d_i = diameter over-bark in an *i* section (cm), *d* = diameter over-bark at 1.3 m above ground level (cm), β_i = regression coefficients, *h* = total height (m), h_i = height in an *i* section (m), $X = h_i/h$, $I_1 = 1$ if $X \leq \alpha_1$, $I_2 = 1$ if $X \leq \alpha_2$, $z = (h - h_i)/h$, $Y = 1$ if $z \geq \alpha_1$, and $p_1, p_2, \ldots, p_n$ = powers.

Max and Burkhart (1976) $$\frac{d_i}{d} = \left[\beta_1(X-1)+\beta_2(X^2-1)+\beta_3(\alpha_1-X)^2 I_1+\beta_4(\alpha_2-X)^2 I_2\right]^{0.5} \quad [1]$$

Parresol et al. (1987) $$\frac{d_i}{d} = \left\{z^2(\beta_1+\beta_2 z)+(z-\alpha_1)^2[\beta_3+\beta_4(z+2\alpha_1)]Y\right\}^{0.5} \quad [2]$$

Hradetzky (1976) $$\frac{d_i}{d} = \beta_0+\beta_1\left(\frac{h_i}{h}\right)^{p_1}+\beta_2\left(\frac{h_i}{h}\right)^{p_2}+\ldots+\beta_n\left(\frac{h_i}{h}\right)^{p_n} \quad [3]$$

Total stem volume was estimated on the plots through integration of the stem sectional solid by rotation of the taper function (BARRIO ANTA et al., 2007). Thus, timber assortments were obtained and, subsequently, classified according to Shimizu et al. (2007) for *T. grandis* stands: 1) Sawlog volume: logs with 2.4 m of length and tip diameter more than 15 cm, and 2) Firewood volume: logs with 1.0 m of length and tip diameter between 4.0 cm and 15 cm, while the remaining volume was considered non-commercial. Also, descriptive statistics and Kolmogorov-Smirnov's test at 0.05 significance level were applied to volume datasets.

Geostatistical modeling and timber volume mapping

Geostatistical analysis was used to modeling the volume spatial patterns of total stem, sawlog, and firewood. Thus, semivariances (4) were calculated considering the geographical position of the plots, the lag distances (*h*) between them and the numerical differences of each variable (Z) on the grid. Subsequently, Spherical (5), Exponential (6) and Gaussian (7) models were fitted by weighted least squares in GEOEST software (VIEIRA et al., 2002), in which this method aims to minimize the sum of squares of the semivariance deviations weighted by the number of pair of plots in each lag distance (REILLY; GELMAN, 2007), Where: $y(h)$ = semivariance of $Z(x_i)$ variable, h = lag distance between plots (m), $N(h)$ = number of pairs of plots for each lag distance *h*, C_0 = nugget effect, C = sill, and a = range (m).

$$y(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[Z(x_i)-Z(x_i+h)\right]^2 \quad [4]$$

$$y(h) = C_0 + C\cdot\left[\left(\frac{3}{2}\right)\cdot\left(\frac{h}{a}\right)-\left(\frac{1}{2}\right)\cdot\left(\frac{h}{a}\right)^3\right] \quad [5]$$

$$y(h) = C_0 + C\cdot\left[1-e^{(-h/a)}\right] \quad [6]$$

$$y(h) = C_0 + C\cdot\left[1-e^{(-h^2/a^2)}\right] \quad [7]$$

Semivariograms were evaluated through smallest weighted sum of squared deviations (*WSSD*), highest coefficient of determination (R^2), and by cross-validation: linear and angular coefficients, coefficient of determination of cross-validation (R^2_{cv}), and relative standard error of the estimate of cross-validation ($SEE\%_{cv}$). In addition, we evaluated the anisotropy by directional semivariograms (WEBSTER; OLIVER, 2007), the residual analysis for volume estimates, and the spatial dependence index (*SDI*) proposed by Seidel and Oliveira (2014) for the models: Spherical (8), Exponential (9), and Gaussian (10), where: C_0 = nugget effect, C_1 = contribution, a = range (m), and $0.5{\cdot}MD$ = half of maximum distance (*MD*) between plots, in which $\left(\frac{a}{0.5\cdot MD}\right)$ is truncated into 1 when it higher than 1.

