

Artigos

Soil attributes and spatial variability of soil organic carbon stock under the Atlantic Forest, Brazil

Atributos do solo e variabilidade espacial do estoque de carbono orgânico do solo sob Floresta Atlântica, Brasil

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ABSTRACT

This study aimed to explore the physical and chemical attributes of the soil and to spatialize the soil organic carbon stock in a stretch of Atlantic Forest by evaluating four soil layers and the interrelationships of physical and chemical attributes as well as the spatialization of soil organic carbon stock by applying cokriging interpolation. Thus, 12 soil samples were collected in a soil layer, and the nutrient content, soil density, texture, soil organic carbon content and the soil carbon stock were determined. A Principal Component Analysis (PCA) grouped the most similar plots in terms of physical and chemical characteristics. Based on the spatial autocorrelation of the soil attributes, the digital elevation model data (altitude and slope) for the studied site were combined to explore the coordinate relationship between the terrain parameters and the soil organic carbon stock. We verified an increase in the soil fertility parallel to the increase in the organic matter content in the soil, helping to understand the differences and similarities of the identified sites in the field. There is a spatial difference in the soil organic carbon stock, with the largest being observed in areas of lower slope and altitude. The physical and chemical attributes of the soil in the Atlantic Forest varied according to the sampled points, being strongly related to the relief. The spatial variability altered soil organic carbon stocks in the forest under study.

Keywords: Soil fertility; Soil organic matter; Geostatistical analysis

RESUMO

Para explorar os atributos físicos e químicos do solo e espacializar o estoque de carbono orgânico do solo em um trecho de Floresta Atlântica (Estacional Semidecidual Submontanal, Espírito Santo, Brasil), este estudo avaliou quatro camadas de solo (0-5, 5-10, 10-20 e 20-40 cm), as inter-relações dos atributos físicos e químicos e a espacialização do estoque de carbono orgânico do solo aplicando a interpolação por "cokrigagem". Foram coletadas 12 amostras em cada camada de solo, sendo determinados os teores de nutrientes, a densidade do solo, a textura e o teor de carbono orgânico, sendo também determinado o estoque de carbono. Os atributos do solo mais significativos na variação dos dados foram verificados pela ordenação por Análise de Componentes Principais (ACP) agrupando as parcelas semelhantes quanto às características físicas e químicas. Com base na autocorrelação espacial dos atributos do solo, os dados do modelo de elevação digital (altitude e declividade) para o local estudado foram combinados para explorar a relação de coordenadas entre os parâmetros do terreno e o estoque de carbono orgânico do solo. Foi verificado o aumento da fertilidade do solo paralelo ao aumento do teor de matéria orgânica, auxiliando no entendimento das diferenças e similaridades dos sítios identificados no campo. Observa-se diferença espacial no estoque de carbono orgânico do solo, sendo o maior verificado nas áreas de menor declividade e altitude.

Palavras-chave: Fertilidade do solo; Matéria orgânica do solo; Análise geoestatística

1 INTRODUCTION

The soil constitutes the largest terrestrial carbon (C) reservoir, representing more than three times the amount of C in vegetation or twice the amount of C in the atmosphere (SCHARLEMANN *et al.*, 2014). It is closely associated with soil fertility as it promotes changes in the physical, chemical and biological properties of the soil (TIESSSEN; CUEVAS; CHACON, 1994). Furthermore, the C present in the soil is related to climate change, as it influences the carbon cycle (SMITH *et al.*, 1997).

While global estimates are important to have an overall carbon pool estimate (CHAVE *et al.*, 2014; BRIENEN *et al.*, 2015; PHILLIPS *et al.*, 2016; POORTER *et al.*, 2016), local estimates and factors which affect soil carbon dynamics at specific sites are also very important in this scenario (MELLO *et al.*, 2018). Detailed knowledge of the spatial variability of the soil attributes is of great relevance for the sustainable management of natural or recovering ecosystems (SONG; ZHANG; WANG, 2014). It is of great importance to study the effects caused by the change in the land use in areas of secondary forests in the Atlantic Forest Biome, since it has already been subjected

to an intense fragmentation process. Moreover, the physical attributes of the soil vary between relatively close points in the same area unit, often significantly, and their patterns can be monitored by spatial distribution through geostatistical analyses.

The interpolation of the soil attributes is crucial to study the variation and the spatial distribution of the soil characteristics. The geostatistical analysis is used to predict the spatial distribution of soil physical and chemical attributes (KE-LIN *et al.*, 2001), and cokriging has been increasingly applied to all aspects of the spatial distribution of soil properties. The cokriging method is an extension of ordinary kriging and can obtain better results (more accurate) using more than one variable in the prediction, and considering the correlation between them (SONG *et al.*, 2013).

The spatial distribution of the soil attributes, such as soil organic carbon, is affected by natural phenomena (BEHRENS *et al.*, 2014). Thus, topography can be used as an auxiliary parameter for the cokriging method. In this context, assessing the physical and chemical soil attributes and the soil organic carbon stock in natural environments is extremely important to maintain its quality, as it can provide subsidies for establishing management systems and contribute to the sustainability of forest ecosystems.

The main objective of this study was to characterize the physical and chemical attributes of the soil and to spatialize the soil organic carbon stock in an area of secondary Atlantic Forest. Thus, the following hypotheses were formulated: (1) The soil fertility is higher with the increasing of the soil organic carbon content and (2) the soil organic carbon content shows spatial variation attributed to altitude and slope.

