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Spatial distribution pattern of *Euxylophora paraensis* Huber in a natural managed forest in the Eastern Amazon

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ABSTRACT: The objective of this work was to characterize the spatial distribution pattern of the *Euxylophora paraensis* (yellow-wood), to support conservation strategies of this species population in a managed 'terra firme' forest in the state of Pará. The study area is located in Fazenda Rio Capim, which belongs to The CKBV Florestal Ltda., in the municipality of Paragominas. For analyzing the spatial distribution of trees, geostatistics was used, based on the semivariogram modeling and kriging mapping. All evaluations had better adjustment to the spherical model, presenting the highest coefficient of determination in relation to the other models tested. *Euxylophora paraensis* presented an aggregate distribution pattern in the study forest, with spatial dependence described by the spherical model, forming tree clusters of size from 300 to 1000 m.

Key words: geostatistics; kriging; semivariogram; yellow-wood-tree

Distribuição espacial de *Euxylophora paraensis* Huber em floresta natural manejada na Amazônia Oriental

RESUMO: O objetivo desse trabalho foi caracterizar o padrão de distribuição espacial de *Euxylophora paraensis* (pau-amarelo), para subsidiar estratégias de conservação dessa espécie em floresta de terra firme manejada no estado do Pará. A área de estudo está localizada na Fazenda Rio Capim, pertencente a CKBV Florestal Ltda., no município de Paragominas. Para a análise da distribuição espacial das árvores utilizou-se a geoestatística, a partir da modelagem de semivariograma e confecção de mapas de krigagem. Todas as avaliações tiveram melhor ajuste ao modelo esférico, apresentando o maior coeficiente de determinação em relação aos outros modelos testados. *Euxylophora paraensis* apresentou padrão de distribuição agregada na floresta estudada, com dependência espacial descrita pelo modelo esférico, formando reboleiras de 300 a 1000 m.

Palavras-chave: geoestatística; krigagem; semivariograma; pau-amarelo

Introduction

Sustainable management of natural forests is a complex task and still represents a challenge given the complexity of tropical forest ecosystems. This complexity makes it difficult to assess the biological parameters, especially those related to growth and production (Vatraz et al., 2012).

The maintenance of the diversity of tree species in natural forests is crucial for the success of forest enterprises in the Amazon region (Alves & Miranda, 2008). Estimation of forest growth is essential for the sustainable management plan (Vatraz et al., 2016). However, not all the sustainability mechanisms of the managed forests are adequately addressed by the managers and the current Brazilian forestry legislation.

In this context, there is the species *Euxylophora paraensis* Huber (Rutaceae), popularly known as *pau-amarelo* (yellowwood) due to the color of its wood. The genus *Euxylophora* is monotypic, presenting only the species *E. paraensis,* occurring in northern Brazil (Buchanan et al., 2000).

Due to the good quality of wood, mainly for the manufacture of furniture (Isidoro et al., 2012), this species was intensively exploited without any planning from the nineteenth century until the late 1990s, which reduced its natural populations to critical levels in the last years.

Due to the strong reduction of its natural populations, *E. paraensis* was included in the official list of national flora threatened with extinction in 2008, according to the Ordinance of the Ministry of the Environment No. 443, of December 17, 2014 (Brazil, 2014). Its management was restricted by the legislation in force and controlled by the official bodies. However, basic information such as growth, recruitment, regeneration, spatial distribution of its natural populations and the effects of forest management on the species are unknown.

Currently, the study of spatial distribution patterns of tree species is a widely used and a promising tool to understand the behavior of several species (Capretz et al., 2012; Loregian et al., 2012; Vieira et al., 2013; Abreu et al., 2014). Knowledge about patterns of spatial distribution of tree species can provide important information on the ecological processes and characteristics of the environment itself and assist in sampling processes regarding the studied species (Capretz et al., 2012). However, this information is still scarce for most forest species in the Eastern Amazon, so there is no record in the literature on the spatial distribution of *E. paraensis*.

