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Spatial Analysis of the Natural Regeneration of Candeia (*Eremanthus erythropappus* (DC.) MacLeish) as Influenced by Non-Candeia Tree Layer Composition

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ABSTRACT

Background: Tree regeneration in native stands harvested for wood is essential to guarantee sustainability of the practice. Understanding how forest species spatially establish themselves in exploited areas enables the verification of ecological processes and possible interactions among ecological variables. For instance, tree species that are light demanding must be managed in a way that ensures that the canopy of the stand is opened enough to permit direct sunlight to reach the seeds, otherwise stand regeneration is not obtained. This is the case of native candeia stands located in southern Minas Gerais State, Brazil. This species is managed for wood used in essential oil extraction. Being a species that occurs in transition zones from forest formations to open fields, this species tends to form monodominant stands in areas that have low fertility soils. **Objective:** The main objective of this study is to determine how candeia regeneration establishes itself after wood harvest under varying intensities of canopy cover. **Results:** We analyzed the influence of uncut mature trees on candeia natural regeneration, by means of spatial dependence analysis and mapping of the natural regeneration of candeia and the tree layer in areas subjected to exploration. The variables analyzed included the number of regenerated individuals of candeia and non-candeia trees present in the tree layer, obtained from circular sample plots. Both variables showed structured spatial continuity, varying only in terms of the degree of spatial dependence. Results showed that there is a spatial relationship between the intensity of candeia that was naturally regenerated and the number of individual trees of other species present in the tree layer in all forest fragments subjected to management. This represents a limiting factor in candeia natural regeneration in areas with high non-candeia tree layer incidence. **Conclusion:** Sustainability of the management practiced in terms of natural regeneration is attained in areas of high candeia dominance (at least 64% of occurring individuals)**.**

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INTRODUCTION

Candeia *Eremanthus erythropappus* (DC.) MacLeish is an income-generating tree species. However, there has been no consolidated management system for its natural habitat or a technology to enable pure or mixed plantations for its commercial use. Therefore, the appropriation of native candeia prior to the year 2000 was predominantly predatory and illegal, and the farmers carrying out this practice received between US$12 and US$17 (R$30 and R$40) per stacked cubic meter of candeia wood (Scolforo *et al*., 2012).

To curtail its illegal use, the Federal University of Lavras initiated a project in 2000 with the objective of generating knowledge and technologies that would enable farmers to practice sustainable use of a native candeia species of high commercial value. The project consists of two components: the development of methodologies for the sustainable management of native candeia stands, and the application of this knowledge to the development of a system of commercial production of candeia and its management.

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The economic importance of candeia lies in the production of fence posts due to the high durability of its wood, and in essential oil extraction, whose main component is alpha-bisabolol, which possesses anti-inflammatory, antibacterial, antifungal, dermatologic, and spasmodic properties (Kim *et al*., 2011). With the adoption of sustainable management techniques, the products of candeia are commercialized at relatively high market prices. For example, small enterprises that extract alpha-bisabolol pay between US$45 and US$54 (R$110 and R$130) per stacked cubic meter of wood, whereas farmers pay US$50 (R$120) for a dozen fence posts. To achieve the desired commercial demands, these posts should measure 2.20 m in length and at least 7 cm in diameter. For the production of oil, the wood of plants with a diameter of at least 5 cm at a height of 1.30 m from the ground (diameter at breast height [DBH]) and all the other wood residue not used for the production of posts are appropriate (Scolforo *et al*., 2012).

Perez *et al*. (2004) have demonstrated that there is an increase in the quantity of oil produced by candeia trees with larger diameters. The average production is 1.585 kg (minimum of 0.109 kg) for trees between 5 and 10 cm in diameter and of 4.042 kg for trees between 30 and 35 cm in diameter. The same authors have also shown that, although trees with a smaller diameter contain smaller amounts of oil compared to those with larger diameters, the oil production per hectare from trees with smaller diameters is significantly higher than from larger trees, since the former occur at a higher density than the latter.

