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Eucalyptus spp. volume determined through geospatial interpolation

Volume de *Eucalyptus* spp. por meio de interpolação geoespacial

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Abstract

Planning and managing forest resources is fundamental for increasing the productivity of forest products and by-products. This study evaluates the use of the ordinary kriging interpolator in the estimation of standing wood volume in *Eucalyptus* spp. plantations in Paragominas city, Pará State, Brazil. For this, we used data from the precut forest inventory, processed by the ordinary kriging method. Measurements took place in 27 georeferenced fields, with plots of 504 m², where trees were rigorously cubed. Geostatistical modeling was performed using ordinary kriging (spherical semivariogram model) with isotropic and anisotropic interpolators, seeking to map the volume of the area. To this end, experimental semivariograms were obtained through the Geostatistical Analyst tool of ArcGIS 10.1 software. Interpolation presented satisfactory results regarding plot volume mapping, in which the average volume fitted by ordinary kriging was statistically similar to the average volume obtained by the forest inventory, 11.3517 m³ and 11.3842 m³, respectively, showing efficiency with an adjusted coefficient of determination of 0.94. The use of ordinary kriging interpolation proved to be effective in plot volume estimation in the forest stands under study.

Additional keywords: forest resources; geostatistics; ordinary kriging; planning.

Resumo

O planejamento e a administração dos recursos florestais são fundamentais para o incremento na produtividade dos produtos e subprodutos florestais. O objetivo deste estudo foi avaliar o uso do interpolador geoestatístico Krigagem Ordinária na estimativa do volume de madeira em pé, em plantios de *Eucalyptus* spp., no município de Paragominas-PA. Para tanto, foram utilizados dados do inventário florestal pré-corte e com processamento pelo método de Krigagem Ordinária. As medições ocorreram em 27 talhões georreferenciados, com parcelas de 504 m², onde também foi realizada a cubagem rigorosa das árvores. A modelagem geoestatística foi feita através do método de Krigagem Ordinária com interpoladores isotrópicos e anisotrópicos de semivariograma esférico, buscando obter o mapa de volume da área. Para isso, foram obtidos os semivariogramas experimentais através da ferramenta *Geostatistic Analist*, no *software Arcgis* 10.1. A interpolação apresentou resultados satisfatórios com relação ao mapeamento do volume das parcelas, em que a média de volume predito pela Krigagem Ordinária foi estatisticamente semelhante à média de volume obtido pelo inventário florestal, 11,3517 m³ e 11,3842 m³, respectivamente, mostrando-se eficiente com coeficiente de determinação ajustado de 0,94. O uso da interpolação Krigagem Ordinária revelou-se eficaz na prognose do volume das parcelas nos talhões do povoamento florestal em estudo.

Palavras-chave adicionais: geoestatística; krigagem ordinária; planejamento; recursos florestais.

Introduction

The forest sector is on the rise in the Brazilian economic activity. The total area of planted trees increased by 0.5% between 2015 and 2016, an increase equivalent to 7.84 million hectares. Species of the genus *Eucalyptus* are the main protagonists of Brazilian forestry (Garlet et al., 2016), accounting for 5.7 million hectares planted throughout the country, with a growth rate of 2.4% per year in the last five years. These plantations are mainly distributed in the states of Minas Gerais (24%), São Paulo (17%), and Mato Grosso do Sul (15%) (Ibá, 2017).

However, for the increase in yield of these plantations to be significant, it is essential to plan and manage resources. This management should consider several elements that interfere with tree growth, including climate, soil, silvicultural practices, genetic breeding, among others (Boyden et al., 2008). Thus, to ensure the success of the forest enterprise, all these factors must be observed through effective and low-cost sampling procedures (Guedes et al., 2012).

In Brazil, the most commonly used method to monitor forest development is the continuous forest inventory (CFI). This technique is based on information obtained from countless permanent sample units/plots installed in cultivated areas periodically monitored, providing essential data for the management of the forest enterprise (Tomppo et al., 2009; Westfall, 2016).

Nonetheless, the maintenance and functioning of CFI plots generates high expenses during the forest cycle. In addition, data obtained from CFI processing are generally considered insufficient by business managers, so that an inventory with higher sampling intensity becomes necessary for accurate estimates of volume and inventory error prior to harvesting. An inventory that meets this demand is the precut inventory (PCI) (Mello et al., 2006; Mello et al., 2009; Mengesha et al., 2014).