There are numerous methodologies created or developed to characterize the pattern of spatial distribution of tree species. Among these methodologies, the geostatistics (Kriging interpolation) techniques have been highlighted in forest studies and their use has been increasing in recent years (Amaral et al., 2013; Valtera et al., 2013; Lundgren et al., 2015; Zhang et al., 2015). Kriging interpolation is a method that uses the position information of the sample and the value that the variable assumes at each point. Thus, from each sampling point we obtain the value of the variable and the coordinates (x and y), which are used to build dispersion maps of the trees.

As already mentioned, *E. paraensis* is a species whose wood has high commercial value, but it is on the list of species threatened with extinction. Therefore, many ecological and silvicultural information needs to be obtained to facilitate its management and conservation. The spatial distribution pattern is one of these ecological information to be obtained, since the definition of the management practices to be adopted will depend on this distribution pattern.

In addition to the spatial distribution, it is important to evaluate the diametric distribution of tree species in tropical forests, since this evaluation allows inferring on entry, mortality and development history of these species, besides quantifying the intensity of changes that occurred in the forest community (Dalla Lana et al., 2013; Reis et al., 2014). This diagnosis over time is a useful tool in silvicultural decisions in forest management, which may allow the sustainability of this activity.

Therefore, due to the importance of this species and the lack of basic studies to implement its proper management and conservation, the objective of this work was to characterize the spatial distribution pattern of *Euxylophora paraensis* (yellowwood) by means of geostatistical analysis in upland forest managed in the state of Pará.

Material and Methods

The study was carried out at the Fazenda Rio Capim Forest Management Unit, owned by CKBV Florestal Ltda., belonging to the CIKEL Group, located between the geographic coordinates: 3° 30’ and 3° 45’ S and 48° 30’ and 48° 45’ W, in the outheastern region of Pará state. The company has six forest management units in the state of Pará, totaling an area of 450,000 ha. Among these units is the Fazenda Rio Capim, with an area of 140,000 ha, with 121,000 ha of forest managed and certified by the Forest Stewardship Council (FSC) since 2001. Four Annual Production Units (APU) were selected: APU 16 (Area 1), APU 19 (Area 2), APU 18 (Area 3) and APU 17 (Area 4) (Figure 1). Areas 1, 2, 3 and 4 were explored in the years 2013, 2014, 2015 and 2016, but the *E. paraensis* species was not harvested.

According to the Köppen classification, the predominant climate in the region is “Aw”, that is, tropical wet, with annual average rainfall of 1,800 mm, annual average temperature of 26,3º C and relative humidity of 81% (Alvares et al., 2013). The vegetation of the study area is of the upland forest type, classified as Dense Ombrophilous Forest (IBGE, 2012).

The APUs (Annual Production Unit) were divided into Work Units (WUs). Each WU was divided into 20 lines with spacing of 50m between each other, to guide the walking and the location of the trees (Figure 2). In each WU, the coordinates (x, y), diameter at breast height (DBH = diameter measured at 1.30 m from the ground) ≥ 40 cm, and height in

