Original Research Article

Soil Fertility as a Predictor of the Geospatial Distribution of Forest Species in Natural Regeneration in Brazil

ABSTRACT

The relationship between soil attributes and the spatial distribution variability of the tree and shrub vegetation, specifically those in process of natural regeneration, can be an important tool for understanding the ecology of populations and communities while enabling the recommendation of species that can be used in restoration programs of degraded areas, especially in the Atlantic Forest of Brazil. Thus, this work aimed to study soil chemical attributes as indicators of spatial distribution of forest species in natural regeneration with higher absolute density in the Lowlands Dense Ombrophilous Forest fragment in Pernambuco, Brazil. For soil chemical characterization, samples were collected at depths of 0.0-0.10 and 0.10-0.20 m. The natural regeneration species sampling was performed in 40 subunits of 25 m², implemented in 40 sampling units of 250 m^2. The individuals with diameter at breast height (DBH) < 15 cm and height ≥ 1.0 m were measured. Thus, the ten natural regeneration species with the highest Absolute Density were defined. Geostatistical analysis was used to characterize the spatial variability of the forest species and soil attributes. *Tovomita mangle* may be indicated for soils with different chemical characteristics and natural fertility; *Brosimum rubescens* and *Inga capitata* for acidic soils with low natural fertility, but with moderate levels of exchangeable Al; *Talisia retusa* should be recommended for alic soils and *Caraipa densifolia* for non-alic soils; and *Anaxagorea dolichocarpa* and *Protium arachouchini* for highly fertile natural soils.

Keywords: Atlantic forest, soil chemical attributes, soil/forest relationship, soil fertility, spatial distribution of vegetation.

1. INTRODUCTION

The Atlantic Forest biome in Brazil is a continuous forest formation along the Brazilian coastal region, extending from the northeast to the south. But, in general, as the colonization and occupation of Brazilian territory occurred initially in coastal regions, the biome was devastated, reducing its area to disjoint fragments of forest, mainly located in inhospitable sites of top discontinuous topography, slopes and hills [1].

Atlantic Forest biome is reduced to approximately 12% of its original area in the state of Pernambuco, Brazil. It is represented by small forest fragments, isolated and surrounded by sugarcane monoculture, as is the case in the municipality of this study's region, which preserves only 10% (about 50.55 km^2) of its forest cover [2]. Some studies on these forest fragments have been carried out [3-6], adding important information about these remnants. Such information can contribute to the maintenance of the native flora populations of the biome, as well as subsidize recovery actions for degraded areas.

The soil is an important factor that interferes with the formation and understanding of the landscape. It has a fundamental role in the environment, providing mechanical support and nutrients for the vegetation's development. It also has direct or indirect relations with the different phytophysiognomies of a region, which allows natural occurrence of different forest formations, even in homogeneous regions in relation to other environmental factors [7, 8].

In order to evaluate the spatial variability of vegetation distribution as a function of soil attributes, geostatistical techniques can be used, which allows the interpretation of the data based on the natural variability structure of the evaluated attributes [9]. The use of geostatistical techniques in forest areas is very advantageous because it considers that the data obtained in the sample units are associated with their space location [10]. Therefore, it is possible to estimate variables in non-sampled areas using interpolators, when they present spatial dependence.

The application of geostatistics techniques allows modeling and describing the spatial variability of vegetation distribution and soil attributes, which helps the elaboration of maps with a desirable level of detail, for a better understanding of these relationships [11].

Several studies of spatial and temporal variation of soil properties have been conducted in Brazil [12], especially in planted forests, with the main objective of optimizing the management of production processes [11, 13, 14]. Some works were also developed in native forests [15-19]. However, studies on the relationship between soil attributes and variability of vegetation spatial distribution, especially in natural regeneration process, are scarce and can be important for understanding the ecology of populations and communities, subsidizing conservation strategies and/or sustainable management of tree species [20], mainly in the Atlantic Forest biome.

Thus, the objective of this work was to evaluate soil chemical attributes as indicators of geospatial distribution of forest species in natural regeneration with higher absolute density in a Lowlands Dense Ombrophilous Forest fragment in Pernambuco, Brazil. Thus, aiming to contribute to the recommendation of forest species in programs to recover degraded areas of the Brazilian Atlantic Forest, under different soil conditions.

2. MATERIAL AND METHODS

2.1 Study area

The study was carried out in a fragment of the Lowlands Dense Ombrophilous Forest [21], with approximately 79 ha in Sirinhaém, Pernambuco, Brazil. Located under the following geographical coordinates: UTM 25L 259089 and 9053293; 259604 and 9053741; 259727 and 9052723; 259920 and 9052956, with an average altitude of 63 m (Fig. 1). According to Köppen's classification, the region presents an AM monsoon climate [22], with an annual average temperature of 25.6ºC.

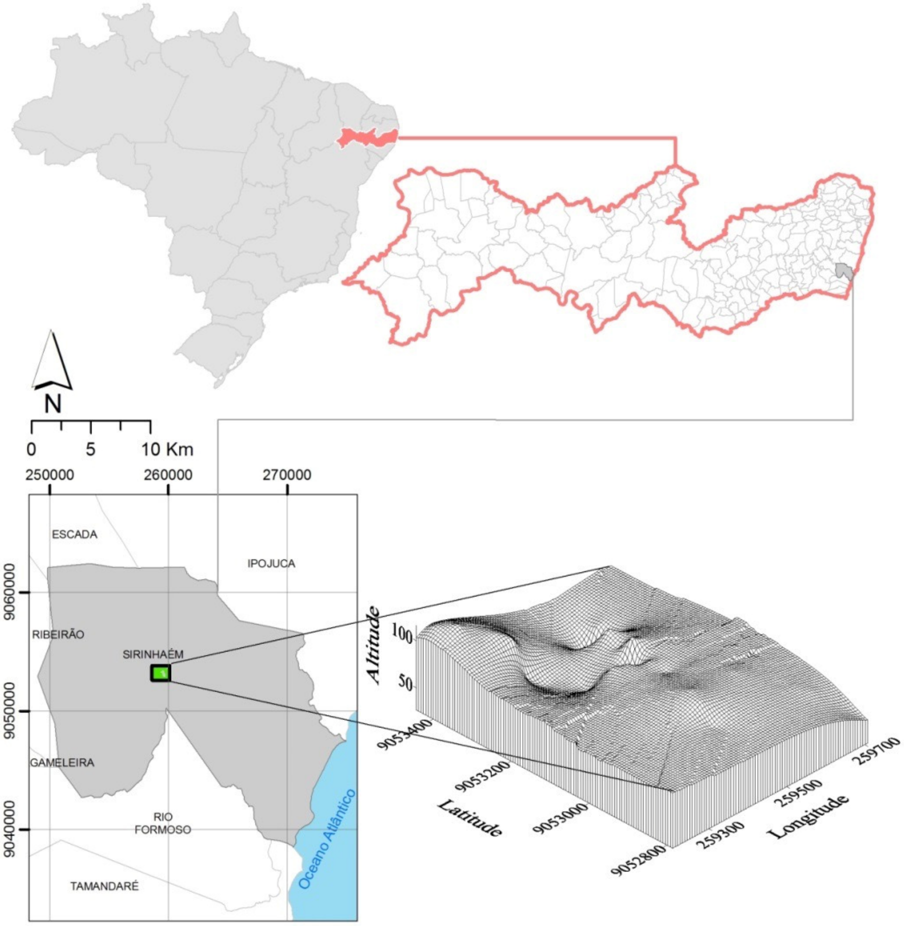


Fig. 1. Geographic location of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil.

The rainfall data of the Pernambuco State Agency for Water and Climate - APAC recorded an annual rainfall of about 1,800 mm [23]. Soils found in the region are of Yellow Latosol, Yellow Argisol, Red-Yellow Argisol, Gray Argisol, Gleissol, Cambisol and Flossic Neosols [24].

