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LANDFORM CURVATURE AND ITS EFFECT ON THE SPATIAL VARIABILITY OF SOIL ATTRIBUTES, PINHEIRAL-RJ/BR

Keywords:
Relief
Geostatistics
Fertility
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ABSTRACT: Understanding the spatial variability of soil chemical and physical attributes is important for improving management practices and soil conservation. In turn, the spatial variability of soil properties results from variation in morphological relief characteristics. Thus, the purpose of this study was to evaluate the influence of landform curvature on the spatial variability of soil chemical and physical attributes in the Mar de Morros region (Pinheiral-Rio de Janeiro State, Brazil). Two adjacent landforms were selected with convex and concave curvature and sampled in a regularly spaced grid of 10 meters. A total of 56 soil samples (0-5 cm depth) from the two landforms were collected and analyzed for physical and chemical attributes. The data were analyzed using descriptive statistics and geostatistics. All chemical attributes showed random patterns of spatial variability in both landforms. The concave landform had higher values of pH and potassium and lower values of aluminum than the convex landform. In contrast, silt content showed spatial dependence in both the concave and convex landforms. Bulk density and clay showed spatial dependence in the convex landform. Bulk density and silt content increased from the shoulder to the footslope of both landforms. The results show that, for this study area, landform curvature has more influence on the spatial dependence of soil physical attributes than of soil chemical properties.

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CURVATURA DA SUPERFÍCIE E SEU EFEITO NA VARIABILIDADE ESPACIAL DOS ATRIBUTOS DO SOLO, PINHEIRAL - RJ / BR

Palavras chave:
Relevo
Geoestatística
Fertilidade
Floresta Atlântica

RESUMO: Compreender a variabilidade espacial dos atributos químicos e físicos do solo é importante para melhorar as práticas de manejo e conservação do solo. Por sua vez, a variabilidade espacial das propriedades do solo resulta da variação das características morfológicas do relevo. Assim, o objetivo deste estudo foi avaliar a influência da curvatura da superfície na variabilidade espacial dos atributos químicos e físicos do solo na região de Mar de Morros (Pinheiral-Rio de Janeiro, Brasil). Foram selecionadas duas pedoformas adjacentes com curvatura convexa e côncava e coletadas amostras de solo em uma grade com espaçamento fixo de 10 metros entre os pontos. Foram coletadas um total de 56 amostras de solo (0-5 cm de profundidade) nas duas pedoformas e analisados os atributos físicos e químicos do solo. Na análise dos dados foi utilizada estatística descritiva e geoestatísitca. Os atributos químicos do solo apresentaram um padrão aleatório quanto a distribuição espacial em ambas as pedoformas. No entanto, a pedoforma côncava apresentou maiores valores de pH e potássio e valores mais baixos para alumínio quando comparada a pedoforma convexa. Por outro lado, os valores de silte apresentaram dependência espacial em ambas às pedoformas. Já a densidade do solo e o teor de argila apresentaram dependência espacial na pedoforma convexa. Os valores da densidade do solo e silte aumentaram no sentido do terço superior para o terço inferior em ambas as pedoformas. Os resultados mostram que para esta área de estudo, a curvatura da superfície tem maior influência na dependência espacial dos atributos físicos do que para os atributos químicos solo.

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INTRODUCTION

In the Mar de Morros region (Pinheiral-Rio de Janeiro State, Brazil), the Atlantic Forest is represented by Seasonal Semideciduous Forest, which historically has been an important area for growing coffee and raising livestock. Areas previously occupied by Atlantic Forest are now predominantly pastures with different degrees of degradation. Some are still used as unmanaged pasture; however, others were abandoned and have reverted to native vegetation in different states of natural succession (MENEZES, 2008).

The rate of natural vegetation succession in anthropized abandoned areas is determined by the physical and chemical characteristics of the soil and is fastest in the most fertile environments.