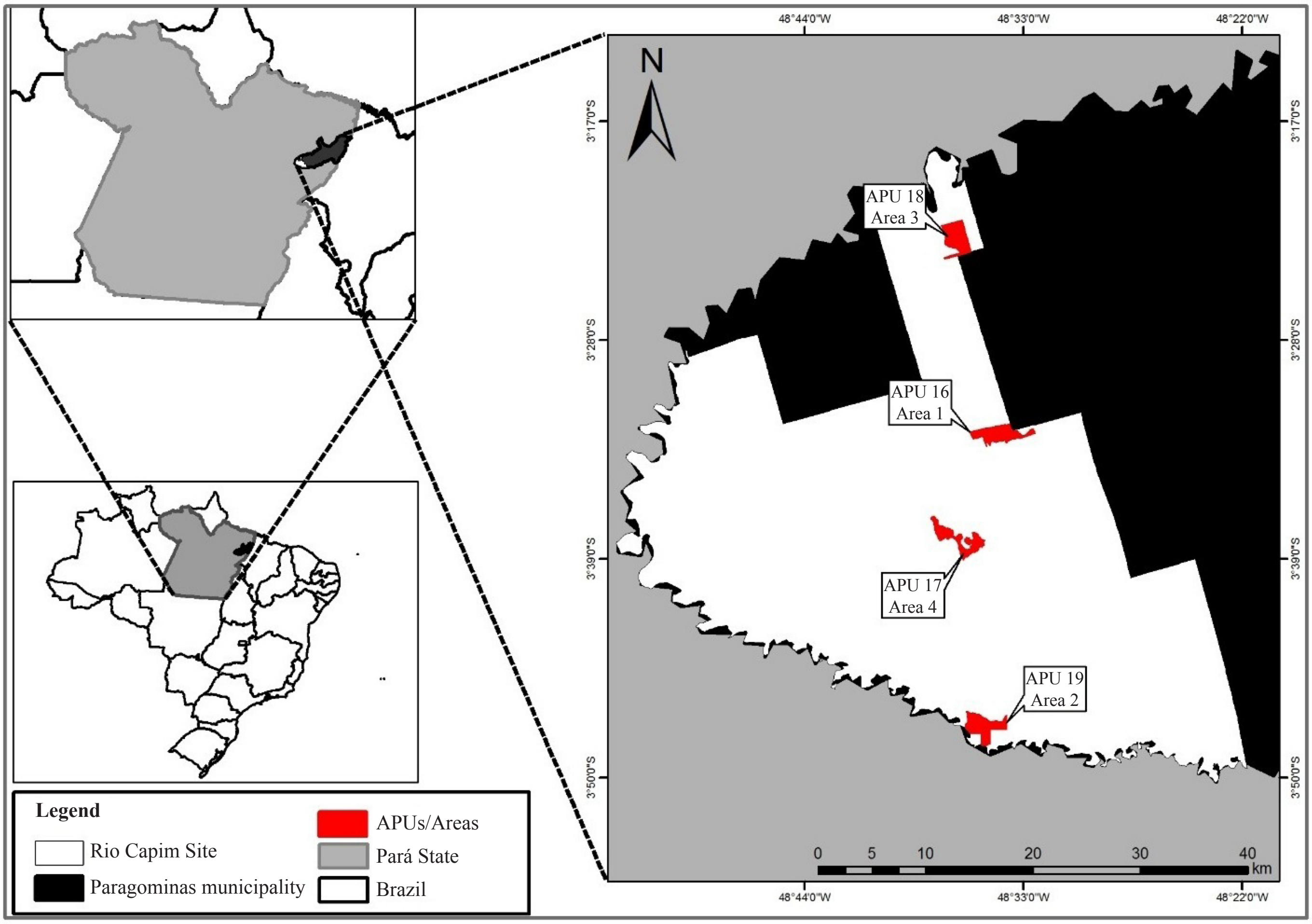

Figure 1. Location of study areas of spatial distribution of *Euxylophora paraensis* in the city of Paragominas, PA - Brazil.

meters were recorded. The individuals of *E. paraensis* were properly plated and georeferenced.

In order to evaluate the spatial distribution of *E. paraensis*, we used geostatistical analysis from the semivariogram modeling and kriging mapping. We also used the sample position information and the value that the variable (number of trees inventoried) assumed at each point. Thus, from each sampling point, we obtained the value of the variable and

