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 spatial distribution variability of 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, as in this area from 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 0.11-0.20 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 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 high natural fertility soils.

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

1. INTRODUCTION

Atlantic Forest biome in Brazil is a continuous forest formation along the Brazilian coast 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].

So Atlantic Forest biome was 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 original 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.

In this context, 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 development of vegetation. 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] in the Atlantic Forest biome.

Thus, the objective of this research 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 from 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 25.6 ºC.

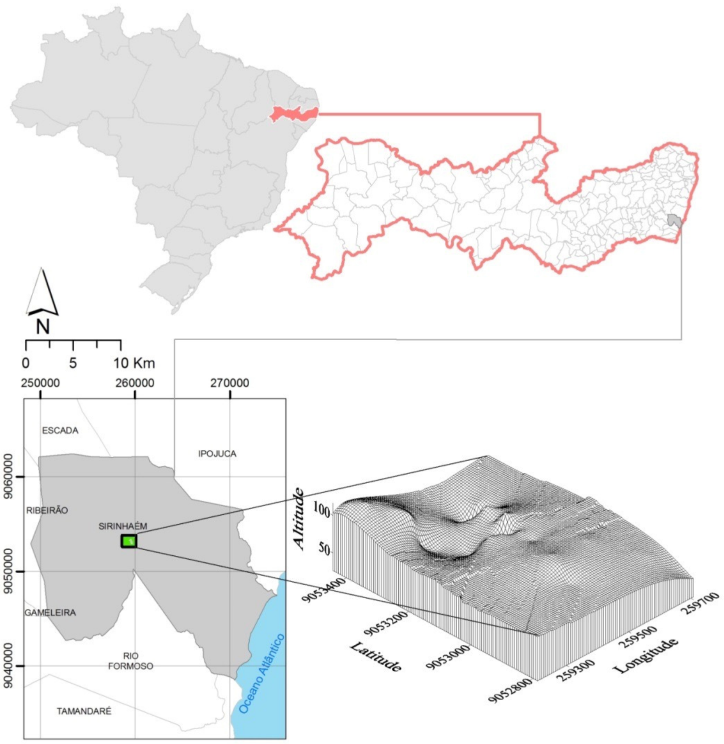

Fig. 1. Geographic location of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil.

The rainfall data of Pernambuco State Agency for Water and Climate - APAC recorded an annual rainfall of about 1,800 mm [23]. Soils found in the region are Yellow Oxisol, Yellow Ultisol, Red-Yellow Ultisol, Gray Ultisol, Entisol, Inceptisol and Fluvent [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 0.11-0.20 m). Soil sampling was concentrated where sampling of the natural regeneration of the species was carried out.

The Ca^{2+}, Mg^{2+} and Al^{3+} were extracted by 1.0 mol L^{-1} KCl solution and determined by titration. P, K^{+}, Fe, Cu, Zn and Mn were extracted by Mehlich-1 solution. 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 by 0.5 mol L^{-1} calcium acetate solution 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 floristic composition of shrub-tree community, equidistant by 25 m and interspersed to the right and left (Fig. 2).

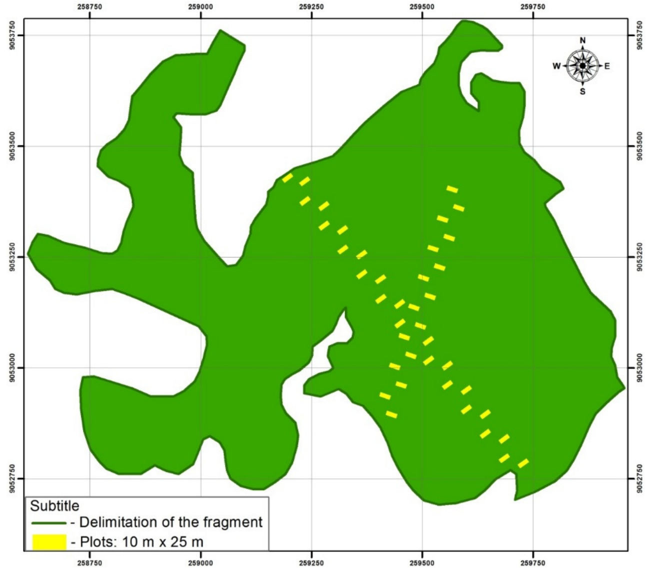

Fig. 2. Schematic diagram of the plots distribution in a fragment of the Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil.