Candeia *E. erythropappus* is an ecotone species occurring in areas of transition between forests (seasonal semideciduous and savannah forests) and higher altitude open fields (Oliveira-Filho, 1999). Despite presenting many characteristics of pioneer species, such as high seed production that are dispersed by the wind, which causes high rates of natural regeneration given the right soil, solar radiation, and moisture conditions, the species has a long life cycle, where trees with more than 70 years have been found. It grows rapidly in open fields, forming pure stands. The species is also established within disturbed gaps in forest fragments, since it is a heliophilic species that benefits from sunlight.

Candeia seeds are positively photoblastic (Pedralli, 1997). According to the same author and Scolforo *et al*. (2012), its tree recruitment through seed banks occurs mainly in the top soil layers (0–10 cm deep) in the presence of litter and under conditions of full sunlight, a factor that is essential for seed germination and seedling establishment. Thus the existence of open gaps is essential for sunlight entry and consequential regeneration establishment in managed candeia stands.

Despite the recognized economic potential of candeia, no studies have demonstrated the sustainable exploitation of the species. Thus a project was conceived by a team from the Federal University of Lavras in 2000 presenting pioneering studies that focused on the ecology, silviculture, wood technology, genetics, and management of candeia (*E. erythropappus*) (Scolforo *et al*., 2012; Oliveira *et al*., 2011; Perez *et al*., 2004).

One of the gaps in literature relating to candeia management involves its natural regeneration, particularly in the application of management practices. This was reinforced by Paludo *et al*. (2011), who considered that the maintenance of natural populations is largely influenced by their natural regeneration and monitoring in remnant areas. These studies are fundamental to the practice of sustainable forest management. In addition, it is also necessary to determine the inherent capacity of candeia to spatially establish itself in a managed area to ensure sustainable management (Silva *et al*., 2008).

Factors that affect spatial distribution and limit regeneration establishment and recruitment include changes in altitude (Dang *et al*., 2010), variation in soil attributes (Lima *et al*., 2010), level of canopy cover (Venturoli *et al*., 2011; Modna *et al*., 2010), and light availability (Venturoli *et al*., 2011). In all cases, light availability appears to be the most significant factor that influences species growth and development (Carnevale and Montagnini, 2002).

Studies that examine the spatial behavior of native forests in Brazil are limited (Higuchi *et al*., 2011). Investigations on the ecology of native forests, as well as the biotic and abiotic factors that may affect its natural regeneration, play an important role in the establishment and sustainability of forest management practices.

Therefore, the aim of this study was to map the natural regeneration of candeia and other native tree species in five fragments subjected to forest management and to examine the relationship between spatial dependence of this regeneration and tree layers using geostatistics as an indicator of sustainable management.

MATERIALS AND METHODS

Management of natural candeia stands:

The management of natural candeia stands in the State of Minas Gerais is permitted in areas where the species presence is dominant, occurring in values above 70 % of all the individuals. A seed tree silvicultural system is applied in the managed stands, allowing the removal of a maximum of 70 % of either the candeia individuals or candeia volume. To ensure that genetic diversity is maintained in the managed areas, a minimum of 100 candeia trees per hectare must remain to act as seed trees (Barreira, 2005). All other non-candeia tree species must also remain in the area.

In most cases, the locations of candeia fragments are in montane regions of difficult access, thus the cutting of candeia trees is conducted using chainsaws, and wood withdrawal from the stand to a nearby road is made by mules. After candeia exploration, a set of treatments are carried out to stimulate natural regeneration of the species. To ensure that the candeia seeds are able to make contact with the soil, the soil is scarified in 5 to 10 cm depths in 60 cm diameter circles about 2.5 meters of one another using a hoe. The managed area must also be protected from domestic animals, fire and weed competition (Gomide *et al*., 2012).

Characterization of the managed areas:

The study areas are located in the southern region of Minas Gerais State, Brazil, covering five municipalities and involving different times of data collection after exploitation. Table 1 describes the fragments in terms of area, number of trees per hectare, total wood volume, wood volume removed during management, and predominance of candeia prior to management.

Table 1: Characteristics of managed fragments (F) analyzed in the present study.

