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Spatial variability of physical attributes of a Spodosol and sugarcane yield[1]

Variabilidade espacial de atributos físicos de um Espodossolo e da produtividade da cana-de-açúcar

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HIGHLIGHTS:

Total porosity, microporosity and macroporosity of the soil did not show spatial dependence.
Among the soil granulometric fractions, only the clay present in the 0.20-0.40 m layer showed spatial dependence.
Sugarcane yield was higher in points with lower bulk density and higher total soil porosity.

ABSTRACT: Agricultural practices promote alterations in the physical properties of the soil, causing changes in its bulk density, porosity, distribution of pore diameter and water retention, which influences the availability to the plants. Precision agriculture acts as a tool that assists in soil management, favoring agricultural yield. The objective of this study was to evaluate the influence of the spatial variability of the physical attributes of a Spodosol on sugarcane yield. Soil sampling and crop yield evaluations were performed at 90 randomly chosen points in the experimental area. Disturbed and undisturbed samples were collected in the soil layers of 0.00-0.20 and 0.20-0.40 m to analyze the attributes: particle size, bulk density, field capacity, total porosity, macroporosity and microporosity. The highest sugarcane yields were observed in regions with more aerated soil, with lower bulk density and higher total porosity, and with greater water retention capacity in the 0.00-0.20 m layer. It was not possible to detect spatial dependence for the granulometric fractions of the soil with the sampling scheme used, except for the clay in the 0.20-0.40 m layer. The spherical model was the one that best fitted to the set of data of the studied variables.

Key words: precision agriculture, spatial dependence, geostatistics, soil physics

RESUMO: As práticas agrícolas promovem alterações nas propriedades físicas do solo, ocasionando modificações na sua densidade, porosidade, na distribuição do diâmetro dos poros e na retenção de água pelo solo que influencia na disponibilidade às plantas. A agricultura de precisão atua como uma ferramenta que auxilia no manejo do solo favorecendo a produtividade agrícola. Dentro desta lógica, o objetivo do presente estudo foi avaliar a influência da variabilidade espacial dos atributos físicos de um Espodossolo na produtividade da cultura de cana-de-açúcar. As amostragens do solo e da produtividade da cultura foram realizadas em 90 pontos escolhidos aleatoriamente na área experimental. Foram coletadas amostras deformadas e não deformadas nas camadas de solo de 0,00-0,20 e 0,20-0,40 m, a fim de analisar os atributos: textura, densidade do solo, umidade na capacidade de campo, porosidade total, macro e microporosidade. As maiores produtividades de cana-de-açúcar foram observadas em regiões com solo mais aerado, com menor densidade do solo e maior porosidade total, e com maior capacidade de retenção de água na camada de 0,00-0,20 m. Não foi possível detectar dependência espacial para as frações granulométricas do solo com o esquema de amostragem utilizado, exceto para a argila na camada de 0,20-0,40 m. O modelo esférico foi o que melhor se ajustou ao conjunto dos dados das variáveis estudadas.

Palavras-chave: agricultura de precisão, dependência espacial, geoestatística, física do solo

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Introduction

Sugarcane yield can be influenced by the integration of several factors that act directly on the crop, including soil physical conditions. Even in an apparently homogeneous area, the physical attributes of the soil show spatial variability, since the soil is formed by a sum of distinct components, which naturally result in a heterogeneous product from the point of view of its characteristics and properties (Gilbert et al., 2015).

In areas with sugarcane cultivation, several soil preparation operations are necessary for planting with the use of agricultural implements and equipment that can cause compaction, degradation and modification of soil structure (Jimenez et al., 2021). Therefore, quantifying the physical attributes of the soil and analyzing its spatial variability is essential for the most adequate decision-making regarding its preparation and management, with the objective of increasing the yield of the crop (Souza et al., 2020).

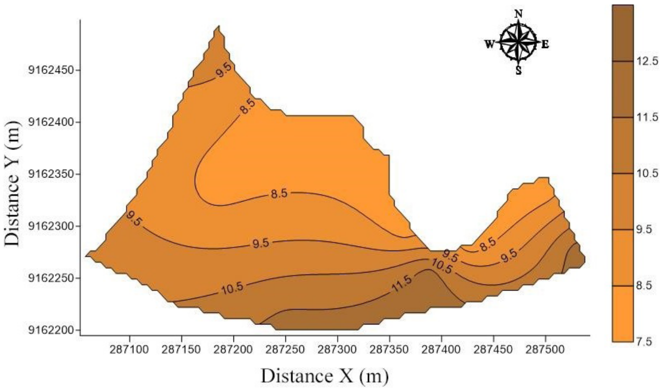
By mapping information about yield and physical conditions of the soil, precision agriculture works as a system that improves the practices adopted in agricultural production. Precision agriculture makes it possible to delimit specific management zones that maximize land use through the creation of maps (Ouazaa et al., 2022).

Santos et al. (2020), when studying the spatial behavior of the physical properties of the soil cultivated with sugarcane, observed spatial dependence for the properties and for the crop. In a study on the spatial variability of penetration resistance in the mechanized sugarcane harvesting system, Alves et al. (2019) detected spatial dependence for the physical attributes in different layers.

Given the importance of soil management in agricultural production areas and the existing relationship between the physical attributes of the soil and the yield of sugarcane, this study becomes relevant because it has as a case study an area of the Zona da Mata Norte of Pernambuco state, Brazil, until then not studied in the perspective of the association of the geospatial modeling to quantitatively describe the spatial variability of the physical attributes of the soil and of sugarcane.

Material and Methods

The experiment was carried out in the city of Goiana (Zona da Mata Norte of Pernambuco state, Brazil) in a plot of the Santa Teresa Sugar Mill, whose geographic coordinates are: 07° 34’ 25” S and 34° 55’ 39” W. The study area has 6.5 ha and an average altitude of 9.5 m (Figure 1).



WGS 84 is the coordinate reference system

Figure 1. Topographic map of the experimental study area in Goiana, Pernambuco state, Brazil

