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Spatial dependence of sugarcane yield according to the altitude and soil physical attributes in a transect

Dependência espacial da produtividade da cana-de-açúcar, altitude e atributos físicos do solo em um transecto

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ABSTRACT - Soil management carried out in areas with sugarcane production causes changes in the soil physical attributes, and geostatistics makes it possible to study the behavior of the spatial distribution of these variations. This study aimed to evaluate the behavior of the spatial distribution of sugarcane yield averages according to the altitude and soil physical attributes along a transect in Goiana, Pernambuco, Brazil. Sugarcane yield averages, altitudes, and soil physical attributes, such as soil bulk density, total porosity, micro and macro porosity, sand (total, coarse, and fine), silt, and clay, in the 0.00-0.20 and 0.20-0.40 m soil layers were determined at 20 m intervals along the transect characterized by a toposequence of Ultisols and Spodosols. Exploratory data analysis was performed with the aid of descriptive statistics. The analysis of spatial dependence was performed using geostatistics. Pairs of semivariances were obtained using the GS+ software. The development and adjustment of the semivariograms were performed using the GEOEAS geostatistical tool. The highest contents of the finest soil particles were found in the lowest sections of the transect, in the 0.20-0.40 m soil layers. The highest amount of macropores was observed in the subsurface soil layer. The areas with the lowest amount of micropores showed the lowest average sugarcane yield, around 32.00 $t.ha^{-1}$. The geostatistical model that best fitted the data set was the spherical model.

Keywords: Spatial distribution. Soil physics. Geostatistics. Spatial variability.

RESUMO - O manejo do solo em áreas com produção de cana-de-açúcar ocasiona modificações nos atributos físicos do solo, e a geoestatística permite estudar o comportamento de distribuição espacial destas variações. O objetivo deste estudo foi avaliar o comportamento da distribuição espacial da produtividade média da cana-de-açúcar, da altitude e dos atributos físicos do solo ao longo um transecto, localizado no município de Goiana, estado de Pernambuco, Brasil. A produtividade média da cana-de-açúcar, a altitude e os atributos físicos do solo: densidade do solo, porosidade total, micro e macro porosidade, areia (total, grossa e fina), silte e argila, nas camadas de 0,00-0,20 e 0,20-0,40 m de profundidade, foram quantificados em 145 pontos com intervalos de 20 m entre os pontos ao longo do transecto caracterizado por uma toposequência de Argissolo e Espodossolo. A análise exploratória dos dados foi realizada por meio da estatística descritiva. A análise de dependência espacial foi realizada por meio da geoestatística. Os pares das semivariâncias foram obtidos utilizando o programa GS^+. A construção e o ajuste dos semivariogramas foram realizados utilizando a ferramenta geoestatística GEOEAS. Os maiores conteúdo de argila e silte foram verificados nos trechos mais baixos do transecto, na camada de 0,20-0,40 m. O maior conteúdo de macroporos foi observado na camada subsuperficial do solo. Os trechos com menor conteúdo de microporos, apresentaram menor produtividade média da cana-de-açúcar, em torno de 32,00 $t.ha^{-1}$. O modelo geoestatístico que melhor se ajustou ao conjunto dos dados foi o esférico.

Palavras-chave: Distribuição espacial. Física do solo. Geoestatística. Variabilidade espacial.

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INTRODUCTION

The sugarcane yield can be directly affected by the action of several combined factors, such as climate, crop variety, management practices, and, mainly, soil conditions. Sugarcane yield is related to the selection of the appropriate variety, rainfall, temperature, and physical, chemical, and biological attributes of the soil (MORINI et al., 2017).

In Pernambuco, Brazil, arable soils with sugarcane are located in the coastal zone (CONAB, 2019). The operations in the use and management of these soils through agricultural practices cause changes, mainly in the physical attributes, such as increased bulk density and decreased total porosity, altering the distribution of pore diameters and water dynamics in the surface and soil profile (VILAS-BOAS et al., 2016).

Changes in soil physical attributes impair the growth and development of sugarcane, as they cause soil disruption, a decrease in pore spaces and aeration, which affects root respiration, in addition to, many times, due to compaction, waterlogging the soil and reducing its drainage capacity (SANTOS et al., 2020).

The distribution of soil on the earth's surface is not uniform, and this characteristic is responsible for the spatial and continuous variation of its attributes. Knowing the spatial variability of soil physical attributes allows for proper management (ALVES et al., 2018). Based on the spatial behavior of these attributes, it is possible to adopt efficient management practices and optimize agricultural yield (DIAS et al., 2017).

The spatial variability of physical attributes can be studied through geostatistics, a tool with relevant applications in characterizing and analyzing spatial variation. Geostatistics stands out as a methodology that provides the geographic location of the estimate made (SILVEIRA JUNIOR et al., 2014) and allows the interpretation of results based on the structure of the natural variability of soil and plant attributes (LUNDGREN; SILVA; FERREIRA, 2017).

The analysis of soil spatial variability and controlling impacts on sugarcane production increases the possibility of estimating crop responses under certain management practices adopted (SOUZA; MARQUES JÚNIOR; PEREIRA, 2014). Through geospatial modeling, it is possible to quantitatively describe the spatial variability of soil and plant attributes, characterize their behavior in agricultural areas, and identify the influence of these attributes on crop yield (SANTOS et al., 2020).