The rate of natural vegetation succession in disturbed abandoned areas is determined by factors, such as seed bank, seedling source, degree of human disturbance, and soil physical and chemical properties. Natural succession is fastest in the most fertile environments (PINTO et al.; 2008). As observed by Souza et al. (2012) in Rio Doce State Park in Minas Gerais, the distribution of tree species of Semideciduous Sub-montane Forest was affected by the gradient of soil physical and chemical attributes. The distribution of tree species in the forest was also related to soil drainage regimes (FERREIRA-JUNIOR et al., 2007).

The spatial variability of soil physical and chemical attributes is determined by the source material, climate and relief characteristics of the landscape (CEDDIA et al., 2009; CAMARGO et al., 2010). Relief forms in these environments vary from convex, through linear, to concave (TROEH, 1965).

Each landform has variability in surface curvature, declivity and altitude, which influence the dynamics (accumulation and dispersion) of water and sediment in the landscape (SANCHEZ et al., 2009; CAMARGO et al., 2010). Convex, linear and concave surfaces influence the source material of sediment and the intensity and direction of water flow within the soil profile (ARTUR et al., 2014). According to Gandolfi (2000), the variation in the surface slope conditions also influence soil humidity and fertility gradients.

Some studies have observed that concave environments show greater spatial variability in soil attributes than do linear environments (SOUZA et al., 2003; MONTANARI et al., 2005; CAMARGO et al., 2010). According to Sanchez et al. (2009), greater variability in the concave environments is linked directly to variability in relief characteristics.

The pattern of soil attributes in different landscape conditions can be understood by characterizing the spatial variability of the soil physical and chemical attributes based on the surface geomorphology. According to Sibaldelli et al. (2015), understanding the spatial and temporal variability of soil attributes is required in studies of agricultural soils and their productive capacities. In non-production forests, understanding the spatial variability of soil properties is important for improving management techniques aimed at recovery from anthropogenic disturbances.

Geostatistics have been used by many researchers to evaluate physical and chemical attributes of the soil (AQUINO et al., 2015; JUNIOR et al., 2014; OLIVEIRA et al., 2013). Thus, the objective of this study is to evaluate the influence of landform curvature on the spatial variability of physical and chemical soil attributes in the Mar de Morros region, in the municipality of Pinheiral, Rio de Janeiro State, Brazil.

MATERIAL AND METHODS

The study was conducted in the municipality of Pinheiral, Rio de Janeiro State, in the Middle Paraíba Region. The study site is located in the Mar de Morros geomorphologic region, in the sub-basin of the Ribeirão Cachimbal, which is in the hydrographic basin of the Paraíba do Sul river. Detailed information about the study area and its location is presented in Figure 1.

Two adjacent landforms were selected, one with convex curvature (convex-divergent) and concave curvature (concave-convergent). Both landforms had a predominantly southeastern aspect and current Semideciduous Sub-montane plant cover (CONAMA, 1994; IBGE, 2012). This vegetation has established itself in the site through natural regeneration and has been present in this environment for more than sixty years.

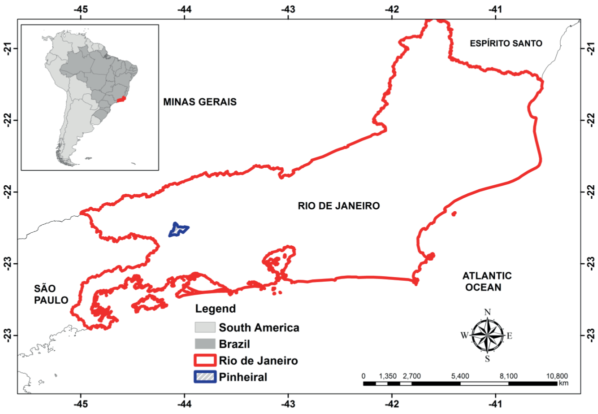

FIGURE 1 Geographical location of the study area. In blue the municipality of Pinheiral, Rio de Janeiro State.

