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Spatial Analysis of Granulometry and Humic Substances of an Ecological Restoration Area in the Brazilian Atlantic Forest

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Abstract: The present study aimed at spatially analyzing granulometry and humic substances (HS) of an ecological restoration area in the Brazilian Atlantic Forest. In the study area, 49 points were systematically distributed, and soil was collected at each point, at a depth of 0-10 cm. The soil attributes evaluated were: total clay, total sand, silt, and organic carbon in the fulvic acid fraction (C-FAF), humic acid fraction (C-HAF), and humic fraction (C-HUM). Semivariogram analysis was performed for each variable, with spherical, exponential, and Gaussian semivariogram models tested. In order to choose the best model, the following parameters were used: Akaike Information Criterion (AIC), determination coefficient (R^2), root mean square error (RMSE), Willmott concordance index (d), and degree of spatial dependence (DSD %). Mapping was performed using the Ordinary Kriging method. The attributes showed spatial dependence. The spherical model was adjusted for all variables. From spatialization, the attributes, except clay, showed a heterogeneous distribution, which may be due to the high range value. The distribution of soil texture depended mainly on soil class and relief. A correlation was observed in the distribution of the silt and C-HUM attributes. The ecological restoration area had HS content values close to those reported in studies conducted under conditions similar to those in the present study. Therefore, it appears that the study area is probably undergoing recovery; however, a thorough and continuous study of the area is essential for confirmation.

Keywords: soil texture, chemical fractionation of organic matter, forest restoration, geostatistics.

I. INTRODUCTION

Ecological restoration aims at restoring forests that are biologically enduring and do not need continuous anthropogenic interference [1]. Usually, the initiatives to restore a certain area aim at enforcing environmental laws, recovering environmental services, or protecting native species [1]. As such, legislation is one of the major drivers for forest restoration in Brazil [2].

One of the most important steps in the ecological restoration process is monitoring, which must be conducted through the regular evaluation of indicators [3]. Although monitoring is fundamental to the success of ecological restoration, appropriate techniques are underused in the restoration of degraded areas [4]. Soil quality monitoring can be of great value in the recovery of degraded areas, aiding in the identification of the physical, chemical, and biological attributes of the soil [5].

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Soil attributes naturally show spatial variability due to formation factors [6], i.e., a given attribute in the samples collected from close proximity may be more similar than that of the collected samples separated by greater distances [7]. This variability may influence soil water movement, organic matter deposition, compaction, and water erosion [8]. Therefore, spatial correlation can be found among soil attributes [9]. Geostatistics has been used to describe and study the spatial variability of soils [10]. Thus, semivariogram analysis using geostatistics can be performed to determine the spatial dependence of a variable. Once the structure of spatial dependence is confirmed, it is possible to develop a map showing the distributions of variables using the Kriging method.

Given that soil attributes show spatial variability, and that studies analyzing the spatial variability of these attributes in ecological restoration areas are still scarce, the present study was conducted with the aim to spatially analyze granulometry and humic substances (HS) of an ecological restoration area in the Brazilian Atlantic Forest.

II. MATERIAL AND METHODS

A. Study Area

The study was conducted in an ecological restoration area, measuring 14,902.8 m², located in Magé municipality, Rio de Janeiro, Brazil. The climate of the region is warm and humid, with no dry season, type "Af" [11], with an annual rainfall of 2,050 mm, and a mean annual temperature of 21.9 °C [12]. The soils in the area are classified as Haplic Gleysol, yellow Latosol, and red Latosol [13], and the relief is predominantly soft wavy.

Before restoration, the area had *Brachiaria sp*. and signs of *Imperata brasiliensis* Trin. Planting was done in 2009, with a spacing of 2.5 x 2.5 m, and a pit size of 40 x 40 x 40 cm. At the base of the seedlings fertilization was done with 300 g limestone + 150 g NPK (06-30-06) + 3 L matured bovine manure/planting pit. All species planted calcário, belonged to the local biome (Atlantic Forest), except one exotic species, the African mahogany (*Khaya ivorensis* A. Chev.).