Siqueira, Silva, and Dafonte (2015), in a study on the spatial distribution of electrical conductivity of an Spodosols and sugarcane yield, in a 6.5 ha area with an irregular grid of 90 sampling points, observed spatial dependence for apparent electrical conductivity of soil and crop yield, with ranges of 180.0 and 110.0 m, respectively. These results suggested that the sampling scheme was sufficient to detect the spatial distribution. This study aimed to evaluate the behavior of the spatial distribution of sugarcane yield averages according to the altitude and soil physical attributes along a transect in Goiana, Pernambuco, Brazil.

MATERIAL AND METHODS

The transect of this study is located in an area in the city of Goiana, Zona da Mata Norte region, Pernambuco - Brazil, located 10 km west of the Atlantic Ocean, under the following geographic coordinates 07° 35' 22" S and 34 ° 55' 34” W, and an average altitude of 46 m above sea level (Figure 1).

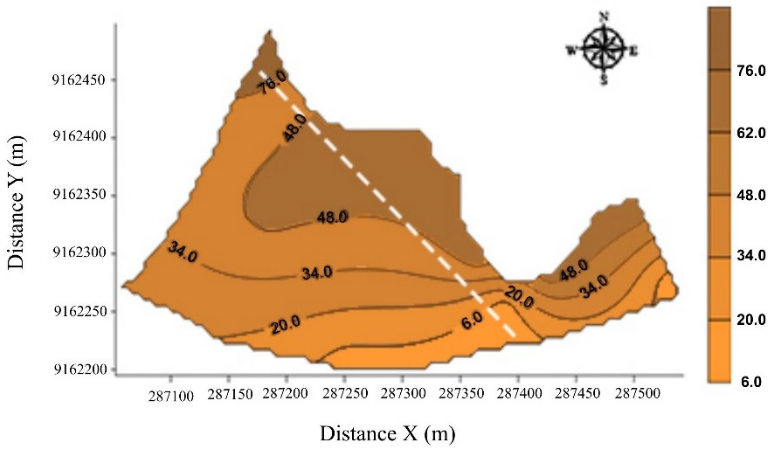


Figure 1. Digital elevation map of the study area and sampling transect location scheme.

For the past 30 years, the area has been managed with sugarcane monoculture, variety RB 86 7515, grown in rainfed conditions with straw burning for harvesting. In the 2019/2020 harvest season, the cultivation was renewed, with the area being plowed, harrowed, and subsequently replanted with sugarcane. The climate in this region is humid tropical, according to the Köppen climate classification, characterized as hot and humid, with an average annual temperature of 25° C and an average annual rainfall of 1800 mm. The study transect has two soil types characterized by a toposequence. The soils are classified as Ultisols and Spodosols (UNITED STATES, 2014). The sampling of sugarcane yield and soil (disturbed and undisturbed samples) was carried out on 11/28/19 at 145 georeferenced points along a 2,900 m transect with a distance of 20 m between points at depths of 0.00-0.20 and 0.20-0.40 m.

Altitude data were collected for each sample point. To estimate the average sugarcane yield, the number of stalks in the sampled transect was multiplied by the average weight of ten stalks (GHELLER et al., 1999). Three ten-meter sugarcane lines were chosen at each sampling point, and the number of stalks was counted to calculate their average weight. Afterward, ten stalks were randomly harvested from the three lines at each point for weighing. The yield - tons per hectare ($t.ha^{-1}$) - was calculated based on the estimated average weight at each sampling point. In the soil samples were analyzed: particle size distribution (total sand, coarse sand, fine sand, clay, and silt) by the densimeter method; bulk density using the volumetric ring method; total porosity, micro and macroporosity using the tension table, as described by

Embrapa (2017).

The exploratory analysis of the data was performed using descriptive statistics to verify the dispersion and central tendency of the studied data set. The main statistical moments were determined: mean, median, standard deviation, coefficients of skewness and kurtosis, and coefficient of variation (CV). Statistica software version 10.0 was used.

In the transect of the study, geostatistics was used to analyze the spatial dependence through adjustments of semivariograms (VIEIRA et al., 2011; SIQUEIRA; SILVA; DAFONTE, 2015) based on the presupposition of stationarity of the intrinsic hypothesis. The GS+ program version 7.0 was used to obtain the semivariance pairs, and the Excel and GEOEAS software spreadsheet was used to construct and fit the semivariograms. The spatial autocorrelation between the sampling points was calculated by the semivariance γ (h), which is estimated by Equation (1),

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

where N (h) is the number of experimental pairs of observations Z (xi), and Z (xi + h) is separated by a distance h.

The premise proposed by Vieira et al. (2011) was fulfilled, which states that if a trend is observed, it must be removed from the data, and the semivariogram adjusted for residuals. A trend analysis was conducted, and a first and/or second-degree polynomial was subsequently adjusted using an electronic spreadsheet. This polynomial was adjusted according to the coordinates for the property values, and the residual was obtained by subtracting the measured value from the value of the polynomial at each point.