F	Municipality	P	Area	NI_i	V_t	V_e	NI_r	IM
1	Baependi	92.3	8.5	836.1	49.7	34.74	585.3	8
2	Pedralva	48.2	1.2	1401.3	53.5	37.42	980.9	24
3	Conceição do Rio Verde	63.6	5.3	1001.3	33.3	23.32	700.9	36
4	Virgínia	59.6	7.0	1417.5	86.5	60.55	992.3	44
5	Itamonte	90.2	2.4	3197.0	165.1	99.1	1918.0	59

Abbreviations (units): P, predominance of candeia prior to management (%); Area (ha); NI_i, number of candeia trees prior to exploitation, (trees per hectare); V_t, total candeia wood volume (m^3/ha); V_e, extracted candeia wood volume (m^3/ha); NI_r, number of trees removed (trees per hectare); and IM, time period between the completion of management and data collection (months).

Table 2 shows the basic information on the location and soil-climatic features of each fragment (F). The information on precipitation and temperature were obtained from Carvalho *et al*. (2008), which was based on climatological data from 1961 to 1990. The soil classification was obtained from soil maps of Minas Gerais (Embrapa-Solos, 2006).

Table 2: Geographical coordinates (latitude and longitude); altitude in meters (A); average annual rainfall in millimeters (P); average annual temperature in ^{o}C (T); and predominant soils in the fragments (F).

F	Latitude	Longitude	A	P	T	Predominant soil
1	21°59’04’’ S	44°45’16’’ W	1450	1700	17	Humic cambisol
2	22°16’48’’ S	45°24’20’’ W	1400	1700	17	Red acrisol
3	21°49’03’’ S	45°03’23’’ W	950	1600	17	Litolic neosoil
4	22°20’04’’ S	45°11’29’’ W	1620	1700	16	Haplic cambisol
5	22°16’45’’ S	44°46’24’’ W	1750	1700	16	Humic cambisol

Sampling and data collection:

The plots around a mature candeia tree (a seed tree not exploited during management) were systematically distributed in the form of a regular polygon with 12 sides (dodecagon), with a radius of 10 m. The total area of each plot was 300 m^2 and this was subdivided into 12 subplots in the format of an isosceles triangle and an area of 25 m^2 each. All the subplots were georeferenced in one of the vertices. The number of subplots in Fragments 1, 2, 3, 4, and 5 was 168, 48, 108, 180, and 60, respectively. Figure 1 shows the format of a plot and subplots.

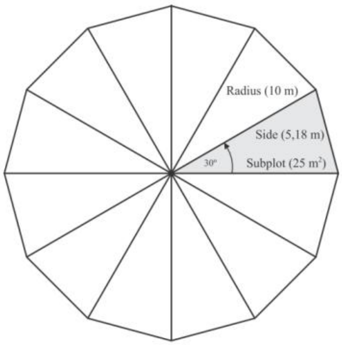

Fig. 1: Format of a plot divided into 12 subplots.

Each regenerated candeia and non-candeia native tree (not exploited during management) were registered in each subplot. Total height (h) was measured for each regenerated candeia seedlings, all candeia individuals with height less than 1.5 m and diameter at breast height less than 5 cm were classified as regeneration.

Spatial analysis of candeia regeneration and tree layer:

The confidence interval for each fragment was determined using classical statistical methods and the spatial pattern for the two variables of interest, namely the number of regenerated candeia trees and the number of non-candeia native tree species present in the tree layer. Experimental semivariograms were elaborated to detect the structure of spatial dependence of the number of regenerated candeia trees in relation to the number of trees of other native species. The semivariance functions for each variable under study were estimated according to the equation described by Cressie (1993).

The implementation of geostatistical techniques depends on a previously established model (Mello *et al.*, 2005). The selection of the correct model that adequately represents the structure of spatial dependence of the random variable is extremely important in the kriging process (Nielsen and Wendroth, 2003). The theoretical, spherical, and exponential models were parameterized by using the maximum likelihood method (Journel and Huijbregts, 1978), defining the following parameters: the nugget effect (τ^2), the sill ($\tau^2 + \sigma^2$), and the range of spatial dependence (ø).