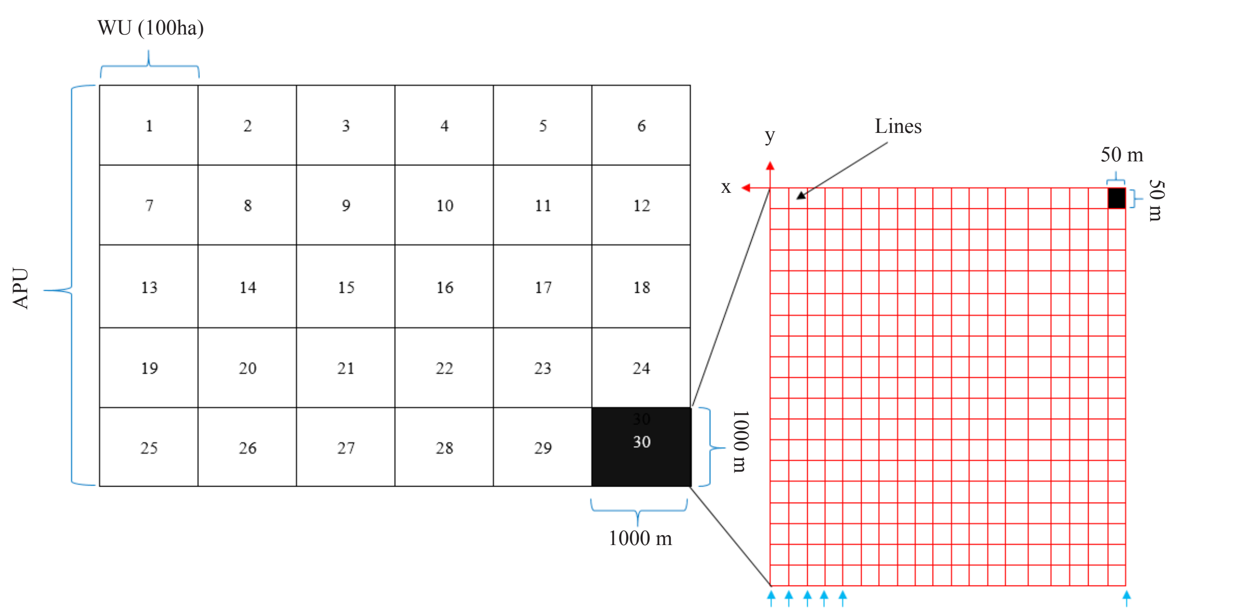

Figura 2. Sketch of the Annual Production Units (APU), Work Units (WU) and lines used in the forest inventory carried out at 100% intensity in APU s 16, 17, 18 and 19 at Fazenda Rio Capim, city of Paragominas, PA - Brazil.

the coordinates (longitude and altitude) of the place where each tree of *E. paraensis* was found (Yamamoto & Landim, 2013).

The first step of the analysis is to obtain the semivariograms, which is the most important step in the procedure of a geostatistical analysis (Silva et al., 2011), since the chosen model was used in the kriging process (contour maps) and will influence all interpolated results and conclusions. The semivariogram was estimated by Eq. 1:

$$y^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[z(x_i) - z(x_i + h) \right]^2 \tag{1}$$

where N (h) is the number of experimental pairs of measured values Z (xi), Z (xi + h), separated by a vector h. The graph of γ* (*h*) versus the corresponding values of *h* is a function of distance (h), and is therefore dependent on the magnitude and direction of the distance (Farias et al., 2002).

After this procedure, we found that the semivariogram model was the one that best fitted the data based on the coefficient of determination (R^2), and this was used in the Kriging process (Dionisio et al., 2015).

The best definition of the variographic parameters for the data was the fit to the spherical model estimated by Eq. 2:

$$\begin{gathered} y(h) = C_0 + C_1 \left[\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3 \right], 0 < h < a \\ y(h) = C_0 + C_1, h \geq a \end{gathered} \tag{2}$$

This model is obtained by selecting the values of the nugget effect, C_0, and of the landing, C_1, then passing a line that intersects the y-axis in C_1 and is tangent to the first points close to h = 0. This tangent will cross the landing in the distance, a' = 2/3a. Thus, the range, a, will be a = 3a'/2. The spherical model is linear up to approximately 1/3a.

Kriging

Generally, the interest of the analysis is not only in modeling the structure of variability. In several situations, the interest is in the estimation of values in non-sampled points, either by a local interest or by the intention of obtaining a detail of the area that goes beyond the allowed by the sample. In this case, it is necessary to use kriging as an estimator through Eq. 3:

$$Z(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i) \tag{3}$$

Therefore, we constructed the kriging maps, which use the spatial dependence modeled in the semivariogram and estimate values in any position of the studied area without trend and with minimum variance, allowing to visualize the behavior of the variable under study through isolines and surface maps (Siqueira et al., 2008; Dionisio et al., 2015).

In order to classify the spatial dependence index (SDI) by the relation of ($C_0/(C_0 + C_1)$), we used the methodology described by Cambardella et al. (1994), which determines how much of the spatial variance is present in the total variance of the sample. 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.

In order to analyze the data and to make the maps of the spatial distribution of *E. paraensis*, the statistical software SURFER Version 11.0 was used.