2.2 Soil chemical attributes

For soil chemical characterization of the forest fragment, four simple samples were collected and homogenized, giving rise to a composite sample. They were sampled in 40 plots (10 m x 25 m) that were distributed systematically in the fragment. Samples were collected at two depths (0.0-0.10 m and 0.10-0.20 m).

The Ca^{2+}, Mg^{2+} and Al^{3+} were extracted with 1.0 mol L^{-1} KCl and determined by titration. P, K^{+}, Fe, Cu, Zn and Mn were extracted with $Mehlich^{-1}$. P was determined by spectrophotometry, K^{+} by flame photometry and Fe, Cu, Zn and Mn by atomic absorption spectrophotometry. Potential acidity (H+Al) was extracted with 0.5 mol L^{-1} calcium acetate and determined by titration, and the total organic C (TOC) determination was performed by oxidation using the K dichromate method. With the results of these chemical analyzes, the sum of bases (SB), base saturation (V), saturation by Al (m), effective cation exchange capacity ($CEC_{effective}$), and potential cation exchange capacity ($CEC_{potential}$) were all calculated [25].

2.3 Natural regeneration

For the sampling of shrub-tree species of natural regeneration, 40 subunits of 25 m² (5 m x 5 m) were systematically allocated. These subunits were implemented on the right side of 40 sample units of 250 m^2 (10 m x 25 m), previously allocated in a permanent form to study the adult shrub-tree community floristic composition, equidistant by 25 m and interspersed to the right and left (Fig. 2).

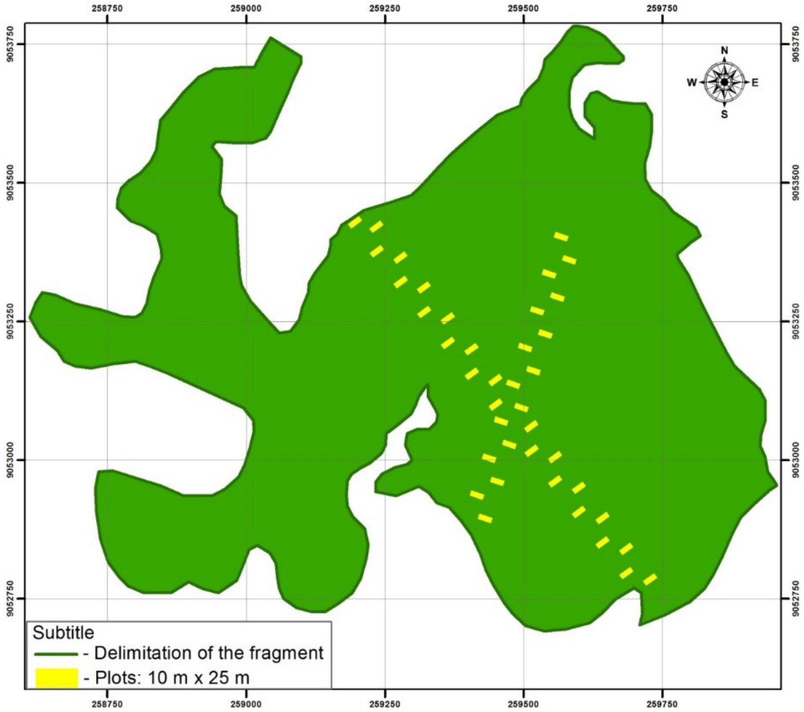


Fig. 2. Schematic diagram of the plots distribution in a fragment of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brasil.

Natural regeneration studies were established based on the level of inclusion [26], with adaptations [27]. The individuals with diameter at breast height (DBH) <15 cm and height ≥1 m were measured. The species' identification was done according to the APG (Angiosperm Phylogeny Group III) classification system [28]. With the data, the ten natural regeneration species with the highest Absolute Density (AD) were defined using the following expression [29]:

$$AD=\frac{n_i}{A}$$

AD is the absolute density (ind. ha^{-1}); n is the number of individuals of species i; and A is the sample area in hectares.

2.4 Geostatistical procedures

Initially, a principal component analysis (PCA) was performed between the ten natural regeneration species with highest AD and the soil chemical attributes in the 0.0-0.10 m depth layer. This was done in order to discard variables that presented the lowest factor loads. After this procedure, geostatistical analysis was used to characterize the spatial variability of the forest species and selected soil attributes.

The geostatistical procedures and correlations between soil attributes and the geospatial distribution of the forest species were performed in the 0.0-0.10 m depth layer, as the species were in process of natural regeneration with the majority of the root system concentrated in the superficial layer. Besides, nutrient concentrations were higher on the soil's surface.

The Kolmogorov-Smirnov test [30] was used to test the hypothesis of normality of the data, and geostatistical analysis was used to characterize the spatial variability [31]. Under the theory of intrinsic hypothesis, the experimental semivariogram was estimated by the equation [32]:

$$\hat{\gamma}(h)=\frac{1}{2\,N\,(h)}\sum_{i=1}^{N(h)}[Z(x_i)-Z(x_i+h)]^2$$

h is the value of the semivariance for a distance h; N (h) is the number of pairs involved in semivariance calculation; Z (x_i) is the value of Z attribute in position xi; Z (x_i+h) is the value of Z attribute separated by a distance h from the position x_i.

The matematical model with the calculated values of the semivariance was adjusted (spherical, exponential and gaussian) and coefficients for the semivariogram were defined (nugget effect, C_0; structural variance, C_1; sill, $C_0 + C_1$; and range, a). The nugget effect is the semivariance value for a distance greater than zero and smaller than the shortest sampling distance, which represents the random variation component; sill is the semivariance value at which the curve stabilizes over a constant value. When sill and nugget effect are found at similar levels, one has the pure nugget effect, or completely random behavior; and range is the distance from origin to where the sill reaches stable values, expressing the distance at which samples are not correlated [32].

The semivariograms exam [33] was used in order to determine the spatial dependence (SD). In case of doubt among more than one model for the same semivariogram, was chose the best coefficient of determination (R^2).

The degree of spatial dependence of the variables was classified [34]. The semivariograms that have a nugget effect of less than or equal to 25% of the sill are considered to have strong spatial dependence, moderate when it is between 25% and 75%, and weak when it is higher than 75%.

The kriging is the interpolated surface of each variable, which shows its spatial distribution. From kriging, it is possible to identify the location and extent of the extreme values, the area's homogeneity degree, and the higher gradient directions [35]. With the use of sampling optimization maps, information is obtained to better understand the spatial distribution pattern, and to define different distribution zones of forest species and soil chemical attributes. The maps of spatial distribution of the studied variables were presented with five regular intervals of specific values for each variable, allowing a better distribution understanding, especially those with small intervals between maximum and minimum values.

Pearson linear correlation coefficient [30] was used to evaluate the degree of correlation between soil chemical attributes and the spatial distribution of forest species. In addition were also used analyses of the kriging maps of species distribution and variability of the soil chemical attributes. Forest species or chemical attributes that showed pure nugget effect were disregarded.

3. RESULTS

3.1 Predominant species in natural regeneration of the forest fragment

The estimated absolute density of the natural regeneration of the Lowlands Dense Ombrophilous Forest studied fragment was of 9,680 ind. ha^{-1}. The ten species of highest AD represented 47.8% of the total sampled individuals in the area, with *Brosimum rubescens* having 1,500 ind. ha^{-1} (Table 1). *Thyrsodium spruceanum* (580 ind. ha^{-1}) was also one of the most abundant species in the study of natural regeneration, followed by *Tovomita mangle* (Table 1).