According to Bognola et al. (2009), forest stands should be approached by sampling methods efficient in the representativeness of the current and temporal state of the population, so that it can provide accurate and low-cost data, being essential as a basis for management actions and forest planning. In this sense, the use of geostatistical interpolators has been consolidated as a viable alternative to obtain greater CFI accuracy (Kanegae Júnior et al., 2006; Guedes et al., 2012; Roberge et al., 2016).

Moreover, Carvalho et al. (2002) state that geostatistical techniques allow to reach good estimates with a smaller number of field data collections. Among the existing interpolation methods, kriging stands out for its ability to more accurately present an assessment of the spatial structure of the data, verifying the auto-correlation, as well as the distribution of the error estimate, which provides greater estimation efficiency (Isaaks & Serivastava, 1989; Silva et al., 2008).

Kriging interpolation is intended to estimate values for any point in the surveyed area, and this estimate derives from a linear combination of the measured values. By adjusting the semivariogram, a spatial link is formed to the variable under study, thus it is possible to interpolate data in any arrangement in the study site without bias in the mean values (Grego et al., 2014).

Given the above, this study evaluates the use of the ordinary kriging interpolator to estimate the wood volume of *Eucalyptus* spp. stands in Paragominas city, Pará State, Brazil.

Materials and methods

The research was carried out on a farm with commercial plantations of *Eucalyptus* spp. clones belonging to the Transportadora Floresta Araguaia (TFA) group. The farm is located on km 42 of PA-125 highway, in Paragominas city, Pará State, Brazil. The area where the experiment was installed is centered on the geographical coordinates 47°08'02.68” South latitude and 03°16'01.54” West longitude (Figure 1). Twenty-seven 6-year-old fields were selected, with a total area of 694.4 hectares and spacing of 3 x 3 m between individuals. The representative soil at the site is classified as a very sandy dystrophic Yellow Latosol (Embrapa, 2013).

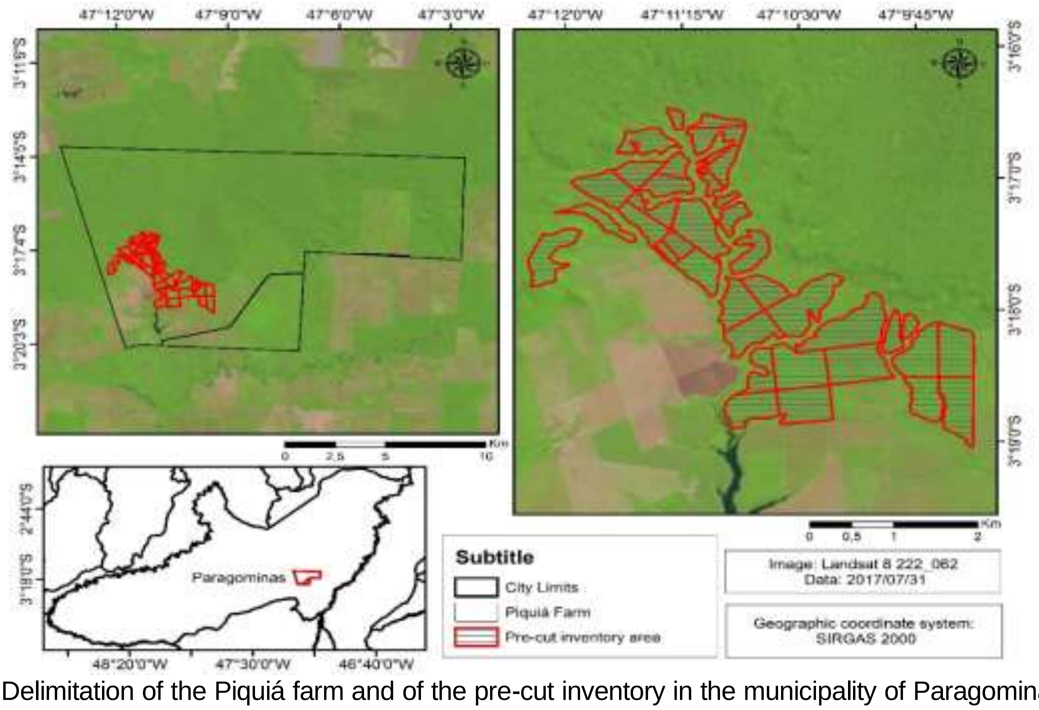

Figure 1 - Delimitation of the Piquiá farm and of the pre-cut inventory in the municipality of Paragominas, state of Para, were the study was conducted.