The soils of both landforms were classified as Inceptsol (*Cambissolo Háplico*). In each landform, soil samples were collected from 0-5 cm depth. We focused on the top 5 cm because this layer is the most sensitive to surface runoff processes, erosion and drainage. In the convex landform, 24 samples were collected in a grid pattern with 10-meter spacing. In the concave landform, 32 samples were collected, and grid spacing was reduced to 8 meters in the central section (Figure 2). This procedure aimed to avoid sampling areas that had surface water flow during rainy periods.

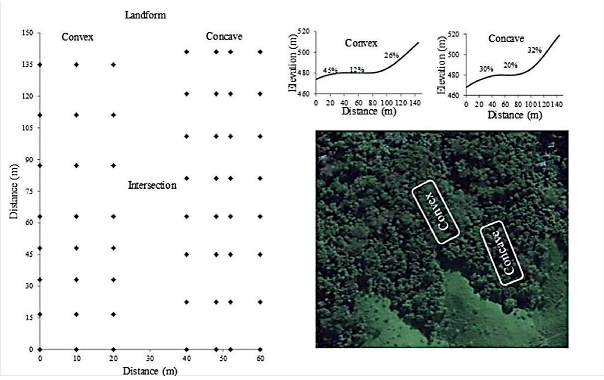

FIGURE 2 Morphological characteristics (curvature and slope), landscape position and the regular grid of soil sampling points from convex and concave landforms.

A total of 56 soil samples were collected from the two landforms. Bulk density (BD) was measured on undisturbed soil samples collected using an Uhland sampler. Soil texture (clay, silt and sand) and chemical attributes (pH, Ca^{2+}, Mg^{2+}, K^{+}, Al^{3+}, P and C) were measured on deformed samples (EMBRAPA, 1997).

Statistical analyses were performed using two approaches. The first analysis consisted of descriptive statistics and geostatistics. This analysis was performed to evaluate whether the soil attributes showed spatial dependence, using GEOSTAT software (VIEIRA et al., 1983). For soil attributes that did not show spatial dependence (i.e., had a completely random pattern), the average value of each attribute was compared between landforms using a Tukey test ($\alpha=0.05$).

The steps of geostatistical analysis were as follows: 1–descriptive statistical analysis; 2–determination of spatial dependence (variography), 3 - modeling and validation of experimental semivariograms and interpolation. All steps were performed using the GEOSTAT software (VIEIRA et al, 1983). The semivariances of soil attributes were calculated according to the equation below, where: g(h) - semi variance estimated at a distance h; N(h) - number of pairs of values Z (x i), Z (x i + h)] separated by a vector h; X i - spatial position of variable Z, and Z - values of variables (physical and chemical attributes of soil).

$$Y(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[Z(x_i)-Z(x_i+h)\right]^2 \qquad [I]$$

The experimental semivariogram was also classified according to the degree of randomness (DR). The DR is calculated through the following equation 2, where: C_0 = intercept or nugget effect and $C_0 + C_1$ = Sill.

$$DR=\frac{C_0}{C_0+C_1}\times 100 \qquad [II]$$

Based on the methodology proposed by Cambardella et al. (1994), the following classes were used: Low Degree of Randomness (DR ≤ 25%), Moderate DR (DR between 25% and 75%), High DR (DR ≥ 75%), and finally Complete Randomness (DR = 100%). In the last class, the semivariogram is classified as pure nugget effect.

The interpolation of the soil attributes was performed using Ordinary Kriging (OK). The OK only utilizes primary data, such as clay content measured at sampled locations u to estimate the clay content at unsampled locations. The stationarity of the mean is assumed only within a local neighborhood W(u), centered at the location u being estimated. Here, the mean is deemed to be a constant but unknown value, i.e., m(u´) = constant but unknown, "u´Î W(u). The OK estimator is written as a linear combination of the n(u) data $Z(u_\alpha)$ with a single unbiasedness constraint:

$$Z^*_{OK}(u)=\sum_{\alpha=1}^{n_\alpha(u)}\lambda_\alpha^{OK}(u)\left[Z_1(u)\right] \quad \text{, with} \quad \sum_{\alpha=1}^{n_\alpha}\lambda_\alpha^{OK}=1$$

The unknown local mean m(u) is filtered from the linear estimator by forcing the kriging weights to sum to 1.