Table 1. Forest species of natural regeneration of higher Absolute Density (AD) and botanical families in fragments of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil

Forest species	**Family**	**AD (Ind. ha^{-1})**
Brosimum rubescens Taub.	Moraceae	1500
Thyrsodium spruceanum Benth.	Anacardiaceae	580
Tovomita mangle G. Mariz	Clusiaceae	560
Anaxagorea dolichocarpa Sprague & Sandwith	Annonaceae	340
Eschweilera ovata (Cambess.) Miers	Lecythidaceae	340
Protium arachouchini March.	Burseraceae	280
Caraipa densifolia Mart.	Annonaceae	280
Talisia retusa R.S. Cowan	Sapindaceae	260
Inga capitata Desv.	Fabaceae	250
Protium heptaphyllum (Aubl.) Marchand	Burseraceae	240
Total	-	4630

3.2 Soil chemical attributes of the forest fragment

The forest fragment's soil showed predominance of the sand fraction (Table 2), with small variations between the depths. However, they are medium textured soils, presenting a sandy clay loam class of textures in the depth of 0.0-0.10 m, and loam clay in the depth of 0.10-0.20 m (Table 2).

Table 2. Soil chemical attributes in depth of the fragment of Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil

Soil attribute	**Depth (m)**	
	0.0-0.10	**0.10-0.20**
pH (H_2O)	3.88	4.15
P (mg dm^{3})	1.33	1.20
Ca^{2+} (cmol$_c$ dm^{-3})	0.47	0.22
Mg^{2+} (cmol$_c$ dm^{-3})	0.64	0.52
K^{+} (cmol$_c$ dm^{-3})	0.07	0.05
Al^{3+} (cmol$_c$ dm^{-3})	1.41	1.22
(H+Al) (cmol$_c$ dm^{-3})^{1}	6.10	4.68
TOC(g kg^{-1})^{2}	25.2	18.0
SB^{3}	1.18	0.79
CEC$_{effective}$ (cmol$_c$ dm^{-3})^{4}	2.59	2.01

$CEC_{potential}$ ($cmol_c\ dm^{-3}$)[5]	7.28	5.47
m (%)[6]	54.44	60.70
V (%)[7]	16.21	14.44
Fe ($mg\ dm^{-3}$)	79.85	75.98
Cu ($mg\ dm^{-3}$)	0.61	0.43
Zn ($mg\ dm^{-3}$)	0.82	0.61
Mn ($mg\ dm^{-3}$)	0.52	0.45
Total Sand ($g\ kg^{-1}$)	481.60	432.90
Coarse Sand ($g\ kg^{-1}$)	384.80	335.90
Fine Sand ($g\ kg^{-1}$)	96.80	971.00
Silt ($g\ kg^{-1}$)	252.70	270.80
Clay ($g\ kg^{-1}$)	265.70	296.30
Textural class	Sandy clay loam	Loam clay

[1]Potential acidity; [2]Total organic carbon; [3]Sum of bases; [4]Effective cation exchange capacity; [5]Potential cation exchange capacity; [6]Saturation by aluminum; [7]Base saturation.

The soil of the fragment was classified of low natural fertility, due to its dystrophic character, considering base saturation (V) as a soil fertility indicator, which represents the sum of Ca^{2+}, Mg^{2+} and K^+ in relation to $CEC_{potential}$ (Table 2).

Low pH values prevailed at different depths of the soil of the fragment: 3.88 and 4.15 at depths of 0.0-0.10 and 0.10-0.20 m, respectively, as well as high (H+Al) concentration, characterizing high acidity (Table 2). It should be noted that the potential acidity (H+Al) was predominantly formed by H^+ ions, because the Al^{3+} concentrations represented only 23.1% of the potential acidity (Table 2). The highest levels of Ca^{2+}, Mg^{2+}, P, K^+, Al^{3+}, (H+Al), SB, $CEC_{effective}$, $CEC_{potential,}$ and V were concentrated in the first 0.10 m depth.

Saturation by aluminum was lower in the superficial layer (54.44%) due to higher concentration of bases in this layer (16.21%), and higher in subsurface layer (60.70%), where base concentration was lower (14.44%) (Table 2). Due to high Al exchangeable concentration, higher than 50%, the soil was classified as alic.

3.3 Geospatial variability of soil chemical attributes and forest species distribution

The geospatial variability of the soil chemical attributes and of forest species of higher AD in natural regeneration, except for *Protium heptaphyllum,* presented spatial dependence (Tables 3 and 4).

Table 3. Models and parameters of semivariograms of soil chemical attributes in fragments of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil

Attribute	Model	C_0[6]	$(C_0 + C_1)$[7]	a (m)[8]	CD (R^2)[9]	SD(%)[10]	CV[11]
SB ($cmol_c\ dm^{-3}$)[1]	Exponential	0.02	0.14	170.9	0.92	13.50	0.980
(H+Al) ($cmol_c\ dm^{-3}$)[2]	Exponential	0.05	1.52	77.4	0.93	3.39	1.121

Mg^{2+} (cmol$_c$ dm^{-3})	Spherical	3.8 x 10^{-3}	0.07	74.1	1	5.31	0.902
K^{+} (cmol$_c$ dm^{-3})	Gaussian	8.7 x 10^{-4}	632 x 10^{-5}	630.2	0.82	13.76	0.765
CEC$_{potential}$ (cmol$_c$ dm^{-3})[3]	Spherical	0.25	2.52	396	0.99	10.08	0.968
V (%)[4]	Spherical	0.90	48.72	60.2	0.96	1.84	1.092
m (%)[5]	Exponential	20.60	133.20	50.1	0.82	15.46	0.212

[1]Sum of bases; [2]Potential acidity; [3]Potential cation exchange capacity; [4]Base saturation; [5]Saturation by aluminum; [6]Nugget effect; [7]Sill; [8]Range; [9]Coefficient of determination; [10]Spatial dependence = (Nugget effect)/(Range) x 100. (SD≤25% is strong; SD>25<75% is moderate; and SD≥75% is weak); [11]Cross validation.

Table 4. Models and parameters of semivariograms of the forest species in natural regeneration with higher absolute density in a fragment of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil

Forest Species	Model	C_0[1]	(C_0 + C_1)[2]	a (m)[3]	CD (R^2)[4]	SD (%)[5]	CV[6]
B. rubescens	Spherica	204.5	6389	119.2	0.98	3.20	0.320
T. mangle	Spherica	83	742.6	130.8	1	11.17	0.240
A. dolichocarpa	Spherica	24.36 x 10^{6}	162.8	107.8	0.97	14.96	1.041
P. arachouchini	Spherica	6.44 x 10^{3}	79.58	129.2	0.97	8.11	1.344
C. densifolia	Spherica	129	715.4	81.4	0.99	18.03	0.293
T. retusa	Spherica	5.62 x 10^{3}	74.56	117	0.91	7.53	0.202
I.capitata	Spherica	56.1	112.3	122	0.98	49.95	0.719
P. heptaphyllum	Linear	-	-	-	-	EPP[7]	-

[1]Nugget effect; [2]Sill; [3]Range; [4]Coefficient of determination; [5]Spatial dependence = (Nugget effect)/(Range) x 100. (SD≤25% is strong; SD>25<75% is moderate; e SD≥75% is weak); [6]Cross validation; [7]Pure Nugget Effect.

The pure nugget effect occurred to *Protium heptaphyllum*, indicating absence of spatial dependence. Therefore, the shortest distance between sampling points (25 m) was not enough to detect the spatial variability among the samples (Table 4).

For the correlation between soil attributes and geospatial distribution of the species in the fragment, *Thyrsodium spruceanum* and *Eschweilera ovata* were also disregarded, as they presented the lowest factor loads in the principal components analysis.

The spherical and exponential models were the ones that best fit the semivariograms of soil chemical attributes, except for the K^{+} concentration that conformed to the gaussian model (Table 3). For the studied species, semivariograms conformed to the spherical model (Table 4).