According to the Köppen classification, the climate of the region in which the city is located is type Aw. In the period between 2015 and 2016, the average temperature was 26.3 ºC, with rainfall of 1800 mm year^{-1} (Alvares et al., 2013).

One hundred and forty-nine (149) sampling plots, measuring 21 x 24 m (504 m^2) each, were installed in the selected fields. The variables measured were total height, measured with the aid of a digital clinometer Haglöf, and circumference at breast height (CBH), using a centimeter tape.

Additionally, following the Smalian method (Campos & Leite, 2006), a rigorous tree cubing was performed to adjust regression equations, aiming to correct forest inventory errors. To this, 15 individuals per clone were felled, distributed in three diameter classes (Table 1).

Table 1 - Diametric distribution of the three eucalyptus clones installed on the Piquiá farm, Paragominas, Pará state, at six years old.

		Eucalyptus urophylla S.T Blake (C1)		
Class	LL (cm)	$\bar{X}$ (cm)	UL (cm)	F
I	9.55	12.68	15.81	
II	15.81	18.94	22.07	5
III	22.07	25.20	28.33	
		Eucalyptus urophylla S.T Blake (C2)		
Class	LL (cm)	$\bar{X}$ (cm)	UL (cm)	F
I	9.68	12.68	15.68	
II	15.68	18.68	21.69	5
III	21.69	24.69	27.69	
		Eucalyptus *platyphylla* F.Muell (C3)		
Class	LL (cm)	$\bar{X}$ (cm)	UL (cm)	F
I	10.19	15.17	20.16	
II	12.68	17.67	22.65	5
III	15.17	20.16	25.15	

C is clone, LL is lower limit, $\bar{X}$ is average diameter at breast height, UL is upper limit, F is frequency of each class.

The normality of volumetric data was tested by the Shapiro-Wilk test at 5% probability using the R software version 3.32. Geostatistical modeling consisted of the interpolation of the volume of each field plot by the ordinary kriging method. This tool was defined by Yamamoto & Ladim (2013) as the most usual interpolation method, due to its simplicity and good results. Moreover, its success is linked to the fact that ordinary kriging was the first estimation method to enable a degree of uncertainty by the kriging variance.

Therefore, the distribution of the response variable in the N-S and E-W directions was evaluated to find where the highest degree of anisotropy is concentrated, aiming to model the database with the appropriate anisotropic correction factor for the conditions of this database. In this study, two interpolators were evaluated (isotropic and anisotropic ordinary kriging).

The existence of spatial dependence for plot volume was verified by the experimental spherical semivariogram, using the Geostatistical Analyst tool of ArcGIS 10.1 software. It was represented by the formula: $Y(h) = C_0 + C \times [1.5\ (h/A)-0.5(h/A)^3]$; wherein Y(h) = theoretical semivariance, C_0 = nugget effect, h = distance, C = sill, and A = range (Lundgren et al., 2015).

The formula proposed by Landim (1998) was used to assess the degree of spatial dependence, in which SP = (sill - nugget effect) / sill, where the sill represents the maximum point in which semivariance is influenced by distance, while the nugget effect corresponds to microstructures that were not obtained at the sampled distance due to sampling or analysis error. According to this formula, spatial dependence is considered weak if SP < 25%, moderate if 25% <SP> 75%, and strong if SP > 75%.

Interpolator evaluation was based on the following precision measurements: estimate standard error (SEE); root mean square error (RMSE); variation coefficient (CV%); and determination coefficient (R^2), calculated by the following equations:

$$SEE = \sqrt{\frac{\sum_i^n \left(Vi - \hat{V}i\right)^2}{n - p}} \quad (1)$$

$$RMSE = \frac{100}{\bar{V}} \sqrt{\frac{\sum_{i=1}^n (V_i - \hat{V}_i)^2}{n}} \quad (2)$$

$$CV\% = \frac{S}{\bar{V}} \times 100 \quad (3)$$

$$R^2 = \frac{\left(\sum_i^n \left(Vi - \bar{V}\right) \times \hat{V}i\right)^2}{\sum_i^n \left(Vi - \bar{V}\right)^2 \times \sum_i^n \left(\hat{V}i - \bar{V}\right)^2} \quad (4)$$

Wherein: Vi = observed volume; $\hat{V}i$ = estimated volume; n = number of observations; p = number of model coefficients; $\bar{V}$ = average volume; S = standard deviation; R^2 = coefficient of determination.