Results and Discussion

In the 2,363 ha sampled in the four areas in the Fazenda Rio Capim, 467 individuals of *E. paraensis* with DBH ≥ 40 cm were found, distributed in the four areas. DBH ranged from 40.1 to 204.0 cm and the average per area is shown in Table 1.

It was observed in the four areas that the density of *E. paraensis* is in accordance with the minimum limit required by the legislation for the maintenance of the species in the exploited area that, according to Normative Instruction No. 1 of February 12, 2015, is “at least four (4) trees per species per 100 ha (100 hectares) in each work unit”, because it is a species threatened with extinction (Brazil, 2015). The lowest density occurred in Area 2, with 0.12 ind. ha^{-1}, which is equivalent to 12 trees of the species in 100 ha. These results demonstrate that, according to Normative Instruction No. 1 of February 12, 2015, the species presents potential for wood extraction in the studied areas.

According to the Ordinance of the Ministry of the Environment No. 443, of December 17, 2014 (Brazil, 2014), *E. paraensis* is a species threatened with extinction, critically endangered, and therefore its cut is forbidden. However, the results of the present study demonstrate that it is possible to explore *E. paraensis* respecting the mechanisms of sustainability and conservation of the species in the study area. Considering the density of trees in the harvesting stock suitable for cutting selection, it is possible to establish a hypothetical situation of sustainable forest management in an area of 100 ha, using Normative Instruction No. 05, of September 10, 2015 from the State Secretariat of Environment and Sustainability (SEMAS, 2015). Thus, we would have 29 (area 1), 8 (area 2), 12 (area 3) and 15 (area 4) trees of *E. paraensis* for a possible exploration, since 4 trees should be maintained in the management area. However, it is important

Table 1. Population parameters of *Euxylophora paraensis* (individuals with DBH ≥ 40 cm) in four managed areas, in the city of Paragominas, PA - Brazil.

Area	Area (ha)	N. ind. (DBH ≥ 40 cm)	Total density (ind ha^{-1})	Volume (m^3 ha^{-1})	Mean DBH (cm)
1	584	195	0.33	0.9455	67.5
2	594	69	0.12	0.2867	68.9
3	624	99	0.16	0.4269	69.5
4	561	104	0.19	0.5142	69.2

to emphasize that the costs involved in the exploration and the volume in each area are relevant factors for deciding to exploring or not, since if the volume of these trees is low, it may not be enough with respect to the financial return to compensate for the costs involved. (Costa et al., 2018).

With the exception of area 1 that presented the highest number of individuals and higher volumetry per unit area, the other areas (2, 3 and 4) showed great similarities in density and volume per hectare, with a higher concentration of individuals in the intermediate diametric classes (60 -80) (Table 1 and Figure 3).

The population structure showed a decline in the number of individuals in the largest diametric classes, which has a positive asymmetric shape (Vieira et al., 2013). The anthropic activities can also be another explanatory factor for the diametric distribution, especially in the larger diameter classes. This type of population structure was also observed by Condé et al. (2016), in upland Dense Ombrophilous Forest, when analyzing the diametrical distribution for the species *Cedrelinga cateniformis* and *Dinizia excelsa*.

Due to the irregular distribution of *E. paraensis* in the four study areas, we observed that the population is not in equilibrium between the different diametric classes. The studied populations did not present a diametrical distribution in the form of "inverted J", that is, in which the number of individuals is reduced from the smallest diameter classes to the largest. The distribution of individuals in the form of "inverted J" is reported by several authors as an indicator of population stability and ability to self-regenerate and reproduce under closed canopy (Gonçalves & Santos, 2008; Bernasol & Lima-Ribeiro, 2010; Figueiredo Filho et al., 2010; Abreu et al., 2014; Silva et al., 2015). In areas 2, 3 and 4, the distribution was characterized as "bell-shaped" (Bernasol & Lima-Ribeiro, 2010), that is, with most individuals in the intermediate classes. This type of structure indicates species that do not reproduce frequently under the closed canopy and that need the opening of clearings for regeneration.