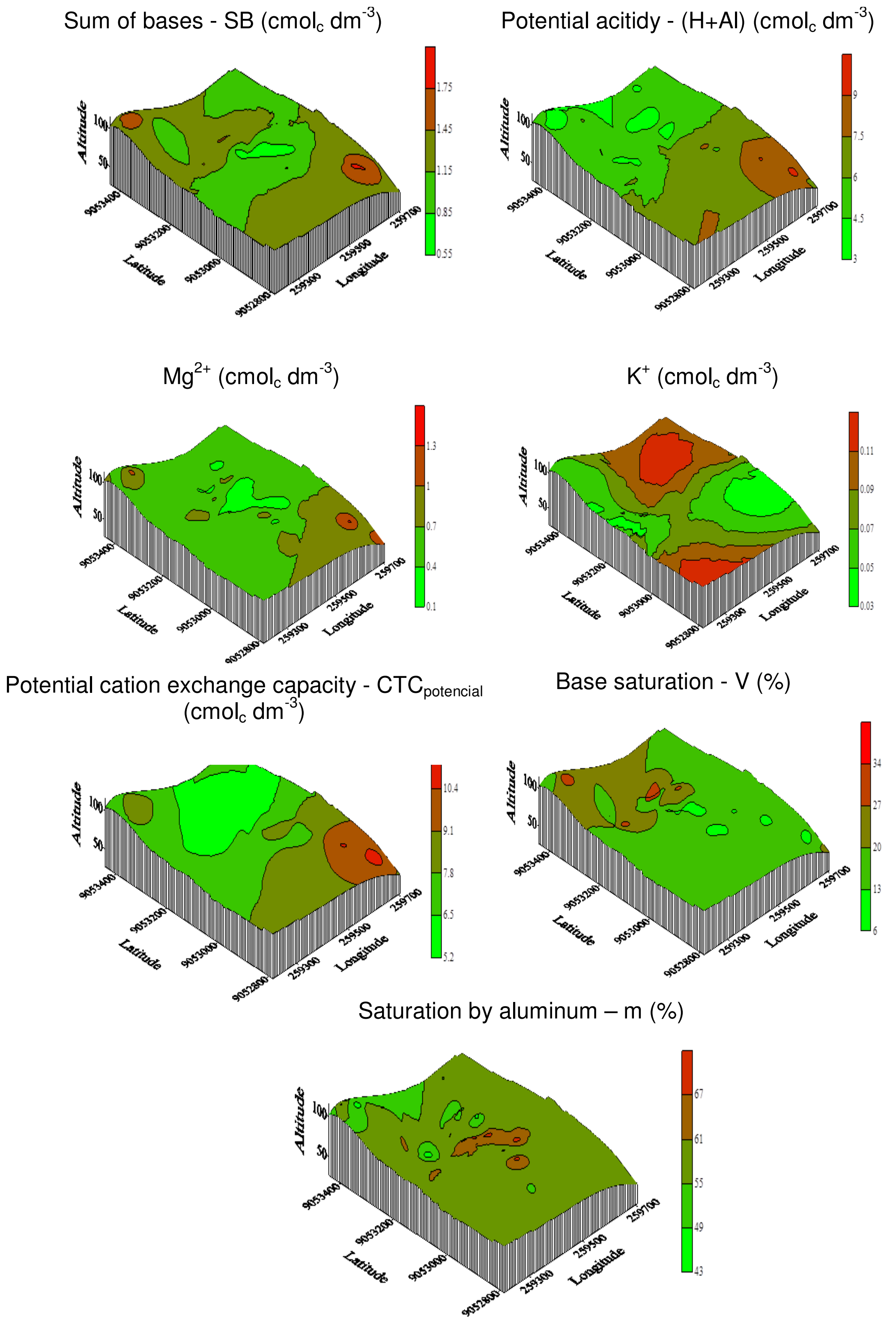
The analysis of the relationship of the spatial dependence degree showed that the species presented a strong spatial dependence, except for *Inga capitata*, which presented moderate dependence (Table 4).

All soil chemical attributes and forest species presented a coefficient of determination (R^2) higher than 0.80 (Tables 3 and 4), that is, at least 80% of the variability in the estimated semi variance values were explained by adjusted models.

Considering the range, the soil chemical attribute that presented the highest value was K^{+} concentration (630 m), with the lowest range observed for saturation by Al (50 m) (Table 3). For the species, the highest range value was obtained for *Tovomita mangle* (131 m) and the lowest for *Caraipa densifolia* (81 m) (Table 4).

3.4 Soil-vegetation relationship

In order to study correlations of soil chemical attributes of the forest fragment and the distribution of the natural regeneration species, kriging maps were elaborated with the adjusted semivariograms models parameters (Fig. 3 and 4), and a Pearson correlation was performed (Table 5). The spatial distribution of *Brosimum rubescens* occurred throughout the fragment area (Fig. 4). However, it concentrated the largest number of individuals, around 300 ind. ha^{-1}, in a small region where more elevated values of SB, (H+Al), CEC$_{potential,}$ and exchangeable Mg were found (Fig. 3 and 4).


Sum of bases - SB ($cmol_c\ dm^{-3}$)

Potential acitidy - (H+Al) ($cmol_c\ dm^{-3}$)

Mg^{2+} ($cmol_c\ dm^{-3}$)

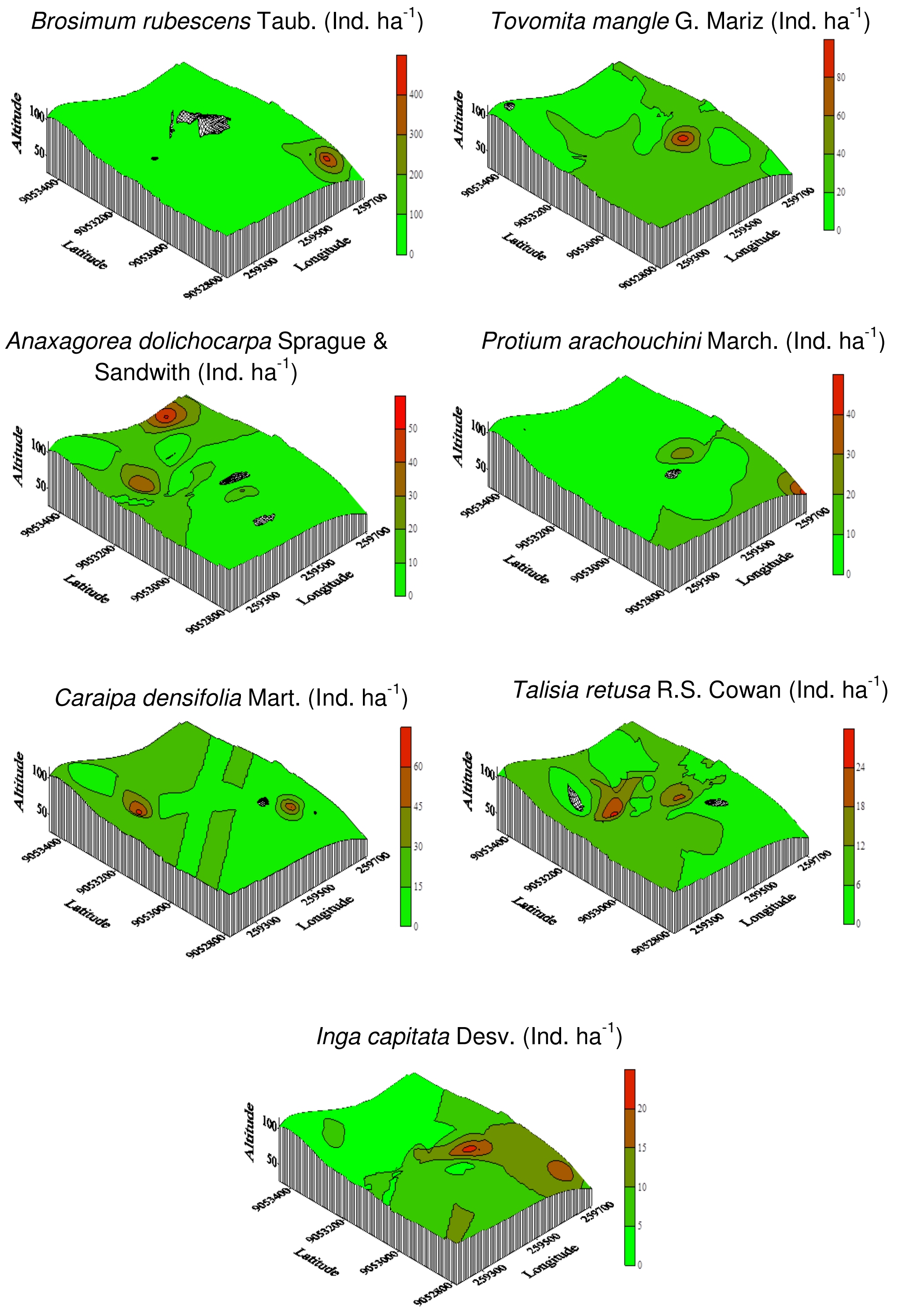
K^+ ($cmol_c\ dm^{-3}$)