2 MATERIAL AND METHODS

2.1 Description of the study area

The studied Atlantic Forest fragment is a Private Natural Heritage Reserve (RPPN Cafundó) created in 1998, located in the municipality of Cachoeiro do Itapemirim (20°43' S – 41°13' W), Espírito Santo state, Brazil. The RPPN Cafundó has four native forest fragments which sums up to 517 hectares in area. The RPPN Cafundó was historically

subjected to anthropogenic disturbances such as hunting, palm heart extraction and selective logging, but its fragments have been preserved since the 1940s by its owners.

The local vegetation is classified as submontane seasonal semi-deciduous forest (IBGE, 2012). The region has an "Aw" type climate according to the Köppen classification, with rainy summer and dry winter, and an average temperature of 22.2°C and average annual precipitation of 1,162 mm (ALVARES *et al.*, 2013). The terrain is characterized by having large flat areas with gentle elevations and rocky outcrops at different points (IBGE, 1987). The soil in the region is classified as "Latossolo Vermelho-Amarelo distrófico" (LVAd), according to the Brazilian soil classification system (EMBRAPA, 2013). A total of 4,557 individuals in the RPPN Cafundó forest fragments were sampled, being distributed in 258 species, 152 genera and 54 families. The families which most stood out in number of species were Fabaceae (44 species) and Myrtaceae (27 species). The total density of individuals with diameter at breast height (DBH) greater than 5 cm was 1,823 individuals ha⁻¹ (ARCHANJO *et al.*, 2012). The density of plants, dominance, species richness, slope and altitude were mensurated (Table 1).

Table 1 – Characterization of arboreal vegetation in the fragment of Atlantic Forest (ARCHANJO *et al.*, 2012), and the slope and altitude of each sample plot

Parcel	Density (ind ha ⁻¹)	Dominance (m ² ha ⁻¹)	Species richness (n° species)	Slope (%)	Altitude (m)
P1	1400	23,55	27	1,0	160
P2	2100	47,98	64	10,0	101
P3	1770	56,08	25	3,0	103
P4	1580	30,16	63	1,0	95
P5	1520	47,58	54	1,0	110
P6	1620	40,05	51	7,0	99
P7	2190	25,56	57	1,0	95
P8	1730	35,10	50	3,5	91
P9	1550	26,27	37	15,0	143
P10	1770	28,96	64	4,0	108
P11	1700	25,93	30	9,0	125
P12	1700	23,24	47	25,0	94

Source: Authors (2021)

2.2 Soil sampling

The disturbed soil samples were collected in twelve 20 m x 50 m (1,000 m²) plots. These plots are part of a network of 25 plots of continuous forest inventory, systematically distributed in the field, covering a total area of 2.5 hectares (ARCHANJO *et al.*, 2012). The soil sampling was carried out at four depths (0-5, 5-10, 10-20 and 20-40 cm) in the 12 sample plots in April 2014 to study the physical and chemical attributes of the soil. Five sub-samples were randomly collected in each plot and depth to obtain representative samples, which were later homogenized, with three composite samples being taken per plot and depth, totaling 36 samples per depth. All samples were kept at a temperature of 4°C, while the moisture at the time of sampling was also preserved.

2.3 Analysis of the soil fertility attributes

The following physical and chemical attributes of the soil were evaluated: pH in water with a ratio of 1:2.5; phosphorus and potassium were extracted with Mehlich¹ solution (0.05 mol L⁻¹ HCl, 0.0125 mol L⁻¹ H₂SO₄); calcium, magnesium and aluminum by KCl¹ mol L⁻¹ extractor and volumetric determination of Al³⁺ with diluted NaOH solution (0.025 mol L⁻¹). The potential acidity was obtained using a 0.5 mol L⁻¹ calcium acetate extractor at pH 7.0. Then, the effective cation exchange capacity (CEC) was calculated from the obtained results. The soil bulk density was determined by the deformed samples based on the test tube method, obtaining the mass by weighing after compacting the soil sample in a beaker to the predetermined volume. In addition, the contents of coarse sand (0,2-2,0 mm), fine sand (0,02- 0,2 mm), silt (0,002 - 0,02 mm) and clay (< 0,002 mm) were analyzed by pipete method proposed by Teixeira *et al.* (2017).

2.4 Soil organic carbon stock assessment

The soil organic carbon content was obtained by dividing the soil organic matter content by the factor of 1.724 (WALKLEY; BLACK adapted by RAIJ *et al.*, 2001). This factor is used for converting organic matter to organic carbon based on the assumption that organic matter has 58% organic carbon in a sample (SPRENGEL, 1826; MACHADO; CAMPOS; SANTOS, 2003). Insignificant differences were assumed between the total carbon and organic carbon (CO) contents, considering total C as equivalent to CO. Soil organic carbon stock was calculated for depths of 0-5, 5-10, 10-20 and 20-40 cm, according to the Equation (1):

$$SOCS_i = OC_i \times SD_i \times t_i \quad (1)$$

In which: $SOCS_i$ = soil organic carbon stock in the layer i , in $Mg\ ha^{-1}$; OC_i = total organic carbon in the layer i , in $g\ kg^{-1}$; SD_i = soil density in the layer i , in $kg\ dm^{-3}$; and t_i = thickness of the layer i , in cm.