The irregular distribution observed in the studied populations of *E. paraensis* may be related to the ecophysiological characteristics of the species. According to Pinheiro et al. (2007) and Gualberto et al. (2014), *E. paraensis* is classified as a shade-intolerant species or light-demanding, necessitating, therefore, opening of clearings for its natural regeneration to occur. Thus, the irregular diametric distribution observed in the four sampled areas can be explained as the typical distribution of a light-demanding species. With this population structure, the exploitation of *E. paraensis* may not be sustainable, and it is necessary to adopt a specific management plan for this species, including the application of silvicultural treatments in order to enable its establishment in all diametric classes and, thus, making its harvest feasible.

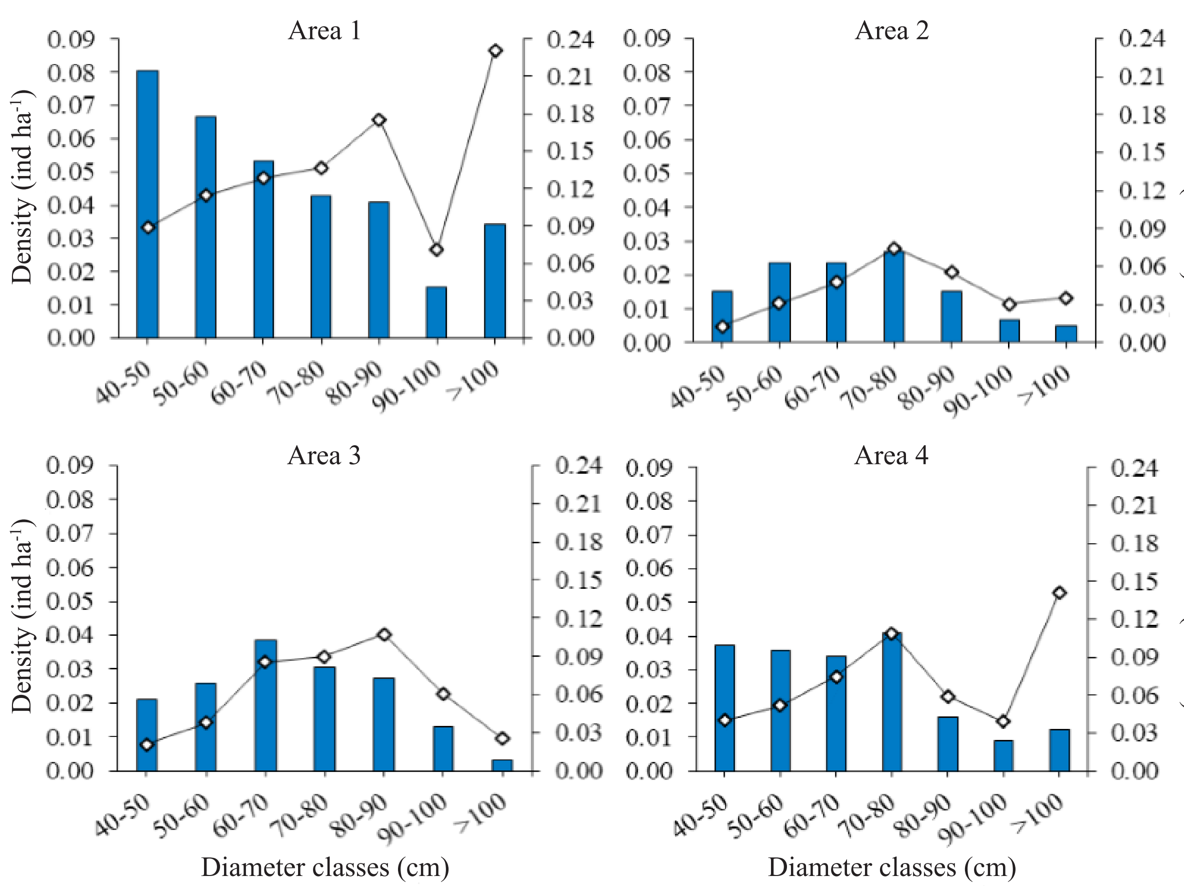

Figure 3. Number of individuals and volume of wood of *Euxylophora paraensis* per diameter class per hectare in four managed areas, in the city of Paragominas, PA - Brazil. Bars indicate the density of individuals (# ind. ha^{-1}) and lines indicate the volume per area unit (# ind. ha^{-1}).