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 identification of species was done according to the APG (Angiosperm Phylogeny Group III) classification system [28]. With the data, ten natural regeneration species with the highest Absolute Density (AD) were defined using the following expression [29]:

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

Comment [AL1]: the variables are better use as italic

AD is the absolute density (ind. ha^{-1}); n is the number of individuals of i species; 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 forest species and selected soil attributes.

Geostatistical procedures and correlations between soil attributes and 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 are higher on the soil surface.

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]:

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

$\hat{Y}(h)$ is semivariance value 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.

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Mathematical 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].

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]. Semivariograms that had a nugget effect of less than or equal to 25% of the sill were considered to have strong spatial dependence, moderate when they were between 25% and 75%, and weak when they were 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, homogeneity degree of the area, and the highest gradient directions [35]. Using 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 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 spatial distribution of forest species. In addition were also used analyses of the kriging maps of species distribution and variability of soil chemical attributes. Forest species or chemical attributes that showed pure nugget effect were disregarded.

Comment [AL3]: add name of softwares which you use for analysis

3. RESULTS

3.1 Predominant species in natural regeneration of the forest fragment

Estimated absolute density of the natural regeneration of 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 a fragment of Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil

Forest speciess	Family	AD (Ind. ha^{-1})
Brosimum rubescens Taub.	Moraceae	1,500 ± 82.17
Thyrsodium spruceanum Benth.	Anacardiaceae	580 ± 36.37
Tovomita mangle G. Mariz	Clusiaceae	560 ± 21.45
Anaxagorea dolichocarpa Sprague & Sandwith	Annonaceae	340 ± 14.24
Eschweilera ovata (Cambess.) Miers	Lecythidaceae	340 ± 12.91
Protium arachouchini March.	Burseraceae	280 ± 11.36
Caraipa densifolia Mart.	Calophyllaceae	280 ± 18.14
Talisia retusa R.S. Cowan	Sapindaceae	260 ± 10.75
Inga capitata Desv.	Fabaceae	250 ± 10.29
Protium heptaphyllum (Aubl.) Marchand	Burseraceae	240 ± 10.07

Comment [AL4]: SD?

3.2 Soil chemical attributes of the forest fragment

The forest fragment 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 0.11-0.20 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	**0.11-0.20**
pH (H_2O)	3.88 ± 0.23	4.15 ± 0.23
P (mg dm^{-3})	1.33 ± 0.52	1.20 ± 0.40
Ca^{2+} (cmol$_c$ dm^{-3})	0.47 ± 0.21	0.22 ± 0.13
Mg^{2+} (cmol$_c$ dm^{-3})	0.64 ± 0.32	0.52 ± 0.23
K^{+} (cmol$_c$ dm^{-3})	0.07 ± 0.04	0.05 ± 0.03
Al^{3+} (cmol$_c$ dm^{-3})	1.41 ± 0.36	1.22 ± 0.25
(H+Al) (cmol$_c$ dm^{-3})^1	6.10 ± 1.75	4.68 ± 1.39
TOC(g kg^{-1})^2	25.2 ± 0.88	18.0 ± 0.53
SB^3	1.18 ± 0.39	0.79 ± 0.29
CEC$_{effective}$ (cmol$_c$ dm^{-3})^4	2.59 ± 0.42	2.01 ± 0.32

Comment [AL5]: SD?

Comment [AL6]: ?

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CEC$_{potential}$ (cmol$_c$ dm^{-3})[5]	7.28 ± 1.74	5.47 ± 1.36
m (%)[6]	54.44 ± 11.85	60.70 ± 10.74
V (%)[7]	16.21 ± 7.09	14.44 ± 7.25
Fe (mg dm^{-3})	79.85 ± 26.82	75.98 ± 27.45
Cu (mg dm^{-3})	0.61 ± 1.79	0.43 ± 0.71
Zn (mg dm^{-3})	0.82 ± 0.88	0.61 ± 0.51
Mn (mg dm^{-3})	0.52 ± 0.65	0.45 ± 0.41
Total Sand (g kg^{-1})	481.60 ± 6.96	432.90 ± 5.50
Coarse Sand (g kg^{-1})	384.80 ± 6.46	335.90 ± 4.91
Fine Sand (g kg^{-1})	96.80 ± 1.31	97.10 ± 1.58
Silt (g kg^{-1})	252.70 ± 6.21	270.80 ± 8.54
Clay (g kg^{-1})	265.70 ± 4.95	296.30 ± 7.70
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 0.11-0.20 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 (m) was lower in the superficial layer (54.44%) due to higher base saturation (V) in this layer (16.21%), and m was higher in subsurface layer (60.70%), where V 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