2.5 Statistical and geostatistical analysis

A descriptive analysis was performed to verify the dispersion of physical and chemical soil attributes using the SPSS 21 software program. Mean, standard deviation, coefficient of variation (CV), asymmetry and kurtosis for the variables were obtained.

A principal component analysis (PCA) was performed in order to verify the correlation between the soil attributes. The principal components which present greater variability of all variables are identified in the analysis, decomposing a correlation matrix (CRUZ; REGAZZI, 2001). The remaining variables H+Al and P were removed from the analysis, as a greater number of eigenvectors associated with the lower magnitude eigenvalues under analysis were observed (CRUZ; REGAZZI, 2001). The components needed to explain 70% of the variance for the PCA.

The cokriging approach was used to estimate the spatial distributions of SOC storage (primary variable) as a function of altitude and slope (secondary variables) in the surface and sub-surface layers. In particular, cokriging is the best evaluation method for regionalized variables of a single development for two or more coordinated regional attributes (Murphy, 2015), and uses a spatial correlation between two or more variables due to autocorrelation of the main variables and cross-correlation of auxiliary variables. The cokriging prediction model can be summarized as follows in Equation (2):

$$Z^*(x_0) = \sum w_{1i}Z_1(x_i) + \sum w_{2j}Z_2(x_j) \quad (2)$$

In which: $Z(x_0)$ is the position of the sampling point; w_{1i} and w_{2j} are two regionalized variables; and $Z_1(x_i)$ and $Z_2(x_j)$ are weight coefficients (KUNKEL *et al.*, 2011; WANG; ZHANG; LI, 2013; XIAOQING; MIAO; SHUYING, 2013). Altitude and slope were used as auxiliary variables for the cokriging method interpolation of the soil organic carbon stock (SONG; ZHANG; WANG, 2014; YAO; YANG; SHAO, 2012).

3 RESULTS

3.1 Descriptive analysis of soil attributes

The soils in the sampled points did not present high acidity ($\text{pH} > 5.92$), and the concentrations of the analyzed chemical attributes decreased with depth, with an exception being observed for Al^{3+} . The soil texture was classified as sandy, the soil bulk density varied between 1.10 and 1.21 Mg m^{-3} , and there was an increase in clay content and soil bulk density in depth (Table 2).

The high asymmetry and kurtosis values of the soil properties indicated non-normal distribution of the data, thus requiring the use of analysis techniques which do not assume data distribution normality. According to the CV of soil attributes, there is considerable variation in the study region (Table 2).

Table 2 – Descriptive statistics of physical and chemical soil attributes in a fragment of Atlantic Forest (submontane semi-deciduous seasonal forest, ES, Brazil)

Statistic	Layer	pH (H ₂ O)	P	K	Ca ²⁺	Mg ²⁺	Al ³⁺	H+Al	SOC	P _{rem}	Bulk	Coarse	Fine	Silt	Clay
											Density	sand	sand		
			mg dm ⁻³	cmol _c dm ⁻³			g kg ⁻¹		mg L ⁻¹	Mg dm ⁻³	g kg ⁻¹				
Mean	0-5	6.09	8.06	84.7	5.95	1.5	0.03	2.95	3.07	48.32	1.10	521.8	159.9	66.4	251.8
	5-10	5.95	6.24	64.11	4.45	1.18	0.05	2.90	2.01	45.82	1.15	489.9	182.7	67.8	259.8
	10-20	5.94	7.33	55.00	3.56	0.97	0.07	2.67	1.40	43.95	1.18	481.5	185.6	64.8	268.2
	20-40	5.92	4.89	42.47	2.49	0.93	0.10	2.58	0.79	41.93	1.21	453.4	188.1	64.6	294.1
S ¹	0-5	0.44	7.59	30.41	2.70	0.65	0.10	1.50	1.55	5.29	0.12	171.75	38.98	44.43	166.62
	5-10	0.48	6.43	27.12	2.31	0.62	0.15	1.28	1.13	5.38	0.10	162.09	59.57	49.27	177.05
	10-20	0.58	9.97	28.21	1.72	0.52	0.20	1.32	0.63	6.28	0.08	162.93	62.58	38.78	190.16
	20-40	0.67	4.97	31.07	1.43	0.54	0.25	1.32	0.45	7.11	0.09	165.72	67.01	38.20	208.97
CV ² (%)	0-5	7.19	94.22	35.91	45.3	43.29	346.41	50.77	50.51	10.95	10.60	32.92	24.38	66.87	66.17
	5-10	8.07	103.17	42.3	51.82	52.44	326.34	44.03	56.35	11.73	8.46	33.09	32.61	72.72	68.16
	10-20	9.85	136.10	51.29	48.45	54.04	292.83	49.35	45.28	14.28	7.11	33.84	33.72	59.87	70.91
	20-40	11.38	101.73	73.15	57.65	57.7	265.52	51.28	57.20	16.95	7.71	36.55	35.62	59.17	71.05
Asymmetry	0-5	-2.11	2.29	0.52	2.37	1.77	3.46	2.2	2.89	-0.44	-0.21	-1.41	-0.71	1.71	1.40
	5-10	-1.59	1.90	0.66	2.28	2.08	3.44	2.06	2.81	-0.28	-0.43	-1.30	-0.26	1.68	1.27
	10-20	-1.33	2.18	2.37	1.61	2.22	3.28	1.84	2.11	-0.96	0.18	-0.96	-0.13	1.51	1.16
	20-40	-0.83	1.61	2.79	2.28	1.42	3.24	1.53	0.88	-0.93	-0.24	-0.84	-0.36	1.08	0.98
Kurtosis	0-5	5.33	5.87	-0.25	7.89	4.52	12	5.84	9.22	0	-0.26	2.16	-0.37	3.72	1.23
	5-10	3.19	2.85	0.45	6.85	5.52	11.9	5.03	8.62	-0.49	-0.59	2.05	-0.61	3.30	0.49
	10-20	1.66	4.41	7.21	4.11	5.99	10.96	3.99	4.88	-0.05	-1.61	0.52	-0.71	1.64	-0.02
	20-40	0.15	2.32	8.93	6.4	2.77	10.78	2.52	-0.79	-0.49	-1.65	-0.18	-0.93	1.16	-0.71