$$SDI_{Sphe}(\%) = 0.375\cdot\left(\frac{C_1}{C_0+C_1}\right)\cdot\left(\frac{a}{0.5\cdot MD}\right)\cdot 100 \quad [8]$$

$$SDI_{Exp}(\%) = 0.317\cdot\left(\frac{C_1}{C_0+C_1}\right)\cdot\left(\frac{a}{0.5\cdot MD}\right)\cdot 100 \quad [9]$$

$$SDI_{Gaus}(\%) = 0.504\cdot\left(\frac{C_1}{C_0+C_1}\right)\cdot\left(\frac{a}{0.5\cdot MD}\right)\cdot 100 \quad [10]$$

Seidel and Oliveira (2016) established a classification for spatial dependence, in which for Spherical model: $SDI_{Sphe}(\%) \leq 7\%$ (weak), $7\% < SDI_{Sphe}(\%) \leq 15\%$ (moderate), and $SDI_{Sphe}(\%) > 15\%$ (strong); for Exponential model: $SDI_{Sphe}(\%) \leq 6\%$ (weak), $6\% < SDI_{Sphe}(\%) \leq 13\%$ (moderate), $SDI_{Sphe}(\%) > 13\%$ (strong); and for Gaussian model: $SDI_{Sphe}(\%) \leq 9\%$ (weak), $9\% < SDI_{Sphe}(\%) \leq 20\%$ (moderate), and $SDI_{Sphe}(\%) > 20\%$ (strong).

Punctual kriging method (CHAUDHRY et al., 2013) was applied to interpolate the total stem, sawlog, and firewood volumes, and thematic maps were made using Surfer software (GOLDEN SOFTWARE, 2014) with five classes weighted through the mean volume ($\bar{x}$) and standard deviation (σ): Class I = $\bar{x} - 2\cdot\sigma$, Class II = $\bar{x} - \sigma$, Class III = $\bar{x}$, Class IV = $\bar{x} - \sigma$, and Class V = $\bar{x} - 2\cdot\sigma$, aiming equivalent volume classes between timber assortments.

RESULTS AND DISCUSSION

Regression coefficient values of taper models (**α_i** and **β_i**) were significant at 0.05 level (Table 1), in which two change points in the stem forms were observed with

Max & Burkhart's model: 3.5% (α_1) and 12.8% (α_2) of the total height; while one form change was evidenced using Parresol's model in the 13.1% stem position (1 - α_1). Stem form of *T. grandis* trees is affected by the planting spacing, since trees with cylindrical form are obtained in stands of highest density (VENDRUSCULO et al. 2016).

TABLE 1 Regression coefficients and statistical parameters of taper models fitted for *Tectona grandis* stands.

Model	α_1	α_2	β_0	β_1	β_2	β_3	β_4	R^2adj.	SEE% d_i	SEE% v_i
Hradetzky	-	-	1.437*	1.133*	-2.013*	-2.235*	1.888*	0.97	7.7	12.8
(Power)	-	-	-	(0.005)	(0.1)	(4)	(5)	-	-	-
Max and Burkhart	0.035*	0.128*	-	-1.748*	0.697*	461.479*	26.145*	0.97	7.8	13.0
Parresol	0.869*	-	-	2.062*	-1.151*	-1,251.7*	480.202*	0.96	8.3	26.8

Where: * = 0.05 significance level.

For Hradetzky's model, the powers (p_n): 0.005 (β_1), 0.1 (β_2), 4 (β_3), and 5 (β_4) were selected for representing the stem profile of *T. grandis* trees in this study, while Figueiredo et al. (2006) selected the powers: 0.006 (β_1), 0.004 (β_2), 0.8 (β_3), 0.5 (β_4), 2 (β_5), and 10 (β_6) for the same species in Acre State. These results confirming the conception of the Hradetzky's model (1976), in which highest powers represent the base of trees, while lowest powers describe the top-part of the stem.