After calculating the experimental semivariogram, a theoretical model was fitted to the data by testing the Gaussian, exponential, and spherical models. The model with the highest R^2, a mean close to zero, and a standard deviation close to one was selected. The fitting of a mathematical model to the data allowed the semivariogram parameters to be defined as follows: a) the nugget effect (C_0), which is the value of γ when h = 0; b) the range of spatial dependence (α), which is the distance at which γ(h) remains approximately constant after increasing with h; c) the sill ($C_0 + C_1$), which is the value of γ(h) at the range and approximates the variance of the data, if it exists. The spatial dependence index (SDI) was determined according to Cambardella et al. (1994), based on the ratio (in percentage) of the nugget effect (C_0) concerning the plateau ($C_0 + C_1$), showing: (a) strong dependence when < 25%; (b) moderate dependence when between 25% and 75%, and (c) weak dependence when > 75%.

RESULTS AND DISCUSSION

The Kolmogorov-Smirnov test at a significance level of 5% indicated normality for the soil's physical attributes after removing the outliers by the boxplot method. The average sugarcane yield, altitude, and silt fraction in the 0.00-0.20 and 0.20-0.40 m soil layers presented a frequency distribution of Log normal (Ln) type (Table 1). Siqueira et al. (2015) studied the stationarity of water content in a Spodosols in Goiana (Pernambuco), sampled in a transect with 128 points, and also found an Ln-type distribution for altitude. Altitude is a variable that presents larger scale variations, requiring the adjustment of this data for better comparison.

The mean and median values of the analyzed variables were similar, which suggested a symmetrical data distribution. Exceptions were identified in the altitude data, silt fractions in both soil layers, and clay in the 0.00-0.20 m soil layer. In these cases, the mean value was higher than the median. This occurred because the mean was more sensitive to extreme values, which are on the right side of the distribution, as indicated by the positive sign of the skewness coefficient (0.04) (Table 1).

The absolute values of negative skewness were lower and higher for bulk density in the subsurface layer (0.02) and sugarcane yield (0.70), respectively. Sugarcane yield showed high negative skewness, and altitude had positive skewness (Table 1).

The greatest positive skewness was observed for macroporosity in the surface layer of the soil (0.70), which indicated the presence of a few high values in this transect for this variable compared with the other variables in the study. Total porosity in the 0.00-0.20 m soil layer showed low negative skewness, while microporosity in both soil layers, and TP, in the 0.20-0.40 m soil layer showed low positive skewness (Table 1).

For the soil particle size distribution, the highest positive skewness was observed for the silt in the superficial layer (1.05). Total sand showed negative skewness (-0.53) in the surface soil layer (Table 1). Rodrigues et al. (2017), evaluating the spatial variability of moisture and soil particle size fractions in an area of banana production, found positive skewness for clay and silt fractions and negative for total sand.

The average sugarcane yield in the transect of this study was higher than the average sugarcane yield in the state of Pernambuco during the 2019/2020 crop season, which was 52.77 $t.ha^{-1}$ (CONAB, 2019). Also, it was higher than the yield found by Siqueira, Silva, and Dafonte (2015) in an area adjacent to the transect of this study (75.54 $t.ha^{-1}$), demonstrating that sugarcane yield varies considerably with changes in soil along the landscape.

Table 1. Statistical parameters for sugarcane yield, altitude, and soil physical attributes analyzed in the 0.00-0.20 and 0.20-0.40 m soil layers along the studied transect.

Variables	Layer (m)	Mean	Median	Min.[6]	Max.[7]	Skew.[8]	Kurt.[9]	CV[10]	D[11]
Yield[1]	_	53.23	55.58	42.46.52	57.27	-0.70	-0.65	7.86	0.20 Ln
Altitude[2]	_	46.24	41.00	6.00	78.00	0.04	-1.44	48.79	0.15 Ln
Bd[3]	0.00 - 0.20	1.60	1.61	1.31	1.87	-0.15	-0.43	7.20	0.04 n
	0.20 - 0.40	1.63	1.63	1.29	1.93	-0.02	-0.35	8.08	0.04 n
TP[4]	0.00 - 0.20	43.60	44.29	28.57	57.65	-0.18	-0.40	13.38	0.07 n
	0.20 - 0.40	42.46	42.76	28.75	57.92	0.04	-0.33	14.41	0.06 n
Mi[4]	0.00 - 0.20	40.62	40.92	26.84	57.35	0.09	-0.21	15.33	0.04 n
	0.20 - 0.40	39.11	39.43	24.79	54.48	0.05	-0.39	16.15	0.07 n
Ma[4]	0.00 - 0.20	2.87	2.65	1.02	5.41	0.70	-0.16	34.19	0.14 n
	0.20 - 0.40	3.20	3.13	1.25	5.42	0.21	-0.50	29.20	0.07 n
Total Sand[5]	0.00 - 0.20	857.04	862.00	724.00	958.00	-0.53	-0.07	6.08	0.09 n
	0.20 - 0.40	853.52	858.00	740.00	950.00	-0.37	-0.24	5.59	0.07 n
Coarse Sand[5]	0.00 - 0.20	634.65	636.00	506.00	754.00	-0.16	-0.49	9.20	0.053 n
	0.20 - 0.40	631.99	634.00	474.00	806.00	-0.16	-0.36	10.62	0.050 n
Fine Sand[5]	0.00 - 0.20	222.98	224.00	152.00	294.00	0.07	-0.47	12.78	0.054 n
	0.20 - 0.40	212.50	214.00	148.00	268.00	-0.19	-0.53	13.04	0.046 n
Silt[5]	0.00 - 0.20	19.36	10.00	0.00	72.00	1.05	-0.09	97.68	0.20 Ln
	0.20 - 0.40	22.59	18.00	0.00	80.00	0.78	-0.13	81.89	0.18 Ln
Clay[5]	0.00 - 0.20	119.40	114.00	34.00	197.60	0.04	-0.24	28.99	0.07 n
	0.20 - 0.40	119.24	122.00	42.00	202.00	0.12	-0.29	30.95	0.08 n