Geospatial variability of soil chemical attributes and 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 a fragment of Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil

Attribute	Mean	SDV[6]	Model	C_0[7]	($C_0 + C_1$)[8]	a (m)[9]	CD (R^2)[10]	SD(%)[11]	CV[12]
SB (cmol$_c$ dm^{-3})[1]	1.18	0.39	Exponential	0.02	0.14	170.9	0.92	13.50	0.980
(H+Al) (cmol$_c$ dm^{-3})[2]	6.10	1.75	Exponential	0.05	1.52	77.4	0.93	3.39	1.121
Mg^{2+} (cmol$_c$ dm^{-3})	0.64	0.32	Spherical	3.8×10^{-3}	0.07	74.1	1.00	5.31	0.902

K^+ ($cmol_c\ dm^{-3}$)	0.07	0.04	Gaussian	8.7×10^{-4}	632×10^{-5}	630.2	0.82	13.76	0.765
$CEC_{potential}$ ($cmol_c\ dm^{-3}$)[3]	7.28	1.74	Spherical	0.25	2.52	396.0	0.99	10.08	0.968
V (%)[4]	16.21	7.09	Spherical	0.90	48.72	60.2	0.96	1.84	1.092
m (%)[5]	54.44	11.85	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]*Standard deviation*; [7]Nugget effect; [8]Sill; [9]Range; [10]Coefficient of determination; [11]Spatial dependence = (Nugget effect)/(Range) x 100. (SD≤25% is strong; 25<SD<75% is moderate; and SD≥75% is weak); [12]Cross validation.

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

Forest Speciess	**Mean**	**SDV[1]**	**Model**	**C_0[2]**	**($C_0 + C_1$)[3]**	**a (m)[4]**	**CD (R^2)[5]**	**SD (%)[6]**	**CV[7]**
B. rubescens	37.5	82.17	Spherical	204.5	6389	119.2	0.98	3.20	0.320
T. mangle	14.0	21.45	Spherical	83	742.6	130.8	1.00	11.17	0.240
A. dolichocarpa	8.5	14.24	Spherical	24.36×10^6	162.8	107.8	0.97	14.96	1.041
P. arachouchini	7.0	11.36	Spherical	6.44 ×	79.58	129.2	0.97	8.11	1.344
C. densifolia	7.0	18.14	Spherical	129	715.4	81.4	0.99	18.03	0.293
T. retusa	6.5	10.75	Spherical	5.62 ×	74.56	117.0	0.91	7.53	0.202
I. capitata	6.2	10.29	Spherical	56.1	112.3	122.0	0.98	49.95	0.719
P. heptaphyllum	6.0	10.07	Linear	-	-	-	-	PNE[8]	-

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[1]Standard deviation; [2]Nugget effect; [3]Sill; [4]Range; [5]Coefficient of determination; [6]Spatial dependence = (Nugget effect)/(Range) x 100. (SD≤25% is strong; 25<SD<75% is moderate; e SD≥75% is weak); [7]Cross validation; [8]Pure Nugget Effect.

The pure nugget effect occurred to *Protium heptaphyllum*, indicating absence of spatial dependence. Therefore, for this species 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.

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 studied species, semivariograms conformed to spherical model (Table 4).