RESULTS AND DISCUSSION

Soil physical and chemical attributes for the convex and concave landforms are presented in Table 1. Mean soil bulk density was not different between landforms. In contrast, clay and sand contents tended to be higher in the convex landform, while the highest value of silt content was observed in the concave landform. These differences in soil texture are likely due to different patterns of water flow in the two landforms, which in the convex landform are dominated by the process of side outflow and the carrying effect of soil particles (OLIVEIRA et al., 2013).

Soil pH, Ca^{+2}, Mg^{+2}, P and K^{+} were higher in the concave landform, while Al^{+2} and C contents were higher in the convex landform. According to Souza et al. (2004), small variations in landform relief are responsible for differences in the variability of chemical attributes in the landscape. Differences in soil chemical properties are also associated with variation in organic matter accumulation processes, nutrient transport and sediment and water dynamics (CAMPOS et al., 2010).

For soil chemical attributes, pH and potassium mean levels were statistically higher in the concave landform, while aluminum and carbon mean levels were statistically higher in the convex landform (Table I). The influence of relief characteristics on nutrient availability in different landforms was also observed by Montanari et al. (2010), which associated the variability in chemical attributes with different drainage conditions. The drainage influenced the redistribution of nutrients in the soil layers. Studies have highlighted the role and influence of water flow in the distribution of soil nutrients. Regions with water accumulation tend to have higher soil fertility and higher silt and sand contents (FERREIRA-JUNIOR et al., 2007; SOUZA et al., 2012).

TABLE I Parameters estimates of the omnidirectional and cross semivariograms Vol = volume, Exp = Exponential.

Attribute	Landform	Average	Variance	SD	CV (%)	Skewness	Kurtosis	S-W (p-value)
				Physical attributes				
Density	convex	1.08	0.01	0.10	9.19	0.47	-0.17	0.91
(Mg·m^{-3})	concave	1.08	0.01	0.10	9.69	0.19	0.28	0.34
Clay (%)	convex	28.00	14.09	3.75	13.4	-0.15	0.16	0.01*
	concave	26.16	26.78	5.18	19.79	-0.67	0.64	0.27
Sand (%)	convex	56.58	16.60	4.07	7.2	1.07	0.71	0.00*
	concave	49.06	71.67	8.47	17.26	0.27	-0.08	0.24
Silt (%)	convex	15.42	15.91	3.99	25.87	0.06	-1.28	0.46
	concave	21.91	16.35	4.04	18.46	-0.22	-0.95	0.25
				Chemical attributes				
pH	convex	4.31b	0.33	0.57	13.25	0.68	-0.67	0.03*
(H_2O)	concave	4.93a	0.53	0.73	14.78	0.61	-0.63	0.02**
Calcium	convex	2.64ns	3.11	1.76	66.78	0.85	-0.5	0.01*
(cmol$_c$kg^{-1})	concave	3.29ns	3.60	1.9	57.75	0.90	0.46	0.03**
Magnesium	convex	1.84ns	0.80	0.9	48.81	0.87	-0.02	0.03*
(cmol$_c$·kg^{-1})	concave	2.26ns	0.78	0.88	39.19	0.13	-1.23	0.13
Aluminum	convex	1.08a	0.74	0.86	79.95	0.36	-1.39	0.01*
(cmolc·kg^{-1})	concave	0.54b	0.37	0.61	112.2	1.24	0.33	0.00*
Phosphorus	convex	1.65ns	0.66	0.82	49.32	-0.07	-0.23	0.99
(Mg·dm^{-3})	concave	1.90ns	0.78	0.88	46.54	0.20	0.03	0.92
Potassium	convex	0.26b	0.01	0.08	31.05	0.93	1.67	0.21
(cmol$_c$.kg^{-1})	concave	0.42a	0.03	0.18	42.2	0.87	-0.17	0.00*
Carbon	convex	1.24ns	0.00	0.02	1.58	0.00	-0.10	0.82
(g·kg^{-1})	concave	1.23ns	0.00	0.03	2.19	0.38	-0.05	0.15