[1]Sugarcane yield ($t.ha^{-1}$); [2]Altitude (m); [3]Soil bulk density ($kg.dm^{-3}$); [4]Total porosity, Microporosity, Macroporosity (%); [5]Total Sand, Coarse Sand, Fine Sand, Silt, and Clay ($g.kg^{-1}$); [6]Minimum; [7]Maximum; [8]Skewness; [9]Kurtosis; Coefficient of Variation; [11]Maximum deviation from the normal distribution; n: data with normal distribution by the Kolmogorov-Smirnov test at 5% significance level; Ln: data with Lognormal distribution by the Kolmogorov-Smirnov test at 5% significance.

The average soil bulk density (Bd) in the two layers of the toposequence transect (Ultisols and Spodosols) in this study was around 1.60 $kg.dm^{-3}$. Reichert, Reinert and Braida (2003). suggest that for clayey soils, density values in the range of 1.40 to 1.60 $kg.dm^{-3}$ may limit root growth of crops, while for sandy soils, this range varies between 1.60 to 1.80 $kg.dm^{-3}$. According to Batista et al. (2019), soil bulk density is one of the physical properties that characterizes soil compaction status. Therefore, it was possible to characterize the spatial distribution behavior of soil density in the area of this study and its compaction influence on sugarcane yield.

The results indicated that microporosity was higher than macroporosity in both soil layers, with average values of 40.62% and 39.11% for microporosity and 2.87% and 3.20% for macroporosity. Due to this ratio, it is common to have greater water retention in denser soils. Furthermore, the reduction of macroporosity and the increase of microporosity may indicate greater limitations in terms of the arrangement of pores in the soil. These changes in soil porosity can be attributed to the presence of organic matter and the fact that the study area is a sediment deposition area.

The coefficient of variation (CV) was low for sugarcane yield (7.86%), for soil bulk density (Bd), in layers of 0.00-0.20 m (7.20%) and 0.20-0.40 m (8.08%), and for the fractions total sand (6.08%), (5.59%), and coarse sand (9.20%), (10, 62%) in layers of 0.00-0.20 and 0.20-0.40 m, respectively. A moderate variation was observed for altitude and other soil physical attributes along the transect, except for the silt fraction, which presented a high CV > 80% (Table 1). The low and moderate variability found for the soil particle size fractions in this study may be associated with using agricultural machinery in the transect and the transport and sedimentation processes, providing greater homogenization of the particle size fractions (SANTOS et al., 2018).

Patterns of spatial variability of sugarcane yield, altitude, and soil physical attributes are shown in Figure 2. According to its low coefficient of variation, sugarcane yield showed a constant spatial distribution along transect stretches, verified in Table 1. Most sampling points showed a yield above 50 $t.ha^{-1}$. The lowest values for sugarcane yield, below 35 $t.ha^{-1}$, were found around 1600 to 1800 m from the transect, and the highest values were observed in the first 100 m of the transect, a stretch with the highest altitudes (Figure 2A).

Bulk density showed similar spatial variations for the studied layers. The highest spatial variation was found for the

0.20-0.40 m layer in the section about 700 m from the transect. Macroporosity ranged from 1.02 to 14.70% and 1.25 to 8.13% in layers of 0.00-0.20 and 0.20-0.40 m, respectively (Figures 2B and 2C). It is possible that the low values of macroporosity are related to deformations in the soil macropores or to pore closure by the silt fraction. Despite its low content, this fraction may have contributed to soil compaction with the agricultural practices that involved heavy implements and machinery (BAQUERO et al., 2016). Greater spatial variation of macropores was observed in the soil surface layer in the 860 to 880 m section of the transect. In contrast, the smallest variations were observed in the subsurface soil layer, mainly in the lower sections of the transect (Figures 2B and 2C).

The spatial distributions of total porosity and microporosity followed the same trend, both in the surface layer (0.00-0.20 m) and in the subsurface layer (0.20-0.40 m) of the soil along the transect. The lowest values of total porosity and microporosity were observed in the depression section of the transect (about 1600 m) in the 0.00-0.20 soil layer (Figures 2D and 2E).

The total sand and coarse sand fractions showed similar spatial variations for both layers of the toposequence along the entire transect.