Source: Authors (2021)

In where: ¹S = Standard deviation; ²CV = Coefficient of variation. In which: P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Al = aluminum; H+Al = potential acidity; SOC = Soil organic carbon; P_{rem} = remaining phosphorus.

The pH and bulk density constituted the first set of attributes with the smallest range of values, with data concentrated with CV values below 10% stand out. The distribution for pH was negative asymmetric, meaning that negative deviations were preponderant in relation to the positive ones. The negative asymmetry value for this set reflected the higher concentration of observations above the mean value. The second set of attributes showed a slightly greater degree of distancing in relation to its position measure and intermediate variability, with CV values between 10 and 100%, and was composed of the following variables: K⁺, Ca²⁺, Mg²⁺, SOC, P-remaining and texture. The third set was composed of the P and Al³⁺ attributes due to the large range of values and variability, demonstrated by CV values above 100%. The

accentuated values for the coefficient of variation verified in some attributes indicate high heterogeneity around the average between the physical and chemical attributes of the sampling points at all depths.

3.2 Multivariate analysis between soil attributes

The PCA resulted in the eigenvalues, explanation percentages of the variance of the principal components and correlation between the principal components (PCs) and the soil attributes (Table 3).

Table 3 – Eigenvalues, explanation percentages of the variance of the principal components and correlation between the principal components (PCs) and the soil attributes of a fragment of Atlantic Forest (submontane semi-deciduous seasonal forest, ES, Brazil)

Components	PC1 ₀₋₅	PC2 ₀₋₅	PC1 ₅₋₁₀	PC2 ₅₋₁₀	PC1 ₁₀₋₂₀	PC2 ₁₀₋₂₀	PC1 ₂₀₋₄₀	PC2 ₂₀₋₄₀
Eigenvalue	7.06	3.41	6.97	3.67	6.38	4.17	6.28	4.47
Var ¹ (%)	54.31	26.19	53.60	28.19	49.07	32.09	48.32	34.41
Accum Var. ² (%)	54.31	80.50	53.60	81.79	49.07	81.16	48.32	82.73
Variables	0-5 cm		5-10 cm		10-20 cm		20-40 cm	
pH (H ₂ O)	0.14	-0.98	0.16	-0.97	-0.02	-0.99	0.48	0.84
P	-0.15	-0.47	-0.08	-0.43	-0.19	-0.51	0.31	0.43
K	0.73³	-0.15	0.76	-0.21	0.88	-0.32	-0.77	0.53
Ca ²⁺	0.84	-0.46	0.85	-0.49	0.68	-0.68	-0.58	0.79
Mg ²⁺	0.91	-0.33	0.91	-0.35	0.88	-0.43	-0.59	0.76
Al ³⁺	-0.10	0.90	-0.05	0.87	0.06	0.84	-0.32	-0.77
CEC	0.88	-0.42	0.89	-0.42	0.79	-0.57	-0.67	0.72
SOC	0.96	0.06	0.95	0.15	0.93	0.21	-0.91	-0.30
Density	-0.82	-0.40	-0.80	-0.48	-0.70	-0.56	0.83	0.44
Coarse sand	-0.88	-0.42	-0.88	-0.40	-0.87	-0.40	0.96	0.16
Fine sand	-0.55	-0.45	-0.60	-0.54	-0.63	-0.47	0.79	0.30
Silt	0.94	-0.15	0.88	-0.30	0.79	-0.34	-0.48	0.70
Clay	0.79	0.58	0.76	0.63	0.79	0.56	-0.92	-0.35

Source: Authors (2021)