The R software (R development core team, 2011) with the GeoR package (Ribeiro Junior and Diggle, 2001) was used for the spatial analysis of the variables.

Two criteria were examined to select the model that best estimated the performance of the different variables. The first criterion was the Akaike Information Criterion (AIC, Akaike, 1983). An ideal model would have the lowest AIC value. Cross validation techniques that compared the reduced average error of each model was used as the second criterion, where the model with the reduced average error closest to zero was selected. According to McBratney and Webster (1986), in the absence of bias, the population value for the reduced average error must be zero.

After model selection, the degree of spatial dependence of each variable was examined using the percentage of structured variance (σ^2) in relation to the sill ($\tau^2 + \sigma^2$), as described by Biondi *et al.* (1994). Spatial dependence, according to Zimback (2003), employed the following intervals: less than 25% (low), between 25 and 75% (moderate), and greater than 75% (strong). Once spatial dependence was established, we used ordinary kriging to estimate the expected number of regenerated candeia trees and the number of non-candeia native trees in the tree layer. The difference between the maximum and minimum value of the estimated variable was divided into three classes of the same magnitude to define classes of low, medium, and high intensity in each fragment, for both the number of regenerated candeia trees and trees of other native species present in the tree layer (Table 3). This approach generated spatial distribution maps for each variable in all fragments and possible spatial relationships among parameters.

Results:

The estimates per hectare for the number of regenerated candeia trees and non-candeia native tree species in the tree layer, including the confidence intervals, are presented in Table 3. These intervals do not take into account the location of the sampling units in the area. The mathematical expectation of these estimates is that the value of the random variable under study remains constant in the entire population, varying only in relation to the standard deviation of the mean. More homogeneous or heterogeneous regions are not distinguished within the fragment, disregarding the fact that nearby areas may be more similar in terms of the characteristic of interest compared to more distant areas. These peculiarities can be identified through geostatistical analysis.

Table 3: Minimum (Min), maximum (Max), mean, coefficient of variation (CV in %), and confidence intervals [$CI_{1-\alpha}(\mu)$] with a significance level (α) of 5% for the number of regenerated candeia trees and trees of other native species per hectare in each fragment (F).

F	Candeia Regeneration					Mature tree layer				
	Min	Max	Mean	CV	$CI_{1-\alpha}(\mu)$	Min	Max	Mean	CV	$CI_{1-\alpha}(\mu)$
1	0	32800	4998	132	$3992 \leq \mu \leq 6003$	0	800	50	318	$26 \leq \mu \leq 74$
2	0	14400	2158	145	$1250 \leq \mu \leq 3067$	0	4000	1075	92	$789 \leq \mu \leq 1361$
3	0	5200	785	151	$559 \leq \mu \leq 1011$	0	2000	415	110	$328 \leq \mu \leq 502$
4	0	17200	1723	174	$1281 \leq \mu \leq 2165$	0	4000	500	156	$385 \leq \mu \leq 615$
5	0	26800	6867	93	$5224 \leq \mu \leq 8510$	0	1200	73	275	$21 \leq \mu \leq 125$

The analysis of the reduced average error supported the selection of the spherical model for the individual regenerated candeia trees because for all the analyzed fragments, the smallest errors resulting from cross validation were those detected using this model (Table 4). This was used in the prediction of this variable in the kriging process.

For the number of individual trees present in the native tree layer that are not candeia, the best model was the exponential one, presenting the lowest AIC values and the reduced average error values closest to zero for all analyzed fragments (Table 5).

Table 4: Akaike Information Criterion (AIC) and reduced average error for the semivariance functions of the variable number of individual regenerated candeia trees.

Fragment	AIC		Reduced average error	
	Exponential model	Spherical model	Exponential model	Spherical model
1	1372.2	1371.1	0.021796	0.020945
2	319.8	318.7	-0.008572	-0.001026
3	547.5	527.0	0.027540	-0.000101
4	1181.2	1181.1	-0.010301	-0.010049
5	464.2	463.0	-0.003828	-0.002383

Table 5: Akaike Information Criterion (AIC) and reduced average error for the semivariance functions of the variable number of individual trees present in the native tree layer that were not of the candeia species.