B. Georeferencing and Sampling

The vertices of the study area were georeferenced with a dual-frequency GPS and a mono-frequency GPS. Using the ArcGIS 10.3 software, a sampling grid was placed in the area, and 49 points were systematically distributed. Then the geographical coordinates of the points were sent to a navigation GPS to serve as a reference during subsequent soil collection.

C. Attribute Analysis

Soil samples were collected at 0-10 cm depth and prepared following the recommendations of Donagema et al. [14]. Subsequently, total clay contents (g kg^{-1}), total sand (g kg^{-1}), and silt (g kg^{-1}) were determined [14]. Chemical fractionation of the soil's organic matter (SOM) was performed using the differential solubility technique [15] adapted from Benites et al. [16], obtaining organic carbon in the fulvic acid fraction (C-FAF), humic acid fraction (C-HAF), and humic (C-HUM) fraction.

D. Geostatistical Analysis

Descriptive Analysis Was Performed Using The R 3.4.0 Software To Obtain The Mean, Median, Minimum Value, Maximum Value, Standard Deviation, And Coefficient Of Variation. Shapiro-Wilk Test Was Performed With A 5% Level Of Significance To Verify Data Normality. Box Plots Were Used To Identify Data Outliers, And When Necessary, The Variables Were Transformed To The Logarithmic Scale, And Discrepant Values Were Excluded.

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The spatial dependence structure of each variable was verified by semivariogram analysis using the geoR package [17]. Three theoretical models (spherical, exponential, and Gaussian) were adjusted by the maximum likelihood method. The Akaike Information Criterion (AIC), the coefficient of determination (R^2), root mean square error (RMSE), Willmott's concordance index (d), and degree of spatial dependence (DSD %) were used to select the best model). DSD can be classified as strong (GDE $\leq$ 25%), moderate (25 $\leq$ GDE $\leq$ 75%), or weak (GDE $\geq$ 75%). When DSD equals 100%, it indicates a semivariogram with pure nugget effect (PNE) [18]. After the confirmation of spatial dependence, the variables were spatialized by Ordinary Kriging, using the ArcGIS 10.3 software.

III. RESULTS AND DISCUSSION

Table I shows the results of the descriptive analysis. Discrepant values of sand and C-HAF variables were excluded to find or improve the spatial dependence structure, following procedures described by Mello et al. [19].

The only variables with normal distribution were clay and FA (fluvic acid). The other variables were not transformed, because, according to Grego et al. [20], unlike classical statistics, in which there is no normality and data are spatially independent, geostatistics only needs the data to be spatially correlated.

Table I. Descriptive analysis of the soil attributes of an ecological restoration area in the Brazilian Atlantic Forest.

Parameters	Attributes					
	Clay	Sand	Silt	FA⁽¹⁾	HA⁽²⁾	HUM⁽³⁾
	g kg^{-1}					
Mean	328.90	445.70	225.40	3.76	2.03	10.25
Medium	334.00	445.00	187.00	3.56	1.81	10.35
Minimum	91.00	80.00	7.00	1.24	0.00	4.29
Maximum	498.00	902.00	580.00	7.15	14.24	21.45
SD⁽⁴⁾	83.77	134.54	122.13	1.32	2.12	3.08
CV⁽⁵⁾ (%)	25.47	30.19	54.19	35.27	104.35	30.10
W⁽⁶⁾	0.80^{ns}	0.02^{*}	0.00^{*}	0.26^{ns}	0.00^{*}	0.01^{*}

(1) Organic carbon in the fulvic acid fraction; (2) Humic acid fraction; (3) Humic fraction; (4) Standard deviation; (5) Coefficient of variation; (6) Shapiro-Wilk test; ^{ns} Not significant; * Significant (p <0.05).

All variables showed spatial dependence (Table II). While weak and moderate spatial dependence were observed in the clay and C-HUM fractions, respectively, strong spatial dependence was observed in the other variables. Silva et al. [21] found different results from the present study. They found a strong spatial dependence in clay and silt and a moderate spatial dependence in sand. Silva et al. [22], in turn, found a strong spatial dependence in C-FAF and C-HUM, and a moderate dependence in C-HAF.