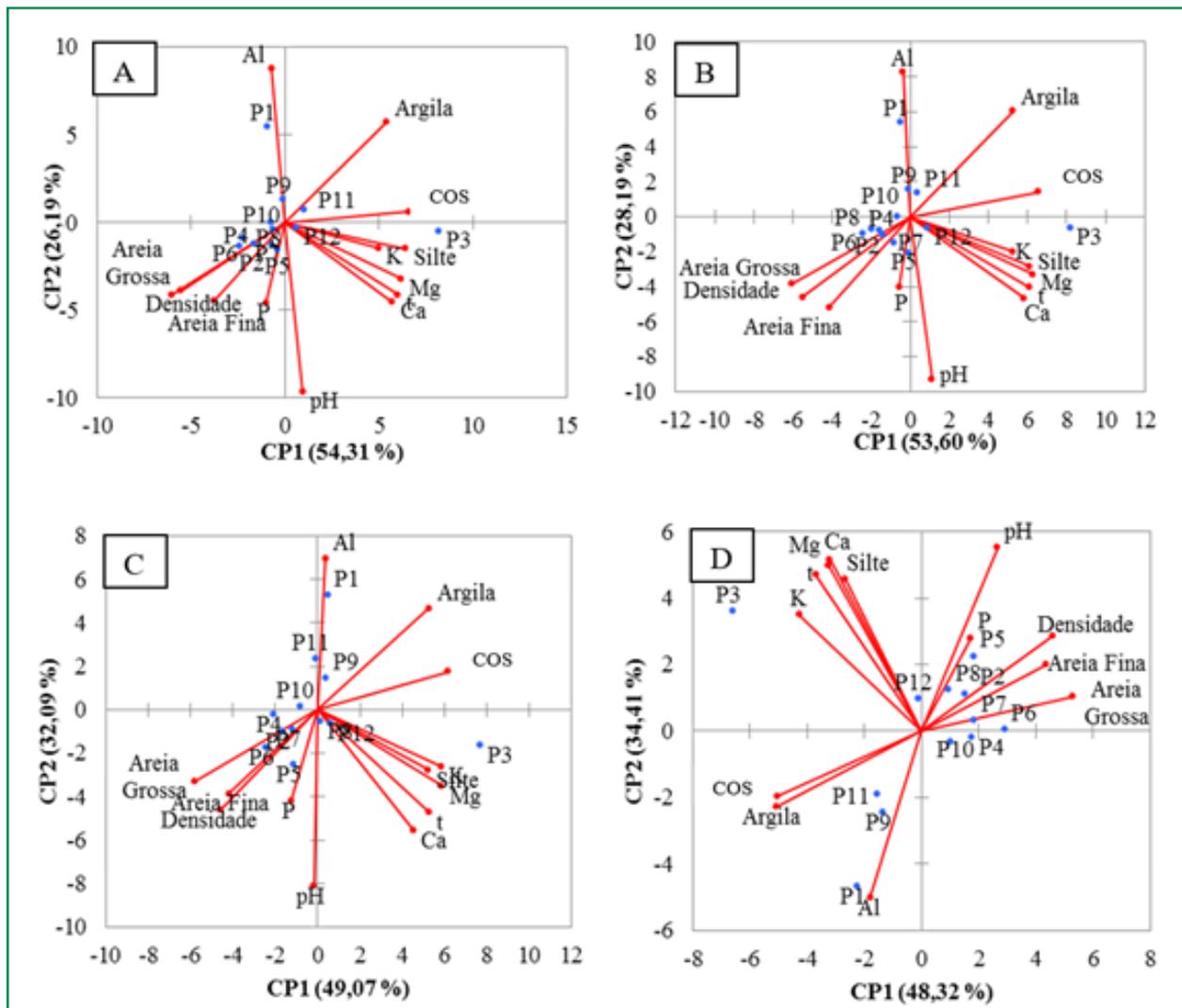
In which: P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Al = aluminum; CEC = effective cation exchange capacity; SOC = soil organic carbon; ¹Explained variance; ²Accumulated variance; ³Values in bold have a strong correlation with the main component.

It was observed that the most important principal components can be summarized in two components per studied soil depth, which presented accumulated variance of 80.50, 81.79, 81.16 and 82.73% for depths 0-5, 5-10, 10-20 and 20-40 cm, respectively (Table 3). A similar pattern was verified for the depths of 0-5, 5-10 and 10-20 cm regarding the correlations between the principal components and the soil attributes. In the first principal component ($PC1_{0-5}$, $PC1_{5-10}$ and $PC1_{10-20}$), which explained 54.31, 53.60 and 49.07% of the variation, respectively, there was a high positive correlation (> 0.70) for the attributes potassium, calcium, magnesium, CEC, SOC, silt and clay, and a high negative correlation (< -0.70) for soil bulk density and coarse sand content. The second principal component of the 0-5 and 5-10 cm surface layers were positively correlated with pH, and negatively correlated with aluminum.

Additionally, the soil organic carbon, clay and basic cations were correlated with $PC1_{0-5}$, $PC1_{5-10}$ and $PC1_{10-20}$ and inversely with soil density and coarse sand content, indicating that the decrease in the soil density and coarse sand promote an increase in the basic cations of the exchange complex due to the higher organic carbon content of the soil (Figures 1A, 1B and 1C).

The attributes furthest from the origin were the most representative of the variation in the data of physical and chemical attributes, with the attributes furthest from the origin in the horizontal direction representing the principal component 1 ($PC1$) and the ones furthest away from the origin in the vertical direction representing the principal component 2 ($PC2$). The sample point P1 in Figures 1A, 1B, 1C and 1D was more representative for aluminum. Sample point P3 exhibited greater connectivity with the calcium, magnesium, potassium, silt and soil organic carbon attributes (Figures 1A, 1B, 1C and 1D). In addition, it was noted that the other sampling points (P2, P4, P5, P6, P7, P8, P9, P10, P11 and P12) were located in the central part of the graphs at all depths studied, probably because they presented intermediate characteristics between the aforementioned sampling points.

Figure 1 – A, B, C, D: Projections of the soil attributes in a fragment of Atlantic Forest (submontane semi-deciduous seasonal forest, ES, Brazil) in the main plane between Principal Components (PCs) 1 and 2 for depths 0-5, 5-10, 10-20 and 20-40 cm, respectively



Source: Authors (2021)

In where: P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; Al = aluminum; t = effective cation exchange capacity; COS = soil organic carbon.