Fragment	AIC		Reduced average error	
	Exponential model	Spherical model	Exponential model	Spherical model
1	168.8	169.9	0.002086	0.005099
2	222.2	222.7	0.001240	0.019079
3	335.4	335.9	0.006649	0.030333
4	684.1	683.6	0.022246	0.022448
5	88.1	88.9	0.000988	0.003027

The range of the semivariogram indicates that sampling units that are distant from each other within this value are spatially correlated. Since the range refers to the maximum extent that the variable is spatially homogeneous, the higher this value, the greater the spatial structuring of the phenomenon under study. Fragment 4 presented the highest range values for both the number of regenerated candeia trees and the number of non-candeia trees, reaching about 1500 meters in both cases.

The value of the nugget effect indicates the unexplained variability from one point to another possibly due to undetectable micro-variations in the sampling distance used (i.e., situations where there was a high variability within a small space, including within the distance lower than those employed for data collection). In this study, we used a minimum distance between samples of 5.18 m, which corresponds to the smaller side of the subplot.

Tables 6 and 7 indicate that the adjusted nugget effect was greater for the number of regenerated candeia trees compared to that of non-candeia trees present in the tree layer. This fact possibly occurred because the nugget effect deals with microvariations that are more frequent in regenerated plants, since they are small and compete for small areas. The distance used in the sampling was not sufficient to explain variations in these individual trees because they have a smaller diameter and occupy smaller areas than established individual trees with larger diameters.

Table 6: Parameters of the spherical model, structured variance (σ^2), range (ø), nugget effect (τ^2), and spatial dependence for the number of regenerated candeia trees per fragment.

Fragment	σ^2	ø	τ^2	Spatial dependence	Dependence
1	551.3	1497.8	146.3	79.0	Strong
2	39.0	66.5	18.5	67.8	Moderate
3	54.2	748.9	4.3	92.7	Strong
4	1285.7	1497.8	6.9	99.5	Strong
5	712.1	740.9	56.3	93.1	Strong

Table 7: Parameters of the exponential model, structured variation (σ^2), range (ø), nugget effect (τ^2), and spatial dependence for the number of non-candeia trees present in the native tree layer per fragment.

Fragment	σ^2	ø	τ^2	Spatial dependence	Dependence
1	0.02	65.80	0.13	15.78	Weak
2	2.40	123.82	3.89	34.40	Moderate
3	0.26	250.01	1.03	20.15	Weak
4	15.73	1497.85	1.62	90.66	Strong
5	0.07	125.19	0.18	28.00	Moderate

The degree of spatial dependence for regeneration was strong in Fragments 1, 3, 4, and 5, indicating that it is strongly influenced by adjacent areas within the practical range. This finding is an excellent indicator for the use of the kriging technique as a tool in the preparation of management plans for candeia. The variable number of non-candeia trees present in the native tree layer demonstrated spatial dependence at three levels, suggesting that a covariate that influences this process needs to be considered to generate better estimates. The fact that this variable shows three levels of spatial dependence and almost 100% of spatial dependence in Fragment 4 demonstrates that the variable presents good spatial structuring, despite being masked by other attributes in some fragments.

Using the selected semivariogram models, it was possible to produce kriging maps for the analyzed fragments, which resulted in the maps of the spatial dispersion of the variables (Figures 2, 3, 4, 5, and 6).

Fig. 2: Kriging maps of the tree layer of non-candeia native species (a) and the regeneration of candeia (b) in Fragment 1.

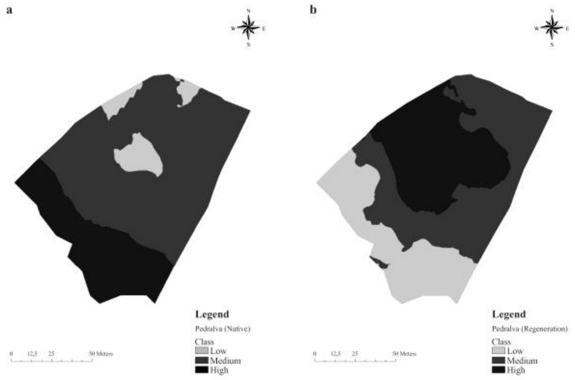

Fig. 3: Kriging maps of the tree layer of non-candeia native species (a) and the regeneration of candeia (b) in Fragment 2.