CV = Coefficient of variation; S-W= Shapiro-Wilk test(α=0.05); *= data transformed with log10X+1; **= data transformed with Box Cox; values followed by different letters in the column for each landform are significantly different ($p<0.05$) by Tukey tests; ns: not significant. SD = Standard deviation.

The variation in carbon content between the landforms is related to differences in litter decomposition rates. According to Santos (2014), higher decomposition rates were observed in convex landforms than in concave ones. This pattern was associated with variations in environmental conditions.

Studies developed by Souza et al. (2003) and Montanari et al. (2005) showed that, in comparison to linear landforms, concave landforms had greater variation in granulometric attributes, organic matter content, superficial flow and slope, indicating that soil attributes have different patterns as a function of landform curvature. According to Resende et al. (1997), concave landforms have areas with higher erosion rates in the highest landscape positions and higher sediment accumulation rates in the lowest landscape positions. This likely explains why concave landforms generally show more heterogeneous distributions of soil attributes.

All soil physical attributes in the concave landform followed a normal distribution. In the convex landform, however, clay and sand contents did not follow a normal distribution (Table I). According to Sirtoli et al. (2008), in concave environments the processes of sediment loss and accumulation occur simultaneously, which leads to soil physical attributes following a normal distribution., In convex environments, in contrast, sediment loss is the dominant process and causes a non-linear distribution.

Soil carbon and phosphorus also followed a normal distribution in both landforms (Table I), which can be related to the distinctive processes of sediment loss and accumulation for phosphorus and to the contribution of decomposing leaf litter for carbon. According to Santos (2014), which evaluated the effect of landform on secondary succession in forest fragments, the distribution of soil chemical attributes in forest environments was influenced by relief characteristics and litter inputs, both of which drive organic-matter dynamics and nutrient cycling in the soil.

Potassium levels in the convex landform and magnesium levels in the concave landform followed normal distributions, while pH, calcium and aluminum did not follow normal distributions in either landform (Table I). According to Artur et al. (2014), higher spatial variability in soil chemical attributes results from microrelief characteristics, which influence the direction of soil water flow.

Comparing statistical parameters, the highest values for variance, standard deviation and coefficient of variation were observed for the concave landform; this pattern can be associated with variation in altitude, slope and landscape position (Figure 3). According to Campos et al. (2010), the distribution of soil physical and chemical attributes are dependent on the conditions of the landforms.

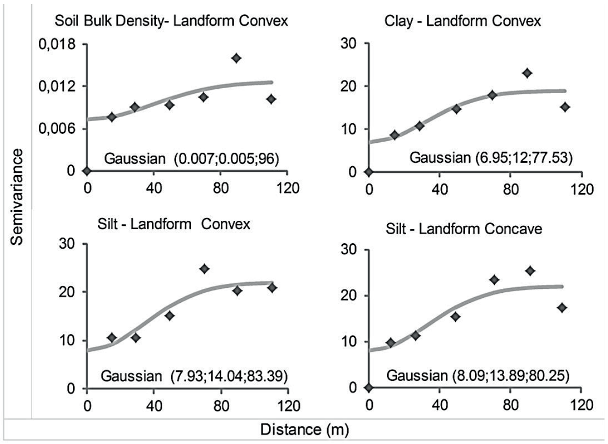

FIGURE 3 Semivariograms of experimental and respective models of soil physical attributes in convex and concave landforms (0-5 cm depth).