Finally, the best kriging model was defined based on the values of precision measurements, so that the chosen model was submitted to cross-validation to verify whether it is suitable to be applied in other databases without bias. In addition, the plot volumes fitted through ordinary kriging were compared with the plot volumes observed in the forest inventory using the t-test at 95% probability to verify whether they differ statistically.

Results and discussion

The plot volumes presented normal distribution by the Shapiro-Wilk test (p-value = 0.29), which is a desirable characteristic, since geostatistical techniques reveal good statistical properties (Mello et al., 2009). The main estimates obtained from the traditional forest inventory showed the total volume of the area to be 155,986.24 m³, with sampling error of 2.83% (Table 2). This percentage can be considered low, since an error of less than 10% represents an accurate estimate (Ibama, 1996).

Table 2 – Results of pre-cut forest inventory for the afforestation of *Eucalyptus* spp, in the municipality of Paragominas, Pará state, with six years old, in plots of 504 m².

Parameter	Result
Average diameter (cm)	16.4496
Average height (m)	21.0469
Average volume by plot (m³)	11.3517
Error (%)	2.83
Total volume of plots (m³)	1691.40

The volume dispersion in the N-S and E-W directions points to a regionalized trend data. In this case, according to Landim et al. (2002), anisotropy (interpolation direction) must be added to the interpolation procedure. Since the trend was concentrated in the E-W direction, this should be the direction used as an anisotropic factor (Figure 2).

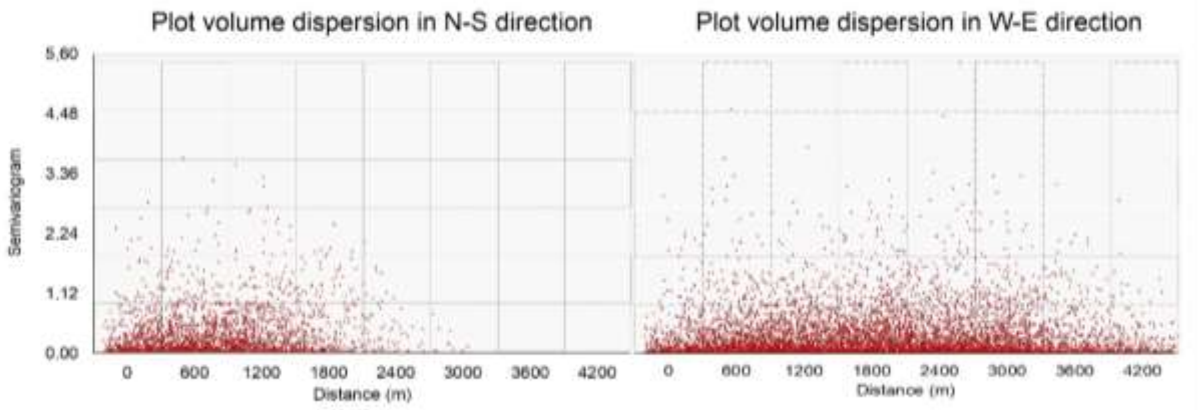

Figure 2 - Dispersion of the variable volume in the way N-S and E-W

By modeling the ordinary kriging, nugget effect and sill values of 0.56 and 4.08, respectively, were obtained for the spherical semivariogram with anisotropy in the [111] direction. For the isotropic spherical semivariogram, in turn, these parameters reached the values of 1.45 and 3.89, respectively. These results show that the unexplained variance (nugget effect) was lower in the anisotropic semivariogram, while the variable sill was also more influenced by distance in this semivariogram model.

In addition, the spatial dependence (SP) was considered strong (86%) for the anisotropic interpolator, and moderate (63%) for the isotropic interpolator. These results differ from those found by Lundgren et al. (2015), in which the authors did not observe the influence of direction (anisotropy) on Eucalyptus wood volume estimation by ordinary kriging.

The theoretical volume range in the semivariogram was approximately 3,845.21 m for the anisotropic semivariogram, and 2,379.37 for the isotropic one, so that spatial dependence was greater in the interpolator with anisotropic factor. Thus, it can be stated that the homogeneity of the area provided a high range, highlighting the accuracy of the ordinary kriging sampling (Mello et al., 2006).

This result is higher than that of Mello et al. (2009), who achieved a range of 280 m when studying the volume of a Eucalyptus plantation. When using the ordinary kriging method on *Eucalyptus urophylla* volume estimation, Leal et al. (2011) also reported a lower range (1,100 m) compared to those found in this study.