There was a spatial dependence of *E. paraensis* described by the spherical model, showing an aggregate distribution pattern of the species, with an aggregation radius ranging from 300 to 1000 m (range of the model) in the four studied areas (Table 2). The range or radius of aggregation is a very important parameter, because it represents the distance in which there is spatial dependence between the samples, enabling an analysis of the dispersion progress of this species in the studied areas and, consequently, in the forest. The aggregate pattern may be the result of environmental heterogeneity, where there are microenvironments favorable to the establishment of the species and to the seed dispersion pattern, and the of the probability of seedling survival (Vieira et al., 2013).

Similar results were found by Abreu et al. (2014) studying the spatial distribution pattern of *Carapa* spp. (Andirobeiras) in the state of Amapá, where they found that this species is distributed in aggregate form. The spatial distribution of a species can be influenced by abiotic factors, such as water availability and light intensity, and biotic factors, such as predator or pathogen action and seed dispersal (Abreu et al., 2014). Specific spatial patterns found in forests are guided by spatial dependence of forest variables, such as density, basal area, height, volume, biomass and those conditioned by different levels of competition (Archanjo et al., 2012). Spatial distribution studies of tree species and their relationship with biotic and abiotic factors are fundamental for the advancement of basic research in ecology, control of biodiversity changes and to develop effective conservation actions for the species (Zhang et al., 2015).

Condé et al. (2016) studied the spatial pattern of Amazonian timber species by the Cartesian and spatial coordinates method, in 9 ha of forest managed in Caracaraí, RR. A random spatial pattern was observed for *Eschweilera bracteosa* and *Manilkara huberi*, both with potential for commercial extraction due to the balance in density and volumetry. However, scattered and rare spatial patterns were predominantly observed in *Cedrelinga cateniformis* and *Dinizia excelsa*, which requires specific demands to manage these species in a sustainable way.

The ratio $C_0/(C_0+C_1)$ provides the measure to estimate the degree of dependence in the samples (aggregation), that is, the degree of randomness that exists in the surveys (Dionisio et al., 2015), and these values ranged from 0.07 to 0.61 in the various sampling areas of the present study (Table 2), indicating that the maximum variation between neighboring points is 61% between the studied areas. These values are in agreement with Journel & Hijbregts (1978), according to whom values below 0.80 indicate aggregate distribution of the variable and values above this index indicate that the phenomenon studied is tending towards randomness.

Figure 4 shows the semivariograms and kriging maps of the spatial distribution of *E. paraensis*. The coefficient of determination (R^2) indicates the quality of fit of the

Table 2. Parameters of the semivariograms of the spatial distribution of *Euxylophora paraensis* in four management areas, in the city of Paragominas, PA - Brazil.

Area	APU	Parameters*			Model	R^2	K^a	Degree of dependence
		C_0	C_1	a (m)				
1	16	2.2	1.4	1000	Spherical	0.97	0.61	Moderate
2	19	0.5	2.35	370	Spherical	0.81	0.18	Strong
3	18	0.7	1.5	320	Spherical	0.97	0.32	Moderate
4	17	0.5	6.3	300	Spherical	0.99	0.07	Strong

* Nugget effect (C_0), spatial variance or contribution (C_1), reach (a), [a] ratio of $C_0/(C_0+C_1)$.