The results of the geostatistical analysis of soil physical and chemical attributes are presented in Table 2 and Figure 3. None of the chemical attributes showed spatial dependence; they had DR values of 100% indicating pure nugget effect. The geostatistical analysis demonstrated that the chemical attributes showed a random pattern in both the convex and the concave landforms.

Consequently, the average values of chemical attributes in each landform could be statistically compared using a Tukey test, since the errors follow a random pattern. Another aspect of the pure nugget effect for chemical attributes is that ordinary kriging is not the best interpolation method for generating maps of these attributes. Ordinary kriging only outperforms other interpolation methods when the attribute shows spatial dependence. Due to the observed lack of spatial dependence, maps of chemical attributes were not generated.

The variability in soil physical attributes and erosion factors in different landforms was evaluated by Sanchez et al. (2009). The authors observed that the morphological characteristics (relief characteristics and slope) of the landform were responsible for different distribution patterns of soil attributes in the landscape. In addition, the landform factor exerted a greater influence on the distribution of soil attributes than did the erosion factor.

The random pattern of spatial variability observed for soil chemical attributes along the topographic gradient can be explained by the influence of nutrient cycling and soil cover (SANTOS, 2014). The soil chemical attributes in the convex and concave environments can be related to sediment loss dynamics and the distribution of plant and animal material along the landforms. Rassol et al. (2014) evaluated the relationships between the soil properties and the slope at the boundary between the Jammu and Caxemira watersheds in Liddar, and observed

TABLE 2 Parameters of the fitted semivariograms models for the soil physical and chemical attributes in the convex and concave landforms.

Landform	Attribute	Model	C0	C1	R (m)	R^2	DR (%)
	Physical attributes						
Convex	BD (kg·dm^{-3})	Gaussian	0.00	0.01	95.99	0.49	0
	clay (%)	Gaussian	6.95	12.00	77.53	0.74	37
	Sand (%)	Pure Nugget Effect	-	-	-	-	100
	Silt (%)	Gaussian	7.94	14.04	83.40	0.82	36
Concave	BD (kg·dm^{-3})	Pure Nugget Effect	-	-	-	-	100
	clay (%)	Pure Nugget Effect	-	-	-	-	100
	Sand (%)	Pure Nugget Effect	-	-	-	-	100
	Silt (%)	Gaussian	8.09	13.90	80.25	0.67	37
	Chemical attributes						
Convex	pH (H_2O)	Pure Nugget Effect	-	-	-	-	100
	Calcium (cmolc·kg^{-1})	Pure Nugget Effect	-	-	-	-	100
	Magnesium (cmolc·kg^{-1})	Pure Nugget Effect	-	-	-	-	100
	Aluminum (cmolc·kg^{-1})	Pure Nugget Effect	-	-	-	-	100
	Phosphorus (Mg·dm^{-3})	Pure Nugget Effect	-	-	-	-	100
	Potassium (cmolc·kg^{-1})	Pure Nugget Effect	-	-	-	-	100
	Carbon (g·kg^{-1})	Pure Nugget Effect	-	-	-	-	100
Concave	pH (H_2O)	Pure Nugget Effect	-	-	-	-	100
	Calcium (cmolc·kg^{-1})	Pure Nugget Effect	-	-	-	-	100
	Magnesium (cmolc·kg^{-1})	Pure Nugget Effect	-	-	-	-	100
	Aluminum (cmolc·kg^{-1})	Pure Nugget Effect	-	-	-	-	100
	Phosphorus (Mg·dm^{-3})	Pure Nugget Effect	-	-	-	-	100
	Potassium (cmolc·kg^{-1})	Pure Nugget Effect	-	-	-	-	100
	Carbon (g.kg^{-1})	Pure Nugget Effect	-	-	-	-	100

BD – Bulky Density; C0: Nugget effect; C1: Contribution; R: Range; R^2: coefficient of determination; DR-Degree of Randomness.

that the slope and hillside positions significantly affected the circulation and accumulation of water, nutrients and sediments in the soil, which caused variability in soil properties along the landscape.