Coefficients of determination ($R^2_{adj.}$) were higher than 0.9 for all taper models, while relative standard errors of the estimate (*SEE*%) were less than 9% for diameters and less than 27% for stem volumes (Table 1). Thus, best fits were obtained through Hradetzky's model, followed by Max and Burkhart's model. On the other hand, the goodness-of-fit of Parresol's model was poor due to the lack of studies for *T. grandis* and other species with similar stem forms, aiming to provide consistent input parameters (α and β) for the non-linear regression analysis.

Graphical analysis of stem profiles (Figure 2) shows homogeneous dispersion of diameter values, confirming the choice of Hradetzky's model to estimate *T. grandis* stem form and its similarity with Max & Burkhart's model estimates. Also, Hradetzky's model presented the best fit to estimate diameters along the *T. grandis* stem according to Favalessa et al. (2012). Other models have been proposed to describe the taper form for the same species, such as Goulding and Murray (FIGUEIREDO FILHO et al., 2006), and Garay (LEITE et al., 2011).

However, high dispersion was verified from 60% of the total height ($h_i/h \geq 0.6$), indicating large tree diameter variation on the final stem form. The pruning system applied to *T. grandis* stands can be related to this result, in which the branches were pruned around 8.0 m of the height for better form of the initial tree stem.

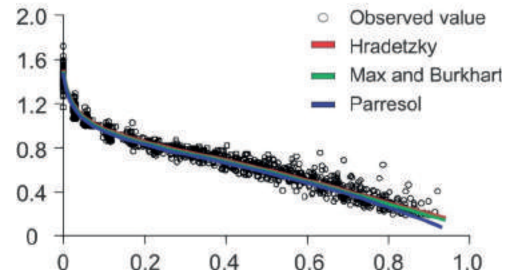

FIGURE 2 Stem profiles estimated through taper models for *Tectona grandis* stands.

However, this tendency in the top-part of the stem, where smallest diameters occur, was also observed by Favalessa et al. (2012) for *T. grandis*, and Queiroz et al. (2008) for *Mimosa scabrella* Benth. Despite the highest dispersion in a stem part, most taper models do not describe the entire stem with the same accuracy (CRECENTE-CAMPO et al., 2009).

By means of the timber assortments estimates, minimum, mean and maximum values were observed for diameter over-bark at 1.3 m above ground level and total height in the Table 2, as well as for total stem, sawlog and firewood volumes. Thus, highest variability was observed for sawlog volume, due to the low tree density with dimension to supply this timber assortment. In addition, the wood volumes were normally distributed by the Kolmogorov-Smirnov's test, with a maximum significant difference (D_{max}) equal to 0.08 at the 0.05 significance level.

With the geostatistical modeling (Table 2), lowest nugget effect (C_0) values were observed for firewood volume, followed by sawlog and total stem volumes, whose values can be attributed to short-range variability that occurs at a scale smaller than the closest sample spacing (ZAWADZKI et al., 2005). In addition, highest ranges values (*a*) for total stem and firewood volumes indicated the distance limit at which two plots are spatially correlated and stochastically dependent (ZAS, 2006).

TABLE 2 Descriptive statistics of forest variables for Tectona grandis stands.

Value	Diameter at 1.3 m (cm)	Total height (m)	Total stem ($m^3 \cdot ha^{-1}$)	Sawlog ($m^3.ha^{-1}$)	Firewood ($m^3 \cdot ha^{-1}$)
Minimum	16.24	15.06	93.21	14.24	42.31
Mean	19.72	17.41	187,52	56.94	49.70
Maximum	22.94	19.81	261,19	108.60	54.72
CV%	7.45%	5.84%	18.59%	35.04%	4.40%
K-S test	0.06ns	0.07ns	0.08ns	0.06ns	0.06ns

Where: CV% = coefficient of variation, K-S test = Kolmogorov-Smirnov's test, and ns = normal distribution.

TABLE 3 Semivariogram parameters fitted to total stem, sawlog, and firewood volumes for *Tectona grandis* stands.