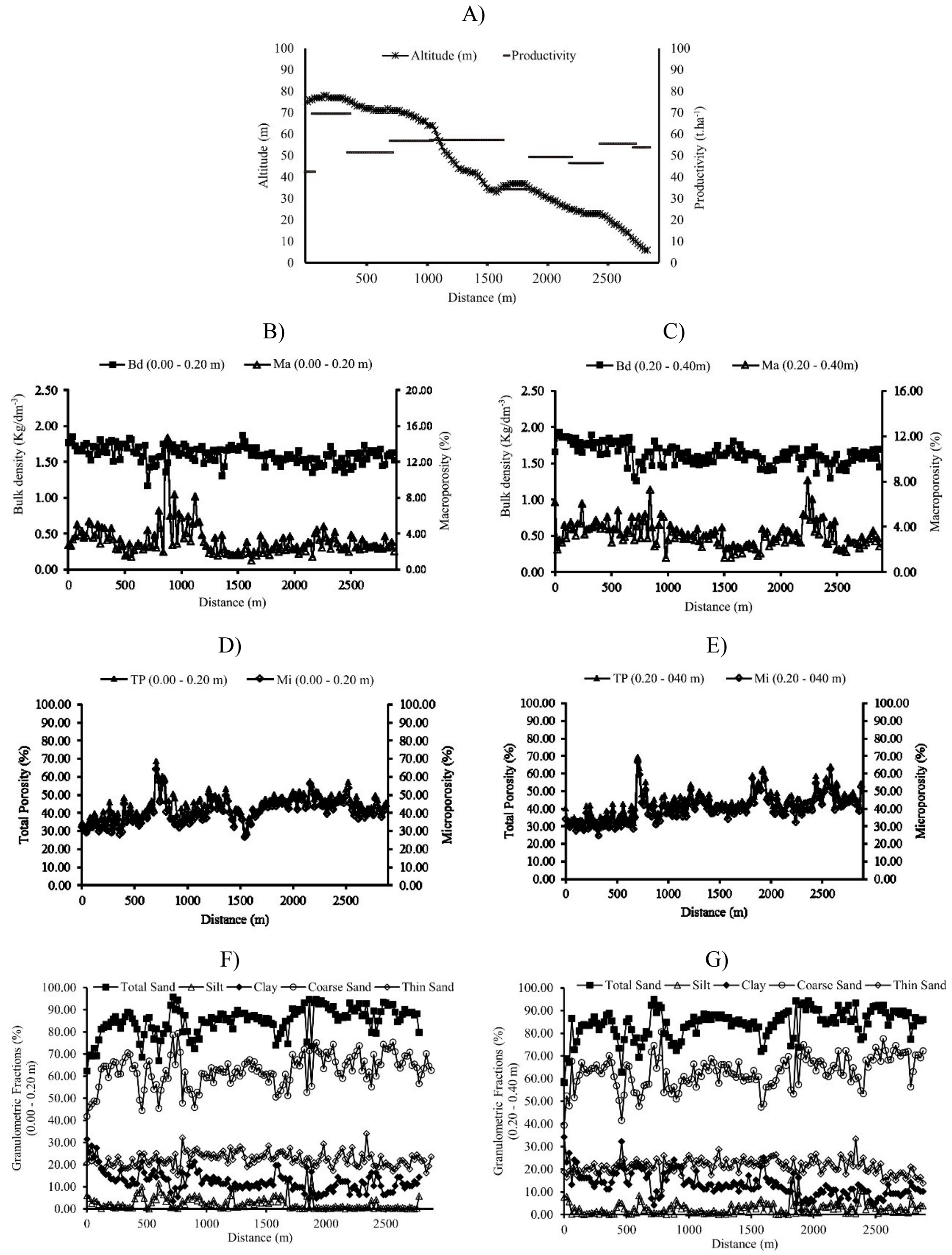


Figure 2. Spatial distribution of sugarcane yield ($t.ha^{-1}$), altitude (m), and soil physical attributes in layers of 0.00-0.20 and 0.20-0.40 m along the 145 sampling points.

Higher spatial variations were verified, for these soil fractions, in the stretch between 500 and 1000 m of the transect. The spatial distribution behavior of fine sand followed the behavior trend of finer soil particles, especially clay, except at the beginning of the transect, characterized by the highest stretch (Figures 2F and 2G).

The silt content reached 0.00% in some sections of the toposequence and showed less spatial variability in the final section of the transect, mainly in the surface layer of the soil. The greatest spatial variability of clay and its highest contents were verified in the subsurface soil layer, in the stretches characterized by the presence of Ultisols of the toposequence (Figures 2F and 2G). This behavior can be explained by Ultisols having a textural B horizon, with an increase of clay over the depth (SANTOS et al., 2018).

The experimental semivariograms for sugarcane yield, altitude, and soil physical attributes (Bd, PT, Mi, and Ma), showed a spatial dependence structure, which meant that the data distribution along the transect was not random for these variables (Figures 3 and 4).

The chosen models were those that presented their adjustments with a mean closest to zero and a standard deviation close to one, according to the Jack-Knifing cross-validation technique, explained by Montenegro and Montenegro (2012). Most of the variables analyzed showed a better fit of the semivariograms with the spherical model.