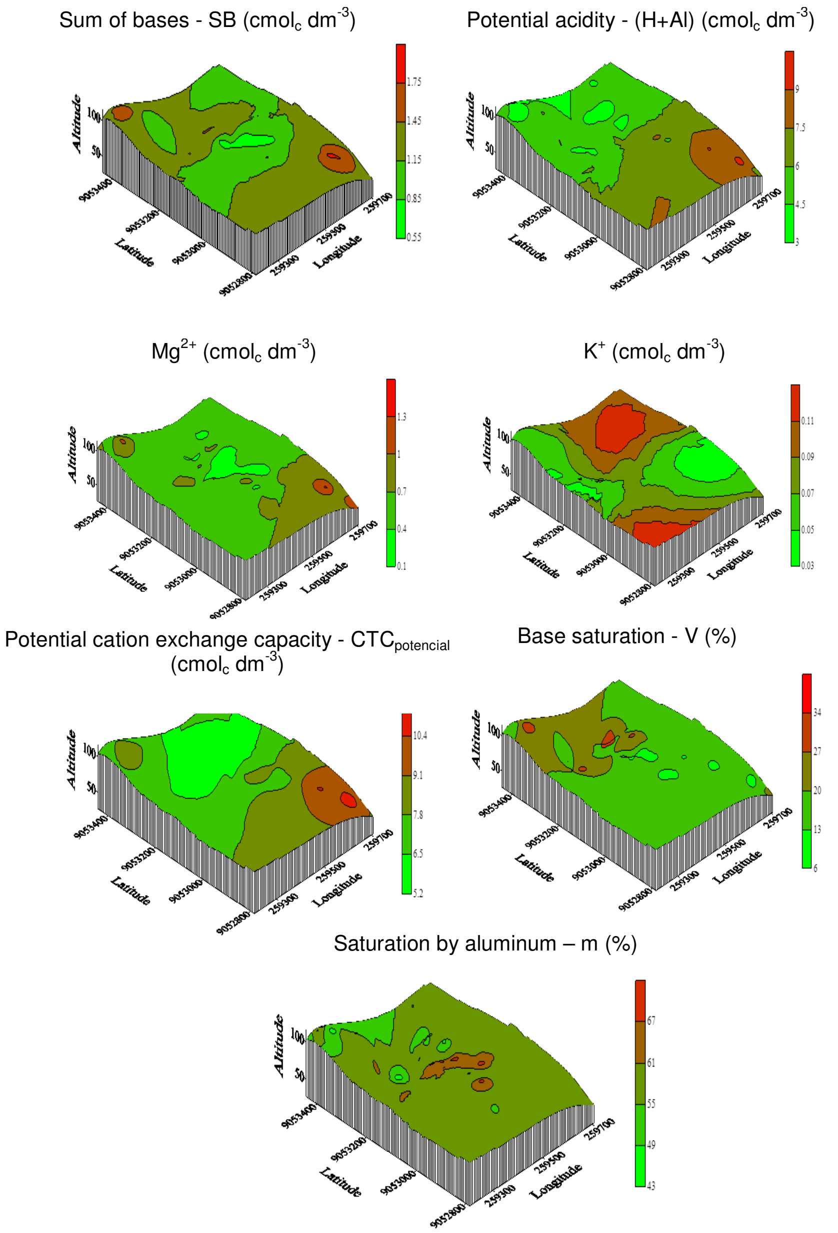
The analysis of the relationship of spatial dependence degree showed that the species presented a strong spatial dependence, except for *Inga capitata*, which presented moderate dependence (Table 4).

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

Considering the range, 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 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 natural regeneration species, kriging maps were elaborated with adjusted semivariograms models parameters (Fig. 3 and 4), and a Pearson correlation was performed (Table 5). 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 acidity - (H+Al) (cmol$_c$ dm^{-3})

Mg^{2+} (cmol$_c$ dm^{-3})

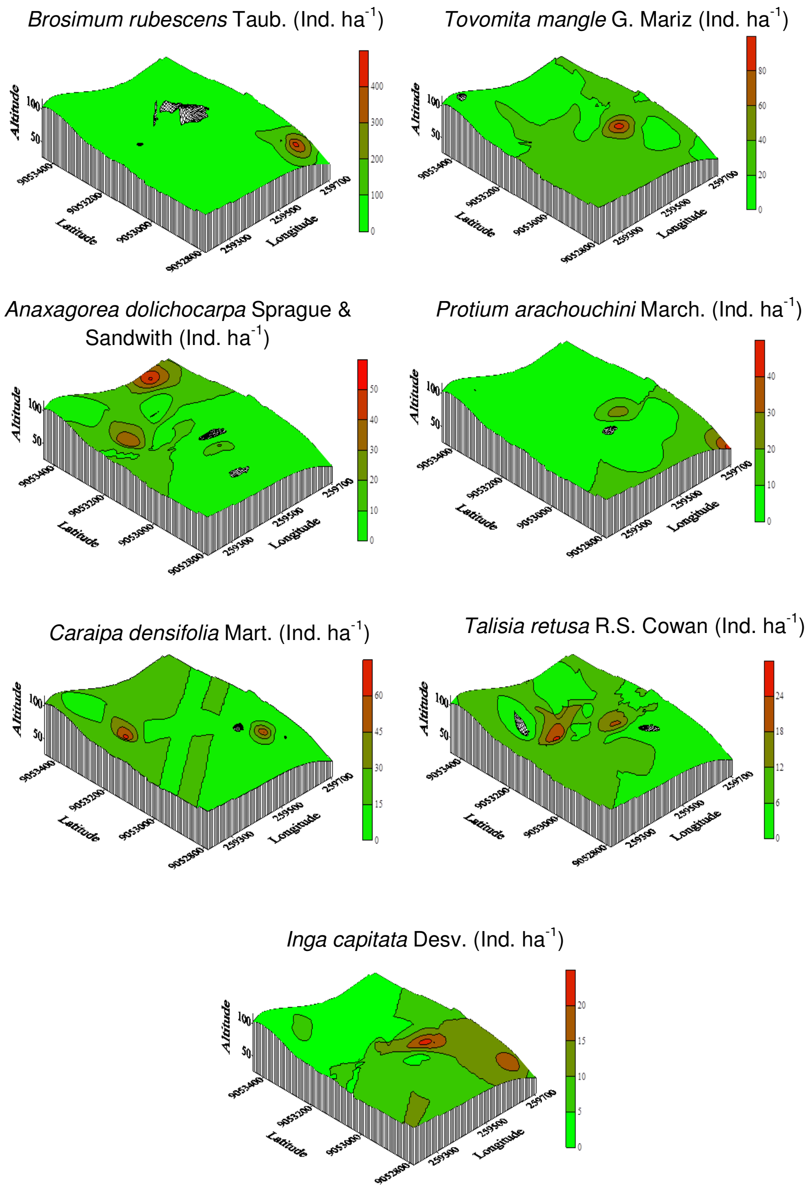
K^{+} (cmol$_c$ dm^{-3})