3.3 Soil Organic Carbon stock

The soil carbon stock ranged from 12.31 to 33.94 Mg ha⁻¹ in the 0-5 cm layer, from 6.76 to 26.07 Mg ha⁻¹ in the 5-10 cm layer, of 11.64 to 33.49 Mg ha⁻¹ in the 10-20

cm layer and 8.60 to 36.13 Mg ha⁻¹ in the 20-40 cm layer, and the sampling point P3 had statistically higher means when compared to the other points for all soil depths. The means values of the soil organic carbon stock varied in the different studied layers (Table 4).

Table 4 – Descriptive statistics of soil organic carbon stock at different depths under an Atlantic Forest (submontane semi-deciduous seasonal forest, ES, Brazil)

Statistic	Soil organic carbon stock (Mg ha ⁻¹)				
	0-5 cm	5-10 cm	10-20 cm	20-40 cm	0-40 cm
Mean	16.27	11.22	16.20	18.53	62.21
Standard deviation	5.84	4.99	6.24	9.20	24.09
CV ¹ (%)	35.90	44.52	38.51	49.68	38.73

Source: Authors (2021)

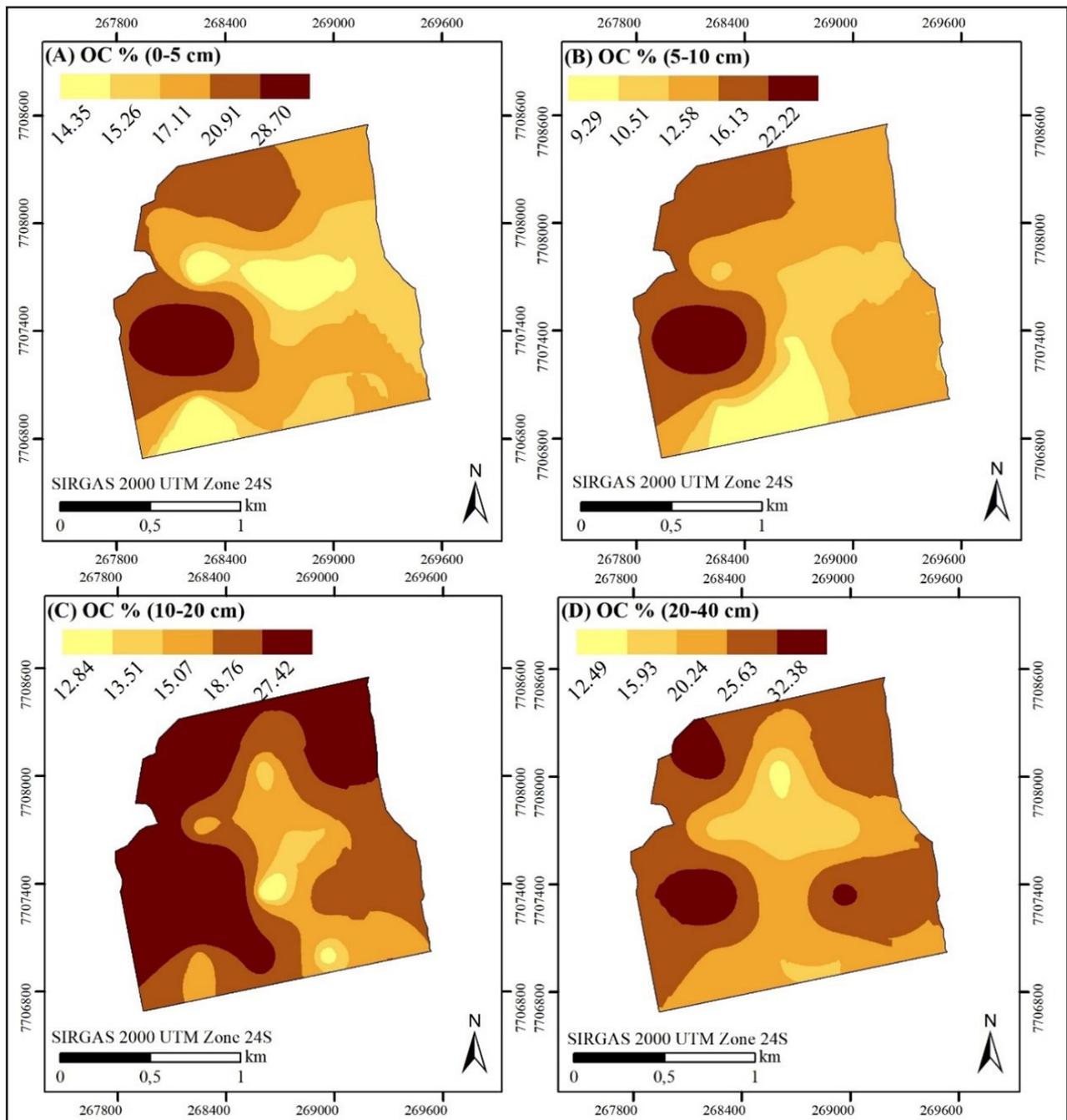
In where: ¹CV= Coefficient of variation

The organic carbon stock varied in the different layers studied between the different reliefs and vegetation characteristics of each plot. The highest carbon stock value evaluated was observed at sampling point P3 in all collected layers, and consequently in the 0-40 cm layer. This pattern found may be due to the location and characteristic of the plot as being lowland with deposition occurrence of organic matter in the rainy season.