Potential cation exchange capacity - $CTC_{potencial}$ ($cmol_c\ dm^{-3}$)

Base saturation - V (%)

Saturation by aluminum – m (%)

Fig. 3. Kriging maps of the spatial distribution of soil chemical attributes in a fragment of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brasil.


Brosimum rubescens Taub. (Ind. ha^{-1})

Tovomita mangle G. Mariz (Ind. ha^{-1})

Anaxagorea dolichocarpa Sprague & Sandwith (Ind. ha^{-1})

Protium arachouchini March. (Ind. ha^{-1})

Caraipa densifolia Mart. (Ind. ha^{-1})

Talisia retusa R.S. Cowan (Ind. ha^{-1})

Inga capitata Desv. (Ind. ha^{-1})

Fig. 4. Kriging maps of the spatial distribution of the forest species in natural regeneration with higher Absolute Density (AD) in a fragment of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brasil.

Table 5. Pearson correlation between soil chemical attributes and spatial distribution of the forest species in natural regeneration with higher Absolute Density (AD) in a fragment of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brasil

Forest species	Soil chemical attributes						
	SB[1]	(H+Al)[2]	Mg^{2+}[ ]	K^+	$CEC_{potential}$[3]	V (%)[4]	m (%)[5]
	$cmol_c\ dm^{-3}$					%	
Brosimum rubescens	Ns	0.389*	0.431*	ns	0.446*	ns	ns
Tovomita mangle	Ns	ns	ns	-0.403*	ns	ns	ns
Anaxagorea dolichocarpa	Ns	-0.315*	ns	ns	-0.340*	ns	ns
Protium arachouchini	Ns	ns	ns	ns	ns	ns	ns
Caraipa densifolia	Ns	ns	ns	ns	ns	ns	-0.338*
Talisia retusa	-0,390*	ns	-0.405*	ns	ns	ns	0.470*
Inga capitata	-0,436*	0.509*	ns	-0.451*	0.412*	-0.568*	ns

*[1]Sum of bases; [2]Potential acidity; [3]Potential cation exchange capacity; [4]Base saturation; [5]Saturation by aluminum. Sig: Significance (T test: NS, * Not significant or significant at P = 0.05, respectivily).*

The specie *Brosimum rubescens* populated areas with higher $CEC_{potential}$, probably of more clayey soils and/or with higher organic matter concentrations, but mostly composed of acid cations (H + Al) and with a preference for higher levels of Mg exchangeable in soil.

The specie *Tovomita mangle* presented a negative and significant correlation with the exchangeable K concentration of the soil of the fragment (Table 5), also verified by the spatial distribution of the species in the kriging maps (Fig. 3 and 4). This indicated that the higher the exchangeable K concentration of the soil (Fig. 3), the smaller the number of individuals of the species (Fig. 4). Additionally, a small relation of the occurrence of *Tovomita mangle*, between 60 and 80 ind. ha^{-1}, was observed in regions of the forest fragment that presented higher (H+Al) concentration (Fig. 3 and 4).

Unlike the two previous species, *Anaxagorea dolichocarpa* showed a correlation with the availability of exchangeable K of the soil in the kriging maps. A higher number of individuals per hectare was also reported in areas with higher exchangeable K concentrations (Fig. 3 and 4), but this behavior was not significant through Pearson's correlation (Table 5). However, it correlated with low values of $CEC_{potential}$ and low levels of (H+Al) (Table 5).

The correlations performed to evaluate the *Protium arachouchini* spatial distribution did not identify any soil chemical attributes that were related to the species (Table 5). However, the kriging maps allowed one to infer that the highest individuals per hectare concentration occurred in areas with higher Mg concentration and higher $CEC_{potential}$, and, in a less expressive way, it presented a correlation with (H+Al) similar to the behavior presented by *Brosimum rubescens* (Fig. 3 and 4).

Caraipa densifolia correlated significantly and negatively with saturation by Al (Table 5), also found in the kriging maps of the species' spatial distribution and chemical attributes in the fragment area (Fig. 3 and 4). The spatial distribution pattern of *Caraipa densifolia* was antagonistic to that presented by *Talisia retusa*, which correlated significantly and negatively with SB and exchangeable Mg and significantly and positively with saturation by Al (Table 5). Thus, the highest number of individuals per hectare of *Talisia retusa* was found in areas with higher percentages of saturation by Al. This behavior was also identified in the *Talisia retusa*'s kriging maps and the soil chemical attributes of the fragment.

For the spatial distribution of *Inga capitata* in the fragment area*,* its occurrence was verified where there were the lowest levels of exchangeable K, lower values of SB, and base saturation (Table 5 and Fig. 3 and 4). In the kriging maps it was also possible to observe that in the lower area, the eastern portion of the fragment, there is a greater concentration of individuals in the higher potential acidity region (H+Al) and higher $CEC_{potential}$, confirming the significant and positive correlation of the species with these attributes.

4. DISCUSSION

4.1 Predominant species in the natural regeneration of the forest fragment

Lopes [36] studying the dynamics of natural regeneration found *Brosimum rubescens* as one of the most abundant species in a fragment of Lowlands Dense Ombrophilous Forest, as this is study. *Thyrsodium spruceanum* was also one of the most abundant species found in the study of the natural regeneration of tree species conducted by Silva [37] in a fragment of Dense Ombrophilous Forest, Brazil.

According to Corrêa [38] *Tovomita mangle* is typically found in the more advanced successional stage of a forest. This species was abundant in the fragment. Therefore, its presence is an indicative that the successional process is evolving in the fragment area. *Eschweilera ovata*, *Anaxagorea dolichocarpa*, and *Protium heptaphyllum* were also highlighted with regards to the number of individuals in a study on natural regeneration developed by Lima [39].

Understanding the factors that interfere or contribute to the establishment of natural regeneration species is critical to ensuring the balance and sustainability of forest ecosystems.

4.2 Soil chemical attributes of the forest fragment

The pH influences vegetation development by interfering on the soil nutrient availability [39]. For Mafra [41] the acidification of the soil in forest areas can be related to the leaching of bases or absorption of these bases by the plants. Some studies also found soils in similar conditions in fragments of the Dense Ombrophilous Forest of Pernambuco, Brazil, with pH values between 4.04 and 4.75 [42, 43].