For the soil particle size fractions, only the fraction corresponding to fine sand showed spatial dependence with adjustment to the exponential model, while the other particle size fractions showed a pure nugget effect (PNE); that is, it was not possible to detect spatial dependence for most of the particle size fractions along the studied transect (Table 2 and Figure 5).

The PNE is due to the absence of spatial dependence among the evaluated variables due to the distance used not being sufficient to identify the spatial variability of the studied attributes (MORAES et al., 2016). As highlighted by Cambardella et al. (1994), uncertainties in the measurements, such as small unobserved variations and the sampling distance used, influence the data statistics, which can lead to outliers and influence the stationarity of the geostatistics.

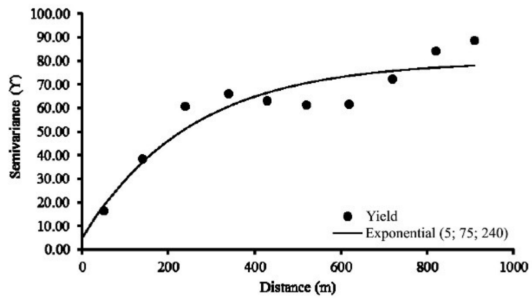
Sugarcane yield presented a semivariogram adjusted by the exponential model (Figure 3A). However, Siqueira, Silva, and Dafonte (2015), analyzing the spatial relationship between sugarcane yield, electrical conductivity, and soil texture, found the best fit of the semivariogram for sugarcane yield with the Gaussian model and highlighted that this adjustment might be linked to the presence of concave relief in the study area.

As predicted, the experimental altitude semivariogram showed a spatial trend, so removing the trend and working with the residual data was necessary. The tendency for the altitude semivariogram occurred due to the altimetric distribution behavior that decreased along the transect. Removing the trend from the semivariogram was necessary and important in the present study due to the non-stationarity of the data; that is, the data showed a continuous increase with distance; this procedure was essential for the elaboration of the semivariogram with the threshold (VIEIRA et al., 2011).

After removing the trend, the altitude had its semivariogram better adjusted to the Gaussian model (Figure 3B). This adjustment can be explained by the altitude showing gradual variations along the transect since the Gaussian model is representative of extremely continuous phenomena, indicating smooth variation at small observation distances (SILVA et al., 2019).

Except for microporosity, in the two depth layers, which had semivariograms adjusted to the exponential model, the other physical attributes (Bd, TP, and Ma) had experimental semivariograms adjusted to the spherical model (Figure 4). Cambardella et al. (1994) point out that the spherical model is characteristic of variables that present more abrupt changes over large distances, being used to describe relatively irregular phenomena, such as the soil physical attributes.

A)



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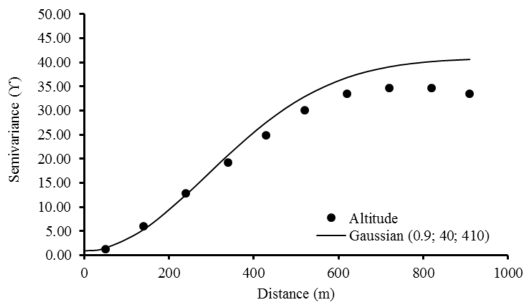

Figure 3. Semivariograms adjusted for sugarcane yield and altitude along the transect.