Volume	Model	C_0	C_0+C	a (m)	SDI (%)	Class	R^2	WSSD
Total stem	Spherical	337.69	1,206.00	1,329	27.00	Strong	0.990	806.96
	Exponential	208.10	1,369.73	1,987	26.80	Strong	0.980	1,334.37
	Gaussian	501.30	1,225.33	1,206	29.78	Strong	0.979	1,029.01
Sawlog	Spherical	0.10	310.69	753	37.49	Strong	0.971	136.03
	Exponential	1.00	332.80	1,100	31.60	Strong	0.974	128.53
	Gaussian	9.50	308.70	579	48.85	Strong	0.971	192.19
Firewood	Spherical	3.08	5.09	1,362	14.80	Moderate	0.920	0.03
	Exponential	2.88	5.49	2,162	15.08	Strong	0.895	0.04
	Gaussian	3.36	5.14	1,254	17.43	Moderate	0.916	0.03

Where: C0 = nugget effect, C = sill, a = range, SDI = spatial dependence index, R^2 = coefficients of determination, and WSSD = weighted sum of squared deviations.

Strong spatial dependence index (*SDI*) was observed for timber assortments, according to the classification proposed by Seidel and Oliveira (2016), especially for sawlog with highest *SDI* values, while moderate *SDI* was obtained with Spherical and Gaussian models for firewood. The spatial dependence of *T. grandis* volume was also verified by Santana (2011) and Pita (2012). In addition, coefficients of determination (R^2) were higher than 0.9, excepting for firewood with Exponential model (Table 3), and lowest weighted sum of squared deviations (*WSSD*) were obtained for firewood volume.

These semivariograms showed different behaviors at the origin, and low dispersion of observed values (Figure 3). The curve's origin of semivariograms, which represents the nugget effect (C_0), increased with the timber assortment diameter reduction, in which firewood volume had lowest spatial correlation between plots at short distances (Figure 2C). In addition, directional semivariograms exhibited structural similarity along distances.

Semivariograms were evaluated through cross-validation, which resulted, respectively for total stem, sawlog, and firewood volumes, in linear coefficients of 1.70, 0.21, and 10.51; angular coefficients of 1.01, 1.00, and 0.79; coefficients of determination (R^2_{cv}) of 0.518, 0.685, and 0.146; and relative standard errors of the estimate ($SEE\%_{cv}$) of 12.90%, 19.76%, and 4.07%. Highest residual dispersion for total stem (Figure 4A) and for sawlog (Figure 4B) confirmed these results, while lowest variability was obtained for firewood volume (Figure 4C).

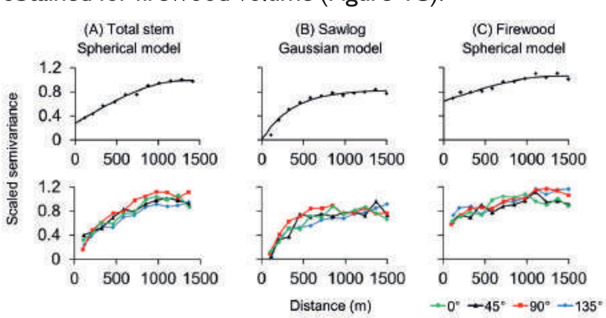

FIGURE 3 Scaled semivariograms fitted to total stem (A), sawlog (B), and firewood (C) volumes for *Tectona grandis* stands.

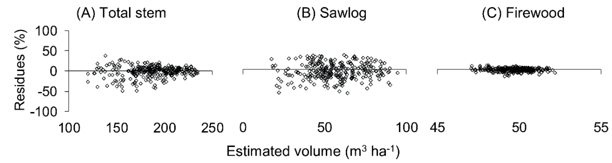

FIGURE 4 Distribution of residues through geostatistical modeling applied to total stem (A), sawlog (B), and firewood (C) volumes for *Tectona grandis* stands.