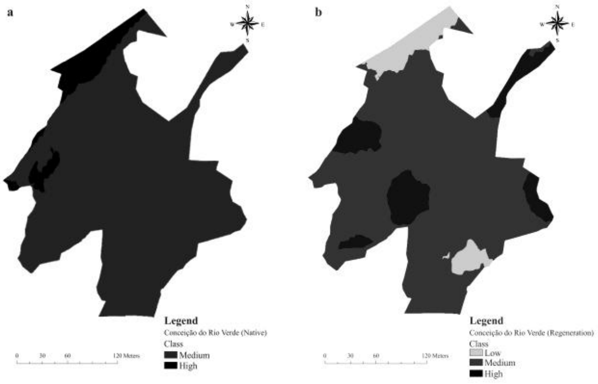

Fig. 4: Kriging maps of the tree layer of non-candeia native species (a) and the regeneration of candeia (b) in Fragment 3.

Discussion:

A negative correlation exists between the density of regeneration of woody species and the level of canopy cover. The kriging maps (Figures 2 to 6) show the existence of an inverse spatial relationship between the number of regenerated candeia trees and non-candeia trees present in the native tree layer. Thus, candeia regeneration did not occur or was less frequent in fragment regions with thicker native tree layers. This implies that the high regenerative potential attributed to candeia when managed might be impaired in some cases.

From an ecological point of view, this relationship suggests that the number of mature individuals present in the tree layer is a factor that directly influences the establishment of newly regenerated candeia trees, probably due to competition for resources such as light and nutrients. According to Souza *et al*. (2007), when the tree layer of candeia occurs in the presence of other native species, the canopy is eventually dominated by these other species, thus significantly decreasing the population size of candeia, leaving only a few trees. This same effect was observed in the regeneration of candeia, because these situations offer limited solar radiation, thus inhibiting its growth (Scolforo *et al*., 2012; Pedralli, 1997). Antos and Parish (2004) have previously claimed that solar radiation availability is one of the factors that favor the dynamics of natural regeneration, which plays an important role in the process of regenerating heliophilic species.

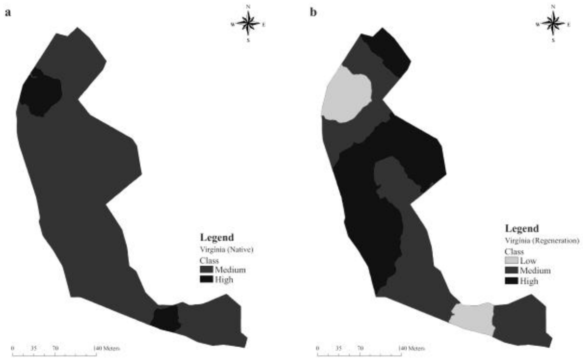

Fig. 5: Kriging maps of the tree layer of non-candeia native species (a) and the regeneration of candeia (b) in Fragment 4.

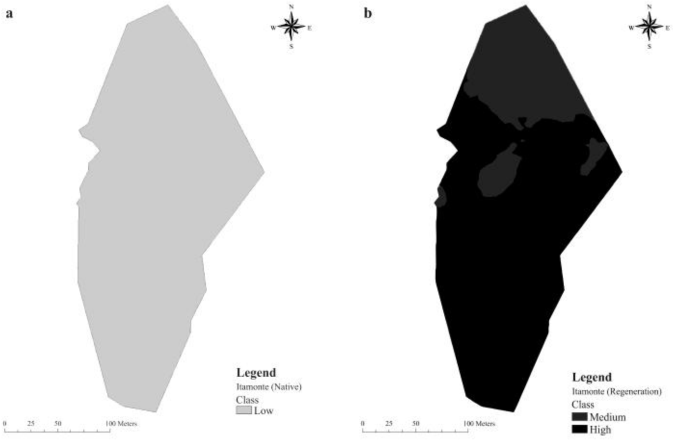

Fig. 6: Kriging maps of the tree layer of non-candeia native species (a) and the regeneration of candeia (b) in Fragment 5.