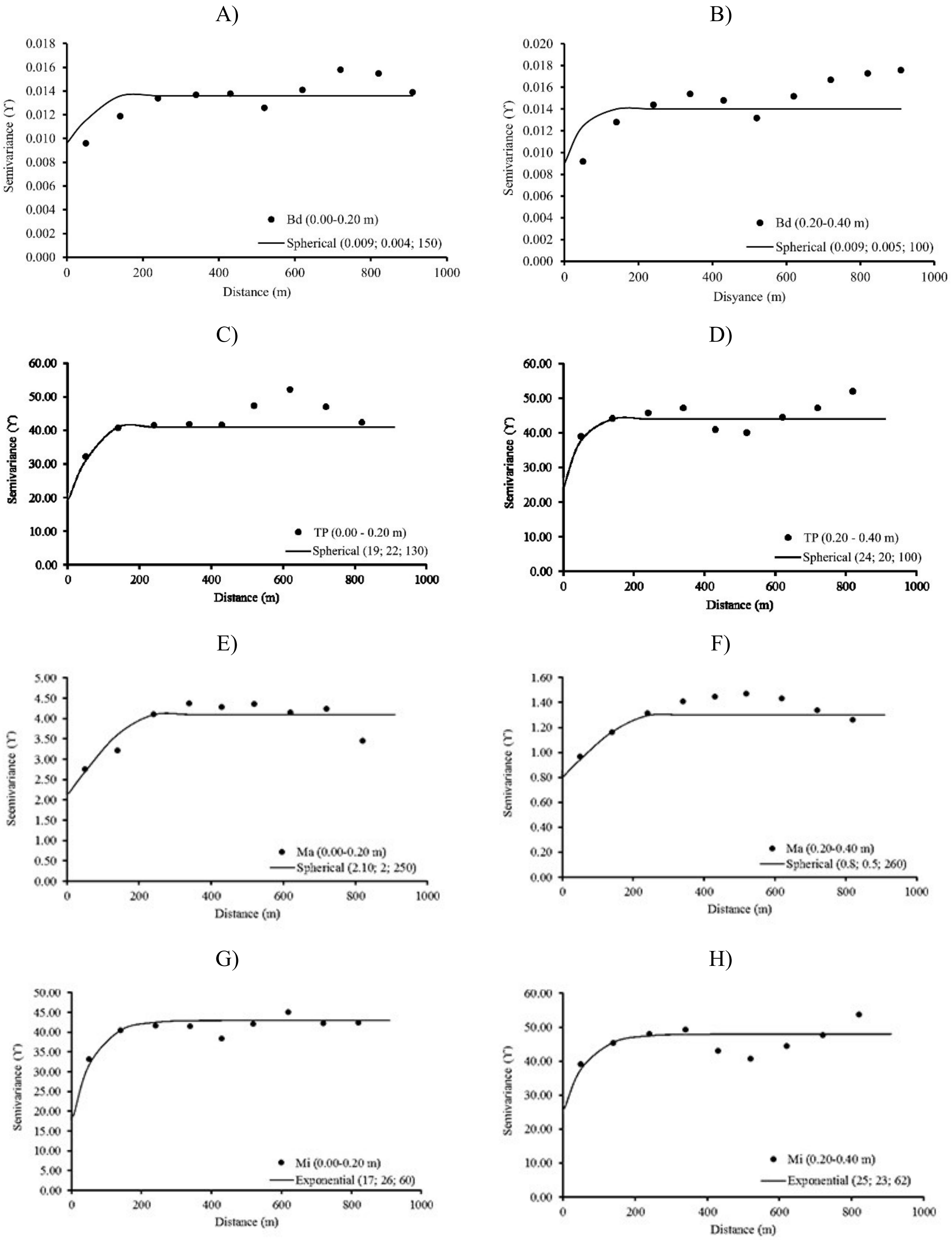

Figure 4. Semivariograms adjusted for bulk density, total porosity, macroporosity, and microporosity, in the 0.00-0.20 and 0.20-0.40 m soil layers along the transect, respectively.

Table 2. Semivariogram adjustment parameters for sugarcane yield data, altitude, and soil physical attributes analyzed in the 0.00-0.20 and 0.20-0.40 m soil layers along the transect.

Variables	layer (m)	C_0	C_1	a (m)	model	R²	SDI (%)	Validation Parameters of Semivariograms	
								Mean	Standard Deviation
Yield ($t.ha^{-1}$)	_	5.00	75.00	250.00	Exp.	0.86	6.25	0.04	1.10
Altitude (m)	_	0.90	40.00	410.00	Gau.	0.91	2.20	0.07	0.87
Bd ($kg.dm^{-3}$)	0.00-0.20	0.009	0.004	150.00	Esf.	0.43	70.59	0.004	0.98
	0.20-0.40	0.009	0.005	100.00	Esf.	0.15	64.29	0.004	0.99
TP (%)	0.00-0.20	19.00	22.00	130.00	Esf.	0.44	46.34	0.003	0.95
	0.20-0.40	24.00	20.00	100.00	Esf.	0.38	54.55	0.006	1.00
Ma (%)	0.00-0.20	2.10	2.00	250.00	Esf.	0.57	51.22	0.005	0.97
	0.20-0.40	0.80	0.50	260.00	Esf.	0.63	61.54	0.001	1.03
Mi (%)	0.00-0.20	17.00	26.00	60.00	Exp.	0.51	39.54	0.001	1.02
	0.20-0.40	25.00	23.00	62.00	Exp.	0.40	52.08	0.006	0.98
Total Sand ($g.kg^{-1}$)	0.00-0.20	*	*	*	PNE	*	*	*	*
	0.20-0.40	*	*	*	PNE	*	*	*	*
Coarse Sand ($g.kg^{-1}$)	0.00-0.20	*	*	*	PNE	*	*	*	*
	0.20-0.40	*	*	*	PNE	*	*	*	*
Fine Sand ($g.kg^{-1}$)	0.00-0.20	8.00	2.00	250.00	Exp.	0.73	80.00	0.002	1.01
	0.20-0.40	6.80	4.00	250.00	Exp.	0.26	92.96	0.01	1.50
Silt ($g.kg^{-1}$)	0.00-0.20	*	*	*	PNE	*	*	*	*
	0.20-0.40	*	*	*	PNE	*	*	*	*
Clay ($g.kg^{-1}$)	0.00-0.20	*	*	*	PNE	*	*	*	*
	0.20-0.40	*	*	*	PNE	*	*	*	*

C_0: Nugget effect; C_1: Structural variance; a: Range; R²: Coefficient of determination; GDE: Degree of spatial dependence. *Geostatistical adjustment was not allowed; Exp.: Exponential; Gau.: Gaussian; Sph.: Spherical; PNE: Pure Nugget Effect.