The lack of spatial dependence in soil chemical attributes may be related to the dynamics of variables, such as relief conditions, vegetation and soil in the different landforms. Some studies, such as Souza et al. (2008) and Lima et al. (2010), evaluating the influence of variability in slope and topographic gradients on soil chemical attributes, observed the spatial dependence of soil attributes based on the type of landform. Their results are different from those observed in this study; it is possible to infer that this difference is related to the size of the study areas and the distribution and number of sampling points.

Soil physical attributes showed spatial dependence, though the details differed between landforms. In the convex landform, all soil physical attributes except sand content had experimental semivariograms that were best fitted by a Gaussian model (Table 2 and Figure 3). The range of spatial dependence varied from 77 to 96 meters for different physical attributes. In the concave landform, only silt content showed spatial dependence, and a Gaussian model was also fitted to the experimental semivariograms. The distribution pattern of soil physical attributes can be explained by variability in the topographical conditions that determine the behavior of water flow and sediments in the study region.

Studying the influence of microrelief on the spatial variability of different granulometric soil fractions in the Apodi Plateau, Oliveira et al. (2013) observed a direct influence of microrelief on the distribution of sand, clay and silt contents, which was associated with the action of pedogenesis in soils due to convergent water flows.

The spatial variability maps of soil physical attributes in the convex landform (soil bulk density, clay and silt contents) and the concave landform (silt content) are presented in Figure 4. In all cases, a Gaussian model was fitted to the experimental semivariograms. In the convex landform, the degree of randomness was low for soil bulk density (DR = 0%) and moderate for clay and silt contents (DR = 36% and 37%, respectively). In the concave landform, the degree of randomness was moderate for silt contents (DR = 37%). Soil bulk density and silt content increased from the shoulder to the footslope of both landforms, while clay content showed the opposite pattern in the convex landform. The influence of relief on the spatial distribution of granulometric fractions in Cambisols was also observed by Oliveira et al. (2013), where the highest clay and silt contents were on the concave surface.

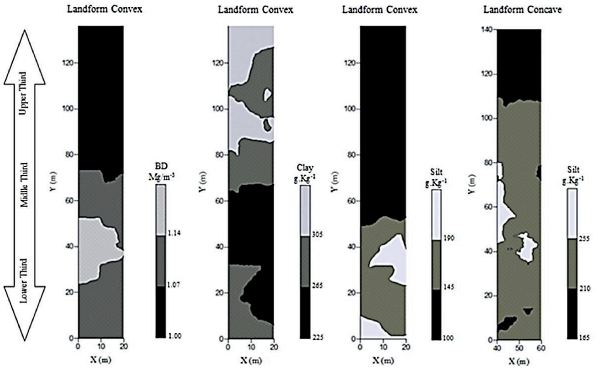

FIGURE 4 Spatial distributions of soil physical attributes in convex and concave landforms (0-5 cm depth).

Variability in relief conditions seems to be the main cause of spatial variability in soil physical attributes in the study area (Figure 4). Similar results were observed by Burak and Passos (2011), who studied the variability of textural fractions and soil porosity in wavy relief, where regions with lower superficial flow and slope had higher clay contents and lower macroporosity values. Understanding the spatial distribution of soil properties due to morphologic variation and their effects on forest ecological succession is important for developing strategies aimed at the recovery of anthropogenic environments.

CONCLUSIONS

The distribution patterns of the soil physical and chemical attributes were different between the two landforms evaluated, which reflected the different effects of slope, altitude and relief characteristics.

Landform surface curvature is a driving factor for the spatial variability of soil physical attributes, where soil bulk density and silt content increased from the shoulder to the footslope in concave and convex landforms. However, an opposite pattern was observed for clay content in the convex landform.

All soil chemical attributes showed a random pattern of spatial variability in both landforms. However, the highest values of soil chemical properties were observed in the concave landform.

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