When analyzing precision measurements, the greater accuracy of the anisotropic semivariogram compared to the isotropic one is noticeable (Table 3). Estimate standard error (SEE) and root mean square error (RMSE) showed more satisfactory results for anisotropic ordinary kriging. Moreover, according to Garcia's classification (1989), the coefficient of variation (CV) was considered moderate (10.21% < CV > 12.69%) for the omnidirectional estimator, and low (CV < 10.21%) for the other one. The adjusted coefficient of determination (R^2) was also numerically higher in the direction-dependent interpolation method (Table 3).

Table 3 – Precise measurements of the estimate by ordinary kriging for the variable volume (m³) of wood of stand of *Eucalyptus* spp at 6 years old.

Anisotropic effect	SEE	RMSE (%)	CV (%)	R^2
Yes	0.11	11.64	10.17	0.94
No	1.13	14.61	12.68	0.59

SEE is estimate standard error; RMSE is root mean square error; CV = variation coefficient; R^2 = determination coefficient.

Similar R^2 values were reported by Leal et al. (2011), who also worked with ordinary kriging to map the productive units of a *Eucalyptus urophylla* stand, as well as by Santos et al. (2017), when studying stands of *Eucalyptus grandis* Hill ex Maiden.

Thus, the spherical semivariogram with anisotropy in the [111] direction was defined as the best model to represent the data used in this study (Figure 3).

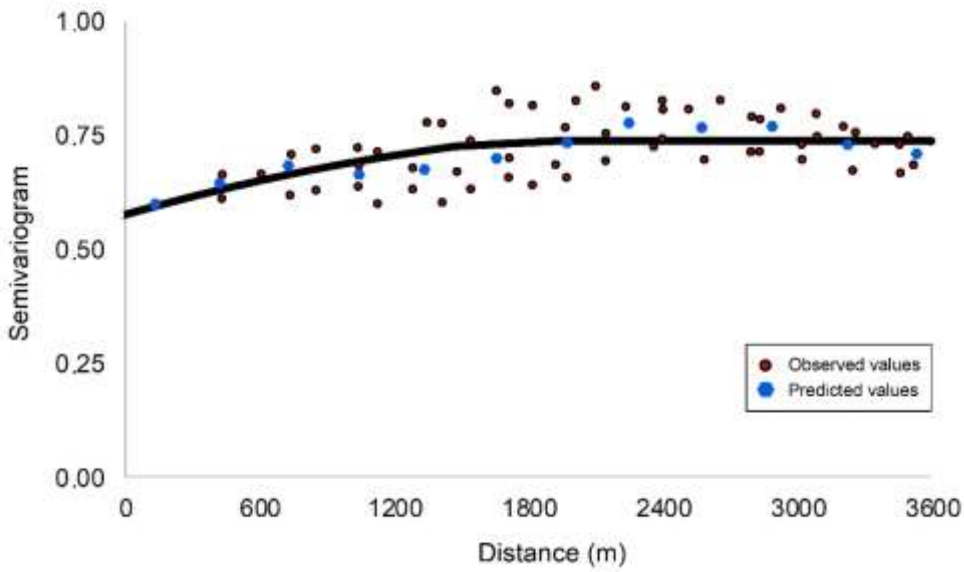

Figure 3 - Semivariogram with spherical model adjustment for volume data (m³), in the direction of 111°, with six years old.

After validating this model, there was no significant difference between the volumes fitted by kriging and the volumes observed in the forest inventory (Table 4), as verified through the T-test (p = 0.05). Validation showed satisfactory SEE and RMSE, as well as low CV and high adj-R^2 (0.99).

Table 4 – Cross validation results for *Eucalyptus* spp. stands, in the municipality of Paragominas, Pará state, at 6 years old.

$\bar{X}$ Observed volume	$\bar{X}$ Fitted volume	SEE (m³)	RMSE (%)	CV (%)	R^2	*p-value*
11.35	11.38	0.27	5.91	10.19	0.99	0.87^{ns}

$\bar{X}$ is mean; SEE is estimate standard error, RMSE is root mean square error, CV is variation coefficient, R^2 is determination coefficient, ^{ns} is not significant by T test (p > 0.05)

The proximity between volume averages, as well as precision measurements, indicates that the estimation was accurate, so that geostatistical estimators generated volume values similar to the forest inventory, as found by Mello et al. (2006). This allowed a possible exchange of the inventory for the geostatistical estimate, reducing the cost of forest measurement due to the possibility of reducing the sampling space when using geostatistics.