Applying these fits, volume maps were made through punctual kriging (Figure 5), in which the spatial distributions for total stem (Figure 5A) and sawlog (Figure 5B) were most similar, especially in highest volume stock area on the stand D. In addition, middle class predominance (49 to 51 $m^3 \cdot ha^{-1}$) was observed for firewood volume (Figure 5C). Therefore, the common usage of mean values does not allow us to identify the spatial strata of timber volumes, in which the combination of geostatistics and forest inventory is needed to detect these spatial distributions (MELLO et al., 2006; GUEDES et al., 2012; LUNDGREN et al., 2015).

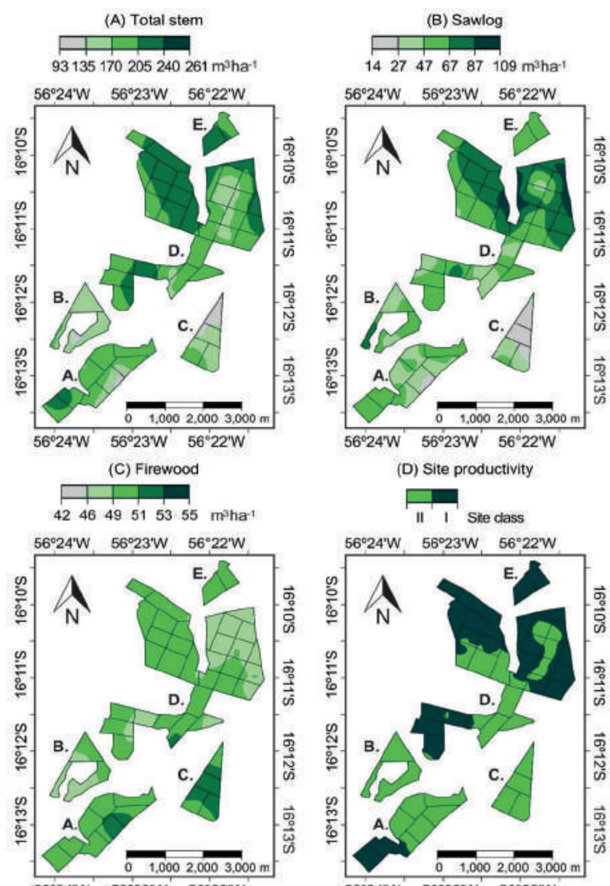

FIGURE 5 Spatial distribution maps of total stem (A), sawlog (B) and firewood (C) volumes, and site productivity adapted from Pelissari et al. (2014), for *Tectona grandis* stands.

Forest site productivity influences on the stem form and tree development (KOHLER et al., 2016), in which the timber volume spatial patterns were correlated to the site spatial variability (Figure 5D), especially for sawlog volume (Figure 5B) on site with highest productivity (Class I) on stand D, such as observed in the kriged site map proposed by Pelissari et al. (2014). Thus, the stand physical-planning, aiming timber assortments, can be applied to reforestation, observing the local edaphic and topographic features that limit the tree growth.

In addition, considering the spatial dependence of timber volumes (Figure 5), the combination of geostatistics and operational research techniques makes it possible to define forest management regimes for each stand, associating the forest-based industries and their demands for wood raw material. Moreover, it is possible to define non-productive areas of some timber assortment for other purposes, such as the stand C with low sawlog volume (Figure 5B) for firewood (Figure 5C).

Thus, the knowledge on spatial patterns allows us to define silvicultural treatments for maximum forest yield. With this, selective thinning applied to young stands, as well as high pruning levels since the first thinning, can be concentrated to the trees present in some areas of stand D with highest sawlog volume stock (Figure 5B), aiming to obtain logs with large size and quality. Also, less intensive silvicultural treatments, such as absence of maintenance pruning of fully-grown trees, can be applied to stands A and C with highest firewood volume (Figure 5C), intending to obtain tree biomass at low production costs.

CONCLUSION

Tectona grandis timber assortment presents spatial dependence on the forest stands, in which geostatistical modeling allowed us to estimate the spatial variability and develop volume maps. Therefore, silvicultural treatments, such as thinning and pruning, as well as for planning spatial interventions, are possible to be recommended for aimed wood products.

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