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 Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil.



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 forest species in natural regeneration with higher Absolute Density (AD) in a fragment of Lowlands Dense Ombrophilous Forest, Pernambuco, Brazil.

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

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, respectively).*

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

The species *Tovomita mangle* presented a negative correlation with exchangeable K concentration in soil of the fragment (Table 5), also verified by spatial distribution of species by the kriging maps (Fig. 3 and 4). This indicated that the higher exchangeable K concentration of the soil (Fig. 3) is associated with the smaller number of individuals of this species (Fig. 4). Additionally, a small relation of *Tovomita mangle* occurrence, 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 by 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 was 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 this species (Table 5). However, the kriging maps allowed 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 was correlated negatively with saturation by Al (Table 5), also found in the kriging maps of 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 negatively with SB and exchangeable Mg 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 kriging maps for *Talisia retus* and the soil chemical attributes of the fragment.

For 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 positive correlation of this 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 in this 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 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 for the concentrations of Ca^{2+}, Mg^{2+}, P, K^{+}, Al^{3+}, (H+Al), SB, $CEC_{effective}$, $CEC_{potential}$, and V, as in this study.

Concentrations of the bases Ca^{2+}, Mg^{2+}, and K^{+} were considered low. However, they were same to results obtained by Teixeira [43], 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. 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 of this study. 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^{2+}, Mg^{2+}, 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 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 reduction in plant height and dry matter production, as well as by decrease of N and P concentration in the aerial part of the two species.

Despite the high soil acidity of study fragment, 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 these forest species in acidic soil, or the chelating effect of organic matter on the Al^{3+}. In fact, the total organic C concentration (TOC) of the soil of fragment was high, mainly in subsurface, and it 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 Al presence 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 spatial dependence range allows one to define the sampling radius, guaranteeing the sampling points independence, the minimization of 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 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 it can not be indicated for recovery of degraded areas in soils of low natural fertility, especially when the exchangeable K concentrations are restrictive.

Spatial distribution of *Protium arachouchini*, resembling the behavior presented by *Brosimum rubescens*, corroborate with Santo [58], who found that *Protium arachouchini* occurs 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 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 this 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 density of *Caraipa densifolia* was observed in areas with higher saturation by 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* can not be recommended, *Talisia retusa* can be alternatively recommended for its tolerance to high levels of Al^{3+}.

In this study, *Inga capitata* showed a 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 showed that the soils of the studied area presented high acidity, high saturation by aluminum, and low base saturation, indicating low natural fertility. There was a correlation between spatial distribution of the species 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. Thus, there is no specific soil chemical attribute that has affected species. For example, where Al levels were high some species did not settle, but others were more tolerant and regenerated.

In general, the attributes that most affected the distribution of the species were: SB, (H+Al), Mg^{2+}, K^{+}, $CEC_{potencial}$, V e m.

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 environment in order to subsidize management techniques for their conservation.

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