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Table II. Parameters and adjusted models for soil attributes of an ecological restoration area, in the Brazilian Atlantic Forest.

Parameters	Attributes					
	Clay	Sand	Silt	FA(1)	HA(2)	HUM(3)
	$g\ kg^{-1}$					
AIC	578.56	523.21	615.94	168.64	135.88	255.65
R^2	0.05	0.16	0.02	0.22	0.27	0.02
RMSE	1.00	0.98	1.02	1.01	0.98	1.01
D	0.50	0.54	0.53	0.56	0.63	0.44
C_0(4)	5742.00	0.00	2230.80	0.34	0.00	5.67
$C_0 + C$(5)	6976.70	7750.99	15090.37	1.89	1.02	9.49
a(6)	105.10	32.13	30.87	44.98	35.65	40.24
DSD (%)	82.30	0.00	14.78	18.15	0.20	59.78
Class	Weak	Strong	Strong	Strong	Strong	Mod.(7)
Model	Sph.(8)	Sph.	Sph.	Sph.	Sph.	Sph.

(1) Organic carbon in the fulvic acid fraction; (2) Humic acid fraction; (3) Humic fraction; (4) Nugget effect; (5) Sill; (6) Range; (7) Moderate; (8) Spherical.

The spherical model was adjusted for all variables, following Grego and Vieira [23]. These authors affirm that most of the studies in the area of soil science using geostatistics, adjust the spherical model using semivariogram.

Following the semivariance model adjustment, it was possible to spatialize the variables in the ecological restoration area using the Ordinary Kriging method (Figure 1). Except the clay fraction (Figure 1A), all attributes showed a heterogeneous distribution in the area, with no specific distribution patterns. According to Silva et al. [6], the smaller the range of the semivariogram, the more heterogeneous is the distribution of the variable, and the variable gets distributed in "spots." This explanation agrees with the findings of the present study, since the clay fraction was found to have a greater reach value (105.10) than the other variables.

The regions with higher clay contents (Figure 1A) are probably the areas where Latosols resulting from sediment deposition can be found. Gleysols, showing superficial horizons with a sandy texture, can also be found in these regions. High sand (Figure 1B) and silt (Figure 1C) contents were quantified in almost the entire study area. The highest concentration of silt in some locations, in turn, may have occurred due to the transport of these particles to regions with a less steeper slopes.

From the distribution maps of silt and C-HUM (Figures 1C and 1F), it was possible to observe a similar pattern in the distributions of these attributes. This may be due to the connections of HS with the soil mineral fraction through polyvalent cations [24]. Fontana et al. [25], analyzing the variabilities in humic fractions for the classification of diagnostic horizons in the fifth or sixth category levels of the Brazilian Soil Classification System (SiBCS), determined the correlations between the HSs and soil attributes and obtained a correlation of 0.58 between C-HUM and silt, which is in tune with the findings of the present study.

Humic substances (Figures 1D, 1E, and 1F) showed a nonuniform distribution pattern in the study area. The findings of the present study agree

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with the findings of Leite et al. [26], who, analyzing the spatial variability of soil organic matter fractions in a degraded recovery area with Jatropha, in southwestern Piauí, Brazil, observed heterogeneous HS distribution.

Greater contents of C-HUM (Figure 1F), followed of C-FAF (Figure 2D), and C-HAF (Figure 1E) were found. Several studies have found that the humic fraction is more prevalent than the other fractions in different biomes [27; 28; 22]. The higher values of C-HUM are due to its greater production and resistance to microbial degradation, besides its binding to the mineral fraction of the soil [29; 30], and also because of its size and a higher degree of stability; contrarily, C-FAF and C-HAF have lower stabilities, and can be carried to deeper or mineralized horizons, thereby decreasing their contents in the soil [31].