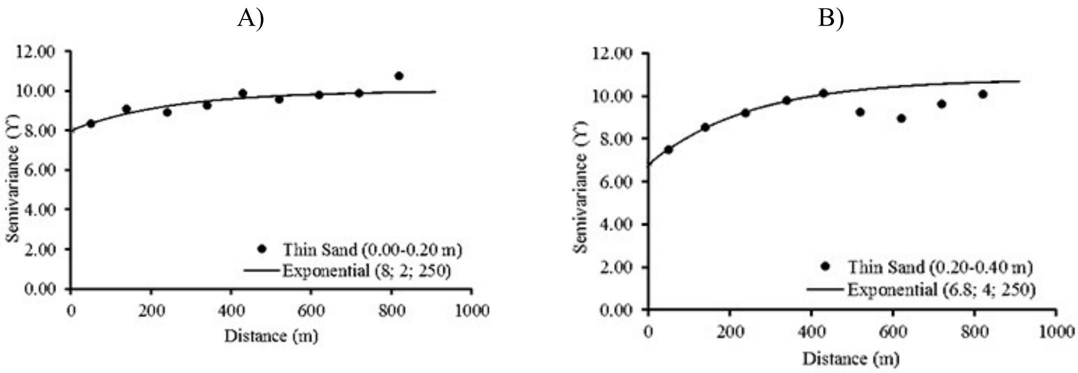

Figure 5. Semivariograms adjusted for fine sand fraction in the 0.00-0.20 and 0.20-0.40 m layers along the transect, respectively.

Ribeiro et al. (2016), when evaluating the behavior of the spatial variability of soil moisture, density, and porosity in the Tabuleiro Costeiro, verified spatial dependence for these variables with a better fit with the spherical model. Sucuru et al. (2019) verified that the spherical and exponential models provided the best estimates of spatial variability for the soil physical attributes in the study of the spatial structure of the physical and chemical attributes along four transects.

In the semivariogram study, the range represents the scale of spatial dependence between sampled points (SILVA et al., 2020). The smallest range was found for microporosity in the 0.00-0.20 m layer, while the largest range was observed for altitude, with values of about 60.0 m and 410.0 m, respectively (Table 2). These results indicate that up to these distances, microporosity and altitude were spatially dependent, and beyond these distances, samples became independent (Figures 3B and 4G). The range is an important measure for planning and experimental evaluation, helping to define the sampling procedure. It indicates the maximum distance within which the analyzed variable is correlated, ensuring that all neighboring points are so similar that they can be used to estimate variable values that are at any other point within its domain (SOUZA; MARQUES JÚNIOR; PEREIRA, 2014).

The lowest values of C0 were verified for the soil bulk density (0.009) in the two soil layers (Table 2), which indicated that the spatial dependence for this variable along the transect was better represented when compared with the sugarcane yield, altitude, and other soil physical attributes. The nugget effect (C_0) represents the discontinuity of the semivariogram for distances smaller than the smallest distance between sampling points. Part of this discontinuity may also be due to measurement errors, but it is impossible to quantify which contributes more, whether measurement errors or variability on a smaller scale than that sampled (ISAAKS; SRIVASTAVA, 1989).

Ribeiro et al. (2016) also found a lower value of C_0 (0.003) for soil bulk density when evaluating the behavior of the spatial variability of soil physical attributes of Tabuleiro Costeiro. As well as Monroy-Rodríguez, Álvarez-Herrera and Alvarado-Sanabria (2017), who, when determining the spatial distribution of soil physical attributes and their relationship with compaction in a transect, found C0 equal to 0.019, the lowest value among the other physics attributes analyzed.

The spatial dependence index was determined according to the classification by Cambardella et al. (1994) and indicated strong spatial dependence (SDI < 25%) for sugarcane yield (6.25%) and altitude (2.20%) and weak spatial dependence (SDI > 75%) for the fine sand fraction, 80.00% and 92.96%, in the 0.00-0.20 and 0.20-0.40 m soil layers, respectively. Most soil physical attributes showed moderate spatial dependence (25% > SDI < 75%) (Table 2). Variables that show a strong degree of spatial dependence are more influenced by intrinsic attributes of the soil, that is, factors related to soil formation (mineralogy and particle size). So, moderate and weak spatial dependencies may be related to human activities, such as plowing and harrowing (CAMBARDELLA et al., 1994).

These results are important to understand how different soil attributes vary spatially and what factors may influence these variations. Moreover, they can assist in the development of more efficient and precise management strategies for sugarcane cultivation.

CONCLUSIONS

The presence of greater particle aggregation in the subsurface layer of soil (0.20-0.40 m) was associated with higher macropore content, which may be related to the soil type characteristics of the toposequence transect. The accumulation of finer soil particles (fine sand, clay, and silt) in the lower sections of the transect led to a reduction in microporosity in the 0.20-0.40 m layer, which may explain the decrease in sugarcane yield in these sections due to compaction.

The spatial distributions of average sugarcane yield and altitude were described by strong spatial continuity along the transect, with a better fit to exponential and Gaussian models, respectively. A moderate spatial continuity along the transect described the spatial distributions of soil physical attributes (soil bulk density, total porosity, microporosity, and macroporosity) with a better geostatistical fit to the spherical model.

The geostatistics technique was a useful tool to detect the spatial dependence of sugarcane yield, altitude, and soil physical attributes (soil bulk density, total porosity, microporosity, and macroporosity) in the two studied soil layers. However, no spatial dependence was observed for most of the soil particle size fractions, and it is recommended to decrease the distance between the transect sampling points to verify a possible spatial continuity for these soil fractions.

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