At all depths studied through the interpolation of data by cokriging, it was observed that the largest soil organic carbon stocks predominated in places with lower altitude and slope (Figure 2).

There was variation between sampling points for carbon stock for all the evaluated layers. The largest soil carbon stock was verified in the region of lower slope and altitude in all layers, being characterized as lowland with deposition occurrence in the rainy season.

Figure 2 – Spatial distribution of soil organic carbon stock (Mg ha⁻¹) using altitude and slope as secondary variables



Source: Authors (2021)

4 DISCUSSION

4.1 Soil attributes

From the averages of the chemical attributes of the 12 sampled plots, it was inferred that the soil has an average level of fertility (DADALTO; FULLIN, 2001). Phosphorus, calcium, magnesium and potassium nutrients were higher and aluminum concentrations were lower when compared to seasonal semi-deciduous forest fragments in the municipality of Pinheiral, RJ state (GUARESCHI *et al.*, 2014), and a forest fragment of Atlantic Forest in secondary succession in Conceição de Macabu, RJ state (GAMA-RODRIGUES *et al.*, 2008). Studies carried out by Benites *et al.* (2010), Espig *et al.* (2008) and Ferreira *et al.* (2006) found lower nutrient concentrations than those found in this study in different forest formations. According to Salgado *et al.* (2006), low fertility in soils under natural vegetation is an expected condition due to the accumulation of nutrients in the shoots and roots and the high degree of weathering of the soil. However, the concentration of nutrients was higher in this study than that found in other tropical forests, probably due to the organic matter depositions in sites with low altitude.

Soils with higher pH were not considered a typical characteristic of tropical forests (FUJII *et al.*, 2011). We found pH values higher than those obtained by Benites *et al.* (2010) and Gama-Rodrigues *et al.* (2008), with pH of 4.80 and 4.35, respectively, both in Atlantic Forest fragments in Rio de Janeiro state. As a consequence of the lower pH value, we analyzed higher acidity in certain sites due to the leaching of basic cations from the soil.

High concentrations of soil organic matter contents were observed in the first layer, indicating the importance of nutrient cycling, especially the litter contribution in increasing the soil organic carbon contents (ZANELLA *et al.*, 2011). The higher organic matter content in the soil acts as a source of nutrients for plants, increasing the capacity to exchange cations, in addition to forming complexes with aluminum, increasing the

availability of nutrients (FONTANA *et al.*, 2011; GUPPY; MENZIES; MOODY, 2005). It can be seen that the chemical attributes of the most superficial layer may be directly related to the forest dynamics of litter production and decomposition (PONGE; CHEVALIER, 2006; PESSOA; CESÁRIO; CASTRO JUNIOR, 2012).

There is greater integration between the vegetation cover and the chemical attributes in soils covered by native vegetation due to the continuous decomposition of the organic material deposited on the forest floor, associated with less losses of nutrients. There is variability in the chemical attributes of the soil in areas of secondary forests due to the greater litter accumulation in the superficial layers, followed by decomposition and release of nutrients (CARRERA *et al.*, 2009).

A decrease in the values of the chemical attributes in depth was observed, with the exception of the aluminum contents, which showed higher values in the deeper layers in some sites. The higher nutrient concentrations present in the topsoil are associated with more efficient nutrient cycling in these layers. Silva *et al.* (2007) observed higher potassium and calcium values in a study carried out in forest, scrub and pasture areas in the superficial layer in the forest area. Similar results were found by Miranda *et al.* (2007), in which the nutrients in the 0-10 cm layer presented higher concentrations than the 10-20 cm layer in an Atlantic Forest fragment in Rio de Janeiro state.

Variations in chemical attributes based on principal component analysis for each soil layer allowed that only two main components were sufficient to explain the variation of the data. The chemical and physical attributes of the soil correlated with the PC1₀₋₅, PC1₅₋₁₀, and PC1₁₀₋₂₀ can be interpreted as improvement in soil fertility as a function of the increase in organic matter and the decrease in soil bulk density. On the other hand, the PC2₀₋₅, PC2₅₋₁₀, and PC2₁₀₋₂₀ suggest the effect of increasing soil pH on decreasing potential acidity and available phosphorus.

The high correlations of soil attributes with the PC1₀₋₅ and PC1₅₋₁₀ can be interpreted and analyzed as places which have a higher concentration of soil organic

matter and clay concentration tend to be more fertile, with higher potassium, calcium and magnesium content and increasing soil cation values. In addition, the clay content and the basic cations were correlated with PC1₀₋₅ and PC1_{5-10'} and inversely with soil bulk density and coarse sand content, indicating that the decrease in these attributes increases the basic cation content in the exchange complex. However, the effect of organic matter on soil fertility was minimized at depth with a decrease in fertility; a pattern also reported by Santos *et al.* (2008) in a typical dystrophic Red Latosol under a subtropical forest fragment. This fact can be confirmed by the PCA of the 10-20 and 20-40 cm layers. The increase in organic matter in these layers decreased the concentration of remaining P, and caused an increase in the potential acidity of the soil in the 20-40 cm layer. The presence of aluminum was observed in the sites with the highest percentage of organic matter in the 20-40 cm layer of the soil, which corroborates the hypothesis that the acidity in this layer is mainly due to the H⁺ cation from the organic compounds.