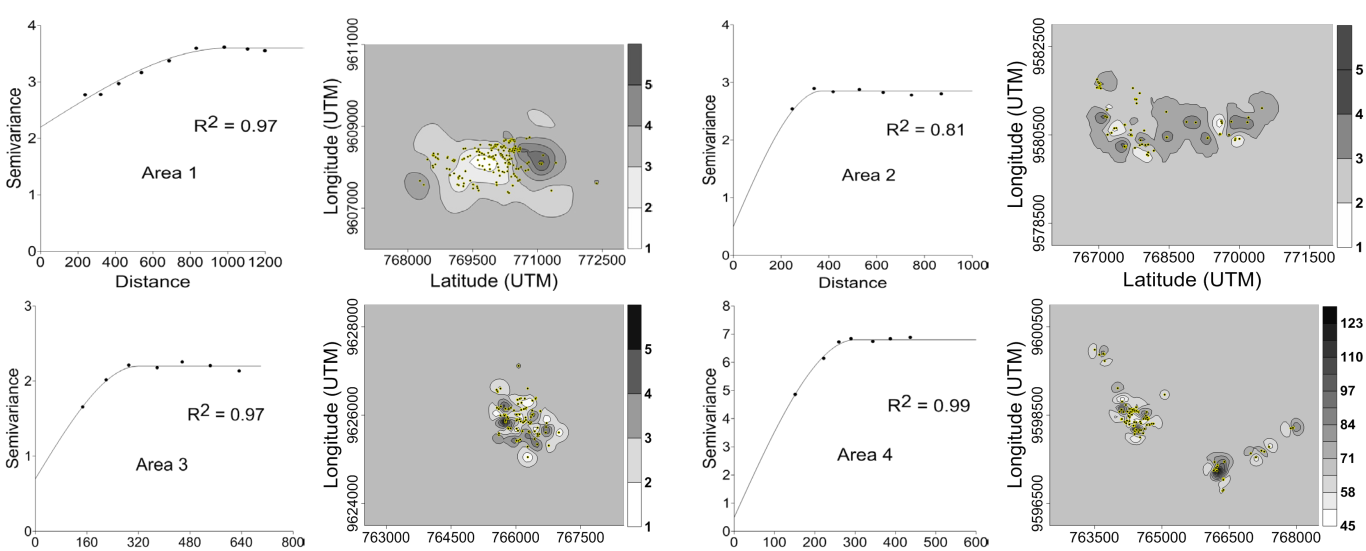

Figure 4. Semivariograms and kriging maps of the spatial distribution of *Euxylophora paraensis* in four management areas in the city of Paragominas, PA - Brazil.

semivariogram model. Values close to 1 (one) indicate good fit of the model (Silva et al., 2011), which was observed in the present study, in which this parameter showed a range from 0.81 to 0.99, giving a high reliability for the estimate. Through the parameters of the semivariograms and kriging models, the maps were elaborated, which allowed visualizing the behavior of the spatial distribution of the trees in the areas. The aggregate distribution of *E. paraensis* is observed in the maps and it is possible to visualize the formation of dead spots (Figure 4).

The kriging maps show the dispersion tendency of *E. paraensis* in the studied areas, from a region with a higher concentration of trees to a lower one. This was very noticeable, especially in areas 1 and 4, confirming that the aggregate distribution is the one that best adjusts to the behavior of this species, characterized by the higher density of specimens in certain sites of the area.

According to Guarino et al. (2014), the spatial distribution of the aggregate type of a population is strongly influenced by the seed dispersion patterns. *E. paraensis* presents barocoric dispersion syndrome (Amaral et al., 2009). The characteristics of this syndrome also help to explain the aggregate distribution of *E. paraensis* found in this work, because the fruit are dispersed by gravity and tend to fall close to the mother plant. Based on this information, it is possible to suppose that the dispersion form of this species can be considered a crucial cause for its mode of aggregation. This aggregate spatial pattern is probably the most common in neotropical tree species (Condit et al., 2000). According to Archanjo et al. (2012), specific spatial patterns found in forests are guided by spatial dependence of forest variables, such as density, basal area, height, volume and biomass, that is, they reflect the occupation of the spaces and uses of the resources available in the environment by the species, conditioned by the different levels of competition.

Conclusions

Euxylophora paraensis presented an aggregate distribution pattern in the studied forest possibly due to its barocoric dispersion syndrome, with spatial dependence described by the spherical model, forming 300 to 1000m (model range) dead spots. This ecological characteristic should be considered in the decision making on the management and conservation of the species.

Euxylophora paraensis showed density in the crop stock (DBH ≥ 50 cm) below 1 ind.ha^{-1}, but the species has trees in all diametric classes in the growth stock (DBH ≥ 40 cm) and it is therefore recommended an economic evaluation for decision making in managing the species, because there are few trees in the harvest stock.

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