Such reduction is explained in the study of Pelissari et al. (2014), who worked with teak stands. The authors claim that geostatistics allows a sampling system with specific sampling intensity for homogeneous subpopulations of the stand, whereby sampling units are installed at optimal intensities for accurate data acquisition with minimal costs.

Moreover, another advantage of geostatistics application is a reduced sampling error. The sampling error was 2.83% when using the forest inventory, and 2.01% when using geostatistics. Thus, according to the PCI, the total volume of the plots was 1,691.40 m³, while by geostatistics this value was 1,696.25 m³, a difference of 4.85 m³ or 0.29% (Table 5).

Table 5 – Estimated volume of plots by ordinary kriging in *Eucalyptus* spp. stands, in Paragominas municipality, Pará state, at six years old.

Parameter	Result
Average volume by plot (m³)	11.3842
Error (%)	2.01
Total volume of plots (m³)	1696.25

This difference shows a slight overestimation by geostatistics in relation to the traditional inventory. However, despite this trend, estimates can be considered accurate. Leal et al. (2011) concluded the same in their work using kriging geospatial interpolation in a stand of *Eucalyptus urophylla*, where interpolation showed a small but not significant trend to overestimate interpolated data.

The kriging map was thus generated, in which one can observe the maximum (near green) and minimum (near red) values interpolated for the wood volume of the stand under study (Figure 4).

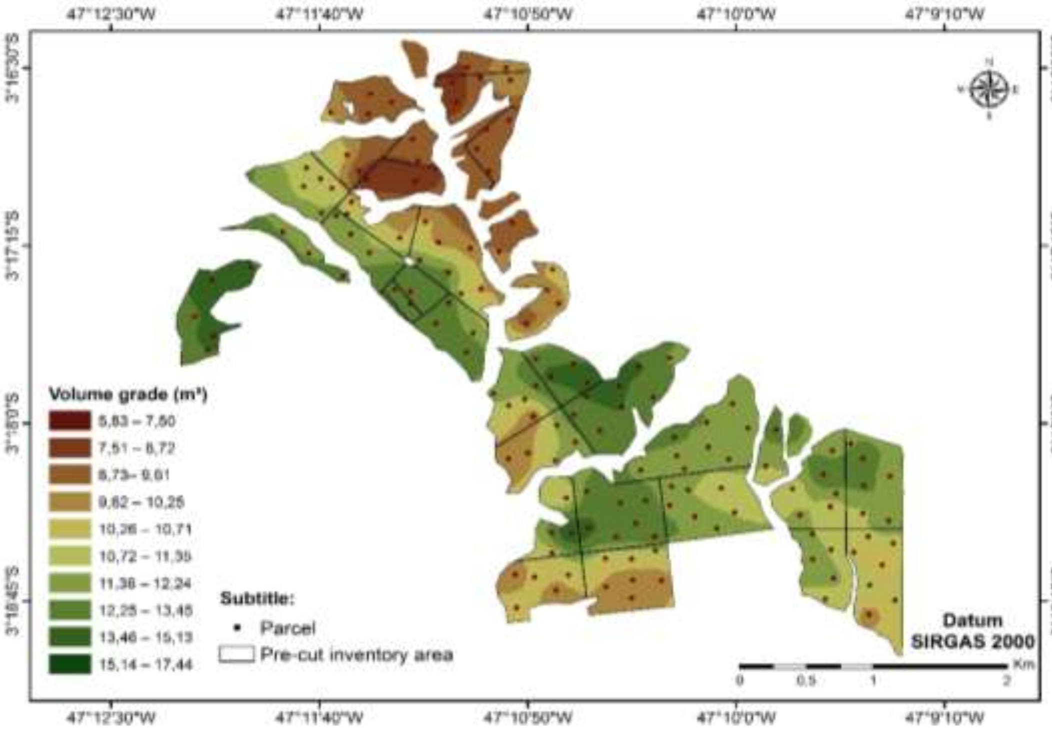

Figure 4 - Ordinary Kriging Map with the interpolated values of volume (m³) for *Eucalyptus* spp. stands, in the municipality of Paragominas, Pará state, at six years old.

Interpolation presented relevant data regarding field volume mapping, besides being effective and fast, corroborating with Leal et al. (2011), who mentions ordinary kriging as a reliable and practical tool to subsidize forest management.

Conclusions

The ordinary kriging interpolation tool is suitable for estimating the wood volume of stands of *Eucalyptus* spp., contributing to the farmer's planning and decision-making process, as well as allowing the quantification of the ideal sampling intensity in forest inventories and, consequently, reducing the costs of this operation.

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