As emphasized by Scolforo *et al*. (2012), the sustainability of candeia management can only be guaranteed when more than 70% of an area consists of individuals of this species. These areas are predominated by candeia and generally occur in shallow soils, thus limiting the development of a highly diverse native forest (Oliveira-Filho, 1999).

Regions predominated by candeia generally present themselves in two ways. The first involves high altitude fields with a 100% predominance of candeia and thus free of competition with other tree species. The second involves transition areas between forests and fields, where the predominance rate tends to be lower but still greater than 70% (Perez *et al*., 2004). When candeia management is carried out without in areas that do not present a high dominance of the species (such as Fragments 2, 3 and 4), the establishment of its natural regeneration is impaired. In these cases, the natural regeneration of this species occurred with a peculiar spatial structure, as shown in Figures 3, 4, and 5, respectively. The intensity of candeia regeneration in those areas varied and showed different strata in regions of greater establishment and others of lesser establishment.

Spatial analysis of the regeneration can help understand the relationship between the natural regeneration of candeia and the native tree layer, allowing to determine possible heterogeneity in regeneration distribution. Aside from the absolute number of candeia regeneration per hectare, assuring an even distribution of these seedlings in the managed area is very important to guarantee a future crop. For instance, the Fragments with the lowest levels of candeia dominance (Fragments 2 and 4, 48.2 and 59.6 % of occurring individuals, Table 1) presented higher values of candeia regeneration per hectare (2158 and 1722 N/ha, respectively, Table 3) than the number of candeia individuals per hectare prior to management (1401 and 1418 N/ha, respectively, Table 1). However, the distribution of the regeneration was not evenly distributed in the areas.

During natural regeneration in managed areas, candeia trees tend occur in aggregates (Silva *et al*., 2008). In the case of these examined fragments, aggregates were concentrated exactly in the areas with a low number of non-candeia native species in the tree layer, thus forming small candeia groups over time.

Other factors related to the soil and climatic conditions of these fragments might also hinder the development and establishment of candeia regeneration and favor the establishment of other species. However, this study did not focus on these factors. Venturoli *et al*. (2011) pointed out that slope and soil cover were some of these factors and Dang *et al*. (2010) have identified slope as a fundamental component in the natural regeneration of tree species.

The ideal situation of candeia sustainable management was observed in Fragments 1 and 5, which represent the managed areas with a >70% predominance of candeia (i.e., the environment in these fragments favors candeia development and hinders the establishment of other species). Therefore, in these places, candeia is free from or experiences a lower degree of competition for resources, mainly solar radiation.

These two fragments have shown medium to high intensity levels of natural regeneration of candeia, which does not occur in the remaining fragments, and a higher degree of spatial homogeneity, as shown in Figures 2 and 6. This behavior allows candeia to spatially establish itself in the entire area without competing with other tree species. In addition, candeia is expected to grow again to a predominance rate of >70% over time, allowing future management of the area, guaranteeing income generation and social development for the farmers (Scolforo *et al*., 2012) under a sustainable approach.

These results suggest that the exploitation of candeia in areas where the species dominance of occurrence is below 64% does not guarantee its sustainable management, since its natural regeneration is compromised by competition for environmental resources.

Conclusion:

There is a strong spatial dependence among individual regenerated candeia trees after management in the fragments analyzed. The spatial dependence is varied among the non-candeia tree species.

The removal of candeia trees in regions where there are many non-candeia trees in the tree layer is not viable from a sustainable point of view. In these circumstances candeia natural regeneration is compromised due to competition for environmental resources, such as solar radiation.

The analysis of candeia natural regeneration and non-candeia tree layer spatial structure in managed areas can help guarantee sustainability of the practice (especially for areas with low candeia dominance), distinguishing between areas with a tendency to form the desirable pure candeia stands from areas with a tendency to form small aggregates of candeia inside the forest.

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