Fontana et al. [27], evaluating the SOM compartments in areas with different vegetational covers in the State Park of Serra do Mar, São Paulo, also observed the prevalence of C-HUM, followed by that of C-FAF. This was further observed by Fontana et al. [32] in the yellow Argisol of a coffee plantation, with secondary forest (Atlantic Forest) and pasture, in Sooretama, northern Espírito Santo.

The higher C-FAF contents than C-HAF contents may be because Latosols with humid tropical climate have higher concentrations of C-FAF than C-HAF. Latosols and Gleysols have between 17 and 24% of carbon in the fulvic acid fraction, and between 10 and 18% of carbon in the humic acid fraction, respectively [33].

Santos et al. [34] quantified the fractions of humic substances in different depths, soils, biomes, and vegetation cover in Brazil. The mean values and standard deviations (in parenthesis) of C-FAF, C-HAF, and C-HUM observed by them in forests were 21.2 g kg^{-1} (10.3), 16.6 g kg^{-1} (10.3), and 49.3 g kg^{-1} (17.5), respectively; in Latosol were 18.7 g kg^{-1} (9.4), 15.0 g kg^{-1} (7.3), and 54.0 g kg^{-1} (16.9); at the depth of 0-5 cm were 17.1 g kg^{-1} (7.8), 17.7 g kg^{-1} (8.7), and 54.9 g kg^{-1} (16.6); and in the Brazilian Atlantic Forest were 18.7 g kg^{-1} (12.1), 18.1 g kg^{-1} (12.1), and 51.6 g kg^{-1} (17.8). These values are close to the values recorded from the ecological restoration area; therefore, it can be assumed that the study area is undergoing recovery, but more detailed studies are needed over time, involving the evaluation of other indicators and comparison.

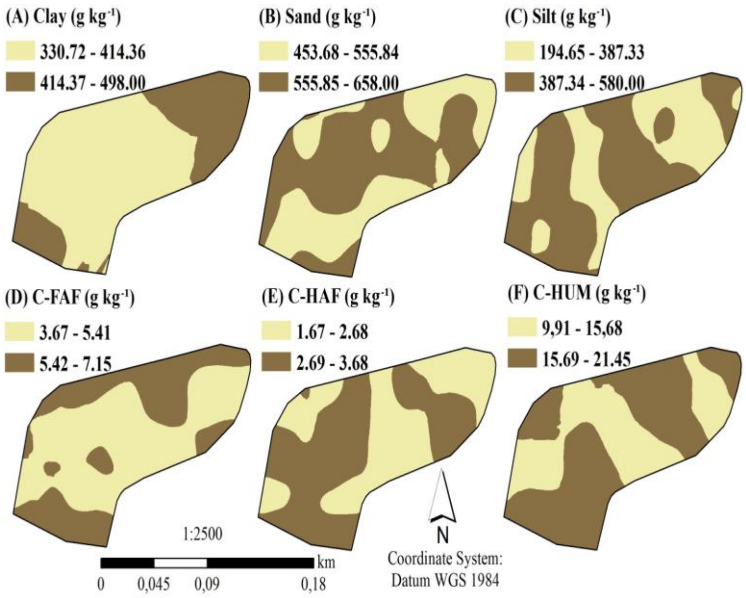

Figure 1. Spatial distribution of granulometry (clay, sand, and silt) and humic substances (C-FAF, C-HAF, and C-HUM) of an ecological restoration area in the Brazilian Atlantic Forest.

IV. CONCLUSION

All attributes analyzed showed spatial dependence. Thus, we could spatialize them, with the spherical model adjusted for all the variables.

Range has been shown to be an important factor determining the distribution of variables, since low range values can produce many "spots" on maps.

From the spatial analysis of the variables, it was observed that soil class and relief influenced the spatial distribution of mineral fractions of the soil, and that of the other formation factors not shown here.

The ecological restoration area had humic substances in levels close to those reported by studies conducted under conditions similar to those in the present study. Therefore, the area is probably undergoing recovery; however, a thorough and continuous study of the area is essential for confirmation.

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