Espig [42] and Teixeira [43] also found similar results to the in-depth behavior of the concentrations of Ca^{2+}, Mg^{2+}, P, K^{+}, Al^{3+}, (H+Al), SB, $CEC_{effective}$, $CEC_{potential,}$ and V, as this study.

The concentrations of the bases Ca^{2+}, Mg^{2+}, and K^{+} were considered low. They were, however, in agreement with the results obtained by Teixeira et al. (2010), which found Ca^{2+} concentrations between 0.04 and 1.14 $cmol_c\ dm^{-3}$, Mg^{2+} between 0.12 and 0.96 $cmol_c\ dm^{-3}$, and K^{+} between 0.04 and 0.16 $cmol_c\ dm^{-3}$. Jandl [44] reported that low Ca^{2+} levels in forest soil suggest that the species access this nutrient from other sources that are not evidenced by chemical soil data. Thus, litter may be one of these sources, because Espig [45] found that Ca was the nutrient with the highest litter concentration (15.73 g kg^{-1}) and with the highest contribution (170.7 kg ha^{-1} $year^{-1}$), in a similar area. This result was confirmed by Godinho [46] in a submontane seazonal semideciduous forest, an ecosystem associated with Atlantic Forest biome, where Ca was also found with higher concentration and content in the litter.

Barreto [47] found that the concentration of the bases Ca, Mg, and K in forest areas was high in the superficial layer and decreased with the depth, favoring the concentration of potential acidity (H+Al).

Furtini Neto [7] affirmed that excess exchangeable Al in the soil can limit the development of species, inhibiting the growth and the acquisition and utilization of nutrients by plants. Beutler [48] studied the effect of exchangeable Al on the initial growth of two forest species, and identified that Al toxicity was characterized by the reduction in plant height and dry matter production, as well as the decrease of the concentration of N and P in the aerial part of the two species.

Despite the high soil acidity of the study fragment, the exchangeable Al concentrations did not impede the development of the forest species, because there was no delay in tree growth. This proves the tolerance and the adaptability of the forest species in acidic soil, or the chelating effect of the organic matter on the Al^{3+}. In fact, the total organic C concentration (TOC) of the soil of the fragment was high, mainly in subsurface, and could have exerted a chelating effect on the exchangeable Al (Table 2).

According to Jansen [49], Al seems to be a beneficial element for some individuals of native species and plants that are adapted to acid soils and high concentration of exchangeable Al do not show symptoms of toxicity. For Hartwig [50], the exudation of organic acids activated by the presence of Al at the root apex of tolerant species is the main mechanism of plants' tolerance to Al^{3+} of the soil. However, due to the differences between the species, other mechanisms should be investigated.

The highest P concentration was observed in the superficial layer, probably due to the decomposition of leaves and branches [51], decreased with depth. Similar behavior was observed in forest fragments studied by Espig [42] and Teixeira [43] in Pernambuco, Brazil.

4.3 Geospatial variability of soil chemical attributes and forest species distribution

Kerry [52] affirmed that the type of result occurring in *Protium heptaphyllum* may also be associated with the small size of the data set, not necessarily meaning that they are spatially independent. Additionally, important spatial variation characteristics may be lost because of the large-scale sampling spacing.

The occurrence of spatial dependence of forest species may represent a positive indicator of fragment conditions because, according to Amaral [19], disturbances in forests can disrupt the spatial dependence of this and other variables, since it allows the emergence of independent regions, eliminating the spatial influence of the variables.

The spherical model adjusted for the studied species corroborates with the results of many studies that found the spherical and exponential mathematical models as the most adapted to describe the semivariograms behavior of attributes of plants and soils [11, 16, 17, 53, 54, 55].

The greater attribute dependence degree, better the estimation of the kriging technique for non-sampled sites [16]. High range values demonstrated the effectiveness of sampling to portray the spatial variation of soil chemical attributes and forest species (Tables 3 and 4). Artur [55] affirmed that the knowledge of the spatial dependence range allows one to define the sampling radius, guaranteeing the sampling points independence, the minimization of the standard error of the mean, and also the number of samples to be collected, serving for further surveys in areas with similar characteristics.

4.4 Soil-vegetation relationship

The pattern of the spatial distribution of trees in a forest has influences from biotic and abiotic processes, and these factors may fit into an intrinsic form to the species (reproductive, social) or extrinsic (wind, luminosity and edaphic conditions) [56].

The wide spatial distribution of *Brosimum rubescens* may have occurred because of the dispersion of their seeds carried by animals, especially mammals. The fruits of this species are fleshy and attractive, having seeds with high self-regeneration capacity and with formation of abundant seedlings bank [57]. Santo [58] found *Brosimum rubescens* occurred preferentially in areas with low exchangeable K and Mg concentrations in a study carried out in the Amazon region. These attributes, except SB, also correlated significantly and positively with *Brosimum rubescens* (Table 5).

In programs for recovery of degraded areas, *Brosimum rubescens* can be used in soils with different chemical characteristics by their dispersion capacity, but it can be preferably used in high potential acidity soils, as long as it presents adequate levels of exchangeable Mg.

Tovomita mangle did not present a specific relation with any chemical attribute, and it can be used in any environment, provided that it presents low levels of exchangeable K. Unlike *Brosimum rubescens* and *Tovomita mangle*, *Anaxagorea dolichocarpa* was more demanding and can not be indicated for recovery of degraded areas in soils of low natural fertility, especially when the exchangeable K concentrations are restrictive.

The spatial distribution of *Protium arachouchini*, resembling the behavior presented by *Brosimum rubescens*, corroborate with Santo [58], who found that *Protium arachouchini* occurr only in typologies with better natural soil fertility, especially with higher organic matter and exchangeable Mg and low Al exchangeable concentrations. At first, as there was no identification of significant correlations between soil attributes and the spatial distribution of *Protium arachouchini*, it could be said that it would be a species to be used in any soil chemical condition. However, kriging maps restricted the species distribution to specific areas, with indicators of higher natural fertility (Fig. 3 and 4), which suggests that caution is required in recommending this species to generic areas, restricting its use for more fertile soils or at least with moderate chemical restriction.

The lowest densities of *Caraipa densifolia* were observed in areas with higher saturation of Al. This restricts the recommendation of this species to non-alic environments, and it should be used only in areas with high natural fertility. The pattern of spatial distribution of *Caraipa densifolia* was antagonistic to that presented by *Talisia retusa*. Therefore, in alic environments, where *Caraipa densifolia* cannot be recommended, *Talisia retusa* can be alternatively recommended for its tolerance to high levels of Al^{3+}.

In this study, *Inga capitata* showed a significant and positive correlation with potential acidity (H+Al) and $CEC_{potential}$. Thus, it is a species that can be recommended for restrictive environments with low natural fertility.

5. CONCLUSION

In conclusion, the results of this study show that the soils of the studied area presented high acidity, high saturation by aluminum, and low base saturation, indicating low natural fertility. For the study conditions, there was a correlation between the spatial distribution of the species with the highest absolute density of natural regeneration and soil chemical attributes, suggesting that the soil contributes effectively to the density of the species. Some recommendations for species selection may be useful in programs for recovery of degraded areas in forest environments where soil chemical attributes are known. For example: *Tovomita mangle* may be indicated for soils with different chemical characteristics and diverse natural fertility; *Brosimum rubescens* and *Inga capitata* for acid soils with low natural fertility, but with moderate Al exchangeable concentrations; *Talisia retusa* should be recommended for alic soils while *Caraipa densifolia* for non-alic soils; and *Anaxagorea dolichocarpa* and *Protium arachouchini* for soils of high natural fertility.