The influence of soil organic matter on phosphorus adsorption has been discussed in studies, showing that it can decrease or increase the soil ability to adsorb phosphorus. Studies such as those by Aquino (2004) and Silva *et al.* (1997) attest that the reduction in phosphorus adsorption has been attributed to the action of carbonic acid released by organic matter on the solubilization of minerals containing phosphorus. When researching the effect of the application of organic residues on phosphorus adsorption, Andrade, Fernandes and Faquin (2001) concluded that the addition of soil organic matter reduced the fixation of P in the studied soils. However, some authors have indicated positive correlations between the soil organic matter content and the phosphorus adsorption, mainly due to the anionic character of organic matter, which enables forming cation bridges with aluminum, iron and calcium adsorbed to it, and the phosphorus would be adsorbed through these bridges (SANYAL; DE DATTA, 1991). Chaves *et al.* (2007) verified that the soil attributes that had a positive influence on the phosphorus adsorption capacity were organic matter, base saturation and clay content.

Another factor which may be related to the lower remaining phosphorus values is the increase in clay concentration in the soil. It is observed that the lowest remaining phosphorus values are also observed in the sites which have the highest clay concentration. This pattern suggests a trend towards increasing phosphorus availability in sites with higher coarse sand contents and decreasing P availability in areas with higher clay contents, since retention becomes weaker and availability easier with a decrease in clay content; this pattern was also evidenced by Burak, Passos and Andrade (2012), Machado *et al.* (2011) and Valladares, Pereira and Anjos (2003).

4.2 Soil Organic Carbon stock

The carbon stock results were similar to those obtained by Hickmann and Costa (2012) when evaluating the concentration and total organic carbon stock of soil and aggregates of a Red Yellow Ultisol under different tillage systems and in a remnant of native forest. The authors found mean values of 14.49, 12.84, 10.29 and 8.80 Mg ha⁻¹ for the 0-5, 5-10, 10-20 and 20-40 cm layers, respectively, for the native forest area. However, for comparative purposes only using 5 cm thickness in the 10-20 and 20-40 cm layers in proportion to the carbon stock in layers in the calculations.

We observed higher soil organic carbon stock in the superficial layer with 16.27 Mg ha⁻¹ in the five initial centimeters. Similarly, Rangel and Silva (2007) in the superficial layers of the soil with a stock of 33.95 Mg ha⁻¹ in the 0-10 cm layer, 16.20 Mg ha⁻¹ in the 10-20 cm layer, and 40.45 Mg ha⁻¹ in the 20-40 cm layer in a seasonal semi-deciduous forest in Lavras, MG state, Brazil. Rangel and Silva (2007) and Scheer *et al.* (2011) state that the greater soil carbon stock can be provided by the higher density value, which was not observed in the present study, as lower bulk density was evaluated in the plots with higher organic carbon concentration, generating greater carbon stocks.

The carbon stock at the sample depth of 0-40 cm was 62.21 Mg ha⁻¹. In a study carried out by Santos (2012) at the sampled depth of 0-40 cm, the highest organic

carbon stock value observed in the forest area was 106.9 Mg ha⁻¹. Furthermore, Rangel and Silva (2007) observed a carbon stock of 90.60 Mg ha⁻¹ for the 0-40 cm layer of native forest. Cardoso *et al.* (2010) observed organic carbon stocks in the 0-40 cm layer of 61.72 Mg ha⁻¹, and Leite *et al.* (2003) found 63.95 Mg ha⁻¹ in the 0-20 cm layer for a native Atlantic forest area.

The greater soil carbon stock found in certain sites may be related to greater absolute dominance and low species richness, inferring that the plant material deposited in this plot has greater decomposition and consequently greater return of organic matter to the soil. There was variation between sampling points for carbon stock for all the evaluated layers, indicating the effect of vegetation and different locations collected on the analyzed variables. The largest soil carbon stock found in the lower slope and altitude region in all sampling layers may have influence from the location (Table 1), being characterized as lowland with deposition occurrence of litter during the rainy season of the year. The highest organic matter accumulations in the soil are generally attributed to the lowest places in the landscape (RESCK *et al.*, 2008). The soil carbon stock estimates vary from place to place and the slope and altitude affect the amount of soil organic carbon.

The accentuated soil organic carbon stock values provided by the native forest come from the continuous and varied depositions of several organic materials with different decomposition degrees arising from the greater diversity of species. Studies carried out by Leite *et al.* (2003), Rangel and Silva (2007), Hickmann and Costa (2012) and Barros *et al.* (2013), who evaluated the effects on the carbon stock of different covers and use and management systems in relation to soils from native fragments, showed that soil carbon concentrations and stocks decreased from the forest condition to other usage and land management forms, showing the importance of conserving natural environments to carbon maintenance.

5 CONCLUSIONS

The physical and chemical attributes of the soil in the fragment of Atlantic Forest (submontane semi-deciduous seasonal forest, ES, Brazil) varied according to the sampled points due to the influence of factors such as soil organic carbon.

Using principal component analysis, attributes interrelated to soil fertility contributed to the first principal component in the most superficial layers (0-5, 5-10 and 10-20 cm). However, the first principal component at depths of 0-5 cm, 5-10 cm and 10-20 was strongly related to relief (intrinsic factor) and clay, silt, coarse sand and density contents (intrinsic character attributes).

The average total soil organic carbon stock in the 0-40 cm layer in the fragment of Atlantic Forest was 62.21 Mg ha⁻¹. The cokriging approach proved the spatial variability of the soil organic carbon stock by the altitude and slope variables.

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