The knowledge of the spatial distribution of native species and soil attributes, through methods that consider the spatial dependence between samples, can contribute with accuracy in the interpretation of data behavior in forest fragments. It aims to define strategies for the recovery of areas with similar characteristics, as well as to predict the variations in the study’s environment in order to subsidize management techniques for their conservation.

REFERENCES

1. Varjabedian, R. Atlantic Rainforest law: Environmental Regression. Estud. Av. 2010;24:147-160. http://dx.doi.org/10.1590/S0103-40142010000100013. Portuguese.
2. Mantovani MC, Scachetti AL, Garrido O, Mikami L, Spina L, Herrera A. et al. Atlantic rainforest remnants atlas. 2009. Accessed 13 July 2016. Available: https://www.sosma.org.br/projeto/atlas-da-mata-atlantica/dados-mais-recentes.html Portuguese.

3. Silva RKS, Feliciano ALP, Marangon LC, Lima RBA. Floristic and ecological succession of the arboreal vegetation in the spring area of an Atlantic forest fragment, Pernambuco, Brazil. Rev. Bras. Ciênc. Agrár. 2010;5:550-559. http://dx.doi.org/10.5039/agraria.v5i4a829. Portuguese.
4. Silva RKS, Feliciano ALP, Marangon LC, Lima RBA, Santos WB. Structure and dispersal syndromes of tree species in a stretch of riparian vegetation, Sirinhaém, Pernambuco State, Brazil. Pesq. Flor. Bra. 2012;32:1-11. http://dx.doi.org/10.4336/2012.pfb.32.69.01. Portuguese.
5. Pessoa MML. Ecological succession in fragments of atlantic rainforest and in *Corymbia citriodora* (Hook.) K.D. Hill & L.A.S. Johnson, in Sirinhaém, Pernambuco [Dissertation]. Recife: Federal Rural University of Pernambuco, Brazil; 2012. Portuguese.
6. Brandão CFLS. Structure of tree component and natural regeneration in Atlantic Rainforest fragments of different sizes in Sirinhaém, Pernambuco [Thesis]. Recife: Federal Rural University of Pernambuco, Brazil; 2013. Potuguese.
7. Furtini Neto AE, Resende AV, Vale FR, Faquin V, Fernandes LA. Soil acidity, growth and mineral nutrition of some tree species at seedling phase. Cerne. 1999;5:1-12. Portuguese.
8. Silva RBM, Francelino MR, Moura RA, Moura TA, Pereira MG, Oliveira CP. Soil-vegetation relation in cerrado enviroment under influence of the group Urucuia. Ci. Fl. 2015;25:363-373. http://dx.doi.org/10.5902/1980509818455. Portuguese.
9. Silva Neto SP, Santos AC, Leite RLL, Dim VP, Neves Neto DN, Silva JEC. Spatial variation of the content of soil organic matter and production of pasture grass marandu. Biosc. J. 2012;28:41-53. Portuguese.
10. Kanege Junior H, Mello JM, Scolforo JRS, Oliveira AD. Evaluation of spatial continuity of dendrometric characteristics of clonal stands of *Eucalyptus* sp. at different ages. Rev. Árvore. 2007;31:859-866. http://dx.doi.org/10.1590/S0100-67622007000500010. Portuguese.
11. Rosa Filho G, Carvalho MP, Montanari R, Silva JM, Siqueira GM, Zambiano EC. Spatial variability of dendrometric properties of eucalyptus and physical attributes of a *Rhodic Eutrudox*. Bragantia. 2011;70:439-446. http://dx.doi.org/10.1590/S0006-87052011000200027. Portuguese.
12. Bognola IA, Ribeiro Junior PJ, Silva EAA, Lingnau C, Higa AR. Univariate and bivariate modeling of the spatial variability of yield of *Pinus taeda* L. Ci. Fl. 2008;38:373-385. Portuguese.
13. Assis AL, Mello JM, Guedes ICL, Scolforo JRS, Oliveira AD. Development of a sampling strategy for young stands of *Eucalyptus* sp. using geostatistics. Cerne. 2009;15:166-173. Portuguese.
14. Guedes ICL, Mello JM, Mello CR, Oliveira AD, Silva ST, Scolforo JRS. Geostatistical techniques and spatial interpolators in the stratification of *Eucalyptus* sp. Stands. Ci. Fl. 2012;22:541-550. http://dx.doi.org/10.5902/198050986621. Portuguese.
15. Wojciechowski JC, Schumacher MV, Kilca RV, Brun EJ, Pires CAF, Silva CRS. Et al. Geostatistics applied to the study of soil physiochemical characteristics in seasonal deciduous forest areas. Ci. Fl. 2009;19:383-391. http://dx.doi.org/10.5902/19805098894. Portuguese.
16. Lima JSS, Souza GS, Silva SA. Sampling and spatial variability of chemical attributes of a soil under regenerating natural vegetation. Rev. Árvore. 2010;34:127-136. http://dx.doi.org/10.1590/S0100-67622010000100014. Portuguese.
17. Neves DA, Lemos F, Gonzalez AP, Vieira SR, Siqueira GM. Using geoestatistics for assessing biodiversity of forest reserve areas. Bragantia 2010;69:131-140. Portuguese.
18. Skorupa ALA, Guilherme LRG, Curi N, Silva CPC, Scolforo JRS, Sá JJG. et al. Soil properties under native vegetation in Minas Gerais, Brazil: distribution by phytophysiognomy, hydrography and spatial variability. R. Bras. Ci. Solo 2012;36:11-22. http://dx.doi.org/10.1590/S0100-06832012000100002. Portuguese.
19. Amaral LP, Ferreira RA, Watzlawick LF, Longhi SJ, Sebem E. Influence of forest disturbance in the spatial distribution of the number of individuals of three species of Araucaria Forest assessed by geostatistical. Rev. Árvore 2013;37:491-501. http://dx.doi.org/10.1590/S0100-67622013000300012. Portuguese.
20. Higuchi P, Silva AC, Van Den Berg E, Pifano DS. Spatial association among individuals of different species of *Miconia* Ruiz & Pav spp. (Melastomataceae). Rev. Árvore 2011;35:381-389. http://dx.doi.org/10.1590/S0100-67622011000300002. Portuguese.
21. Martins L, Cavararo R. Technical Manual of the Brazilian vegetation. Phytogeographic system. Inventory of forest and rural formations. Techniques and management of botanical collections.

Procedures for mappings. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística; 2012. Portuguese.

22. Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. Köppen's climate classification map for Brazil. Meteorol. Z. 2013;22:711-728. http://dx.doi.org/10.1127/0941-2948/2013/0507.
23. Oliveira PRS, Guedes RVS, Silva CAWS, Santos EP, Oliveira FP, Silva-Júnior HD. et al. Climate Bulletin: Climate Synthesis. Recife: Agência Pernambucana de Águas e Clima; 2016. Portuguese.
24. Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR. et al. Brazilian System of Soil Classification. Brasília: Embrapa; 2013. Portuguese.
25. Donagema GK, Campos DVB, Calderano SB, Teixeira WG, Viana JHM. Manual of Soil Analysis Methods. Rio de Janeiro: Embrapa Solos; 2011. Portuguese.
26. Finol UH. Nuevos parâmetros a considerarse en el analisis estrutural de las selvas virgenes tropicales. Rev. For. Ve. 1971;14:29-42. Spanish.
27. Marangon LC. Floristic and phytosociology of area of semideciduous seasonal forest aiming to study dinamic of tree species in Viçosa, MG. [Thesis]. Federal University of São Carlos, Brazil; 1999. Portuguese.
28. APG. An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG III. Bot. J. Linn. Soc. 2009;16:105-121.
29. Mueller-Dombois D, Ellemberg H. Aims and methods for vegetation ecology. New York: John Wiley & Sons; 1974.
30. Fisher RA. Statistical methods, experimental design and scientific inference. New York: Oxford University Press; 1990.
31. Vieira SR, Hatfield JL, Nielsen DR, Biggar JW. Geostatitical theory and application to variability of some agronomical properties. Hilgardia. 1983;51:1-75. http://dx.doi.org/10.3733/hilg.v51n03p075
32. Trangmar BB, Yost RS, Ueharaa G. Application of geoestatistics to spatial studies of soil properties. Adv. Agron. 1985;38:45-94. https://doi.org/10.1016/S0065-2113(08)60673-2
33. Robertson GP. GS+ geostatistics for the environmental sciences: GS+ user's guide. Michigan: Gamma Design Software; 1998.
34. Cambardella CA, Moorman TB, Novak JM, Parkin TB, Karlen DL, Turco RF. et al. Field-scale variability of soil properties in Central Iowa Soils. Soil Sci. Soc. Am. J. 1994;58:1501-1511.
35.Guimarães WD, Gripp Junior J, Marques EAG, Santos NT, Fernandes RBA. Spatial variability of the physical attributes of soil under pasture. Rev. Ciên. Agron. 2016;47:247-255. http://dx.doi.org/10.5935/1806-6690.20160029. Portuguese.
36. Lopes IS, Feliciano ALP, Marangon LC, Alencar AL. Dynamics of natural regeneration in the understory of *Pinus caribaea* Morelet. var. caribaea in Biological Reserve Saltinho, Tamandaré - PE. Ci. Fl. 2016;26:95-107. http://dx.doi.org/10.5902/1980509821094. Portuguese.
37. Silva WC, Marangon LC, Ferreira RLC, Feliciano ALP, Costa Junior RF. Natural regeneration's study of arboreal species in humid forest fragment in city of Catende, south zone of Pernambuco. Ci. Fl. 2007;17:321-331. http://dx.doi.org/10.5902/198050981964. Portuguese.
38. Corrêa, MM. Cutting ants (Hymenoptera, Formicidae) as agents modifying the light availability and structure of the plant community in northeastern Atlantic forest [Thesis]. Federal University of Pernambuco, Brazil; 2006. Portuguese.
39. Lima AS, Feliciano ALP, Marangon LC, Oliveira LSB, Pessoa MML. Natural regeneration of one Dense Rainforest fragment the Watershed of River Capibaribe, PE-Brazil. Rev. Bras. Ci. Agr. 2013;8:273-278. http://dx.doi.org/10.5039/agraria.v8i2a2369. Portuguese.
40. Alt F, Oelmann Y, Herold N, Schrumpt M, Wilcke W. Phosphorus partitioning in grassland and forest soils of Germany as related to land-use type, management intensity, and land use–related pH. J. Plant Nutr. Soil Sci. 2011;174:195-209. http://dx.doi.org/10.1002/jpln.201000142
41. Mafra AL, Guedes SFF, Klauberg Filho O, Santos JCP, Almeida JA, Rosa JD. Organic carbon and soil chemical attributes in forest areas. Rev. Árvore. 2008;32:217-224. http://dx.doi.org/10.1590/S0100-67622008000200004. Portuguese.
42. Espig AS, Freire FJ, Marangon LC, Ferreira RLC, Freire MBGS, Espig DB. Nutrient distribution between the forest vegetation and the soil on remnants of Atlantic Forest. . Rev. Bras. Ci. Agr. 2008;3:132-137. http://dx.doi.org/10.5039/agraria.v3i2a342. Portuguese.

43. Teixeira LJ, Feliciano ALP, Galindo ICL, Martins CM, Alencar AL. Relationships between tree floristic and soil characteristics in an Atlantic Forest patch, Tamandaré, Pernambuco, Brazil. Rev. Floresta 2010;40:625-634. http://dx.doi.org/10.5380/rf.v40i3.18924. Portuguese.

44. Jandl R, Alewell C, Prietzel J. Calcium loss in Central European forest soils. Soil Sci. Soc. Am. J. 2004;68:588-595.

45. Espig AS, Freire FJ, Marangon LC, Ferreira RLC, Freire MBGS, Espig DB. Litter seasonality, composition and nutrient input in remnant of Atlantic forest in the state of Pernambuco, Brazil. Rev. Árvore 2009;33:949-956 http://dx.doi.org/10.1590/S0100-67622009000500017. Portuguese.

46. Godinho TO, Caldeira MVW, Rocha JHT, Caliman JP; Trazzi PA. Quantification of biomass and nutrients in the accumulated litter in a section of Submontane Seasonal Semideciduous Forest, ES. Cerne 2014;20:11-20. http://dx.doi.org/10.1590/S0104-77602014000100002. Portuguese.

47. Barreto AC, Lima FHS, Freire MBGS, Quintino RA, Freire FJ. Chemical and physical characteristics in soil under forest, agroforest system and pasture. Rev. Caatinga 2006;19:415-425. Portuguese.

48. Beutler AN, Fernandes LA, Faquin V. Aluminum effect on the growth of two forest species. R. Bras. Ci. Solo. 2001;25:923-928. http://dx.doi.org/10.1590/S0100-06832001000400015. Portuguese.

49. Jansen S, Watanabe T, Smets E. Aluminium accumulation in leaves of 127 species in Melastomataceae, with comments on the Order Myrtales. Ann. Bot. 2002;90:53-64. http://dx.doi.org/10.1093/aob/mcf142.

50. Hartwig I, Oliveira AC, Carvalho FIF, Bertan I, Silva JIG, Schmidt D. et al. Associated mechanisms of aluminum tolerance in plants. Semin: Cien. Agrar. 2007;28:219-228. Portuguese.

51. Oliveira PC, Carvalho CJR, Sá TA. Trees of ecological services in the Brazilian Amazon. Univ. Sci. 2010;15:265-277. http://dx.doi.org/10.11144/javeriana.SC15-3.toes. Portuguese.

52. Kerry R, Oliver MA. Determining nugget: sill ratios of standardized variograms from aerial photographs to krige sparse soil data. Precis. Agric. 2008;9:33-56. http://dx.doi.org/10.1007/s11119-008-9058-0

53. Corá JE, Araujo AV, Pereira GT, Beraldo JMG. Assessment of spatial variability of soil attributes as a basis for the adoption of precision agriculture in sugarcane plantations. R. Bras. Ci. Solo. 2004; 28:1013-1021. http://dx.doi.org/10.1590/S0100-06832004000600010. Portuguese.

54. Chiba MK, Guedes Filho O, Vieira SR. Spatial and temporal variability of weed population in an Oxisol under no-till system. Acta Sci. Agron. 2010;32:735-742. http://dx.doi.org/10.4025/actasciagron.v32i4.5445. Portuguese.

55. Artur AG, Oliveira DP, Costa MC, Romero RE, Silva MVC, Ferreira TO. Spatial variability of soil chemical attributes associated with microrelief. Rev. Bras. Eng. Agríc. Ambient. 2014;18:141-149. http://dx.doi.org/10.1590/S1415-43662014000200003. Portuguese.

56. Silva KE, Martins SV, Santos NT, Ribeiro CAAS. Spatial patterns of tropical tree species. In: Martins, SV, editor. Ecology of tropical forests in Brazil. Viçosa: Federal University of Viçosa; 2009. Portuguese.

57. Marimon BS, Felfili JM. Seed rain in a monodominant Brosimum rubescens Taub. forest and an adjacent mixed forest in the Araguaia River Valley, Mato Grosso State, Brazil. Acta Bot. Brasilica. 2006;20:423-432. http://dx.doi.org/10.1590/S0102-33062006000200017. Portuguese.

58. Santo NMC. Phytopathology of forest disjunctions (forest islands) in a savannah area of Boa Vista, Roraima [Dissertation]. Boa Vista: Federal University of Roraima, Brazil; 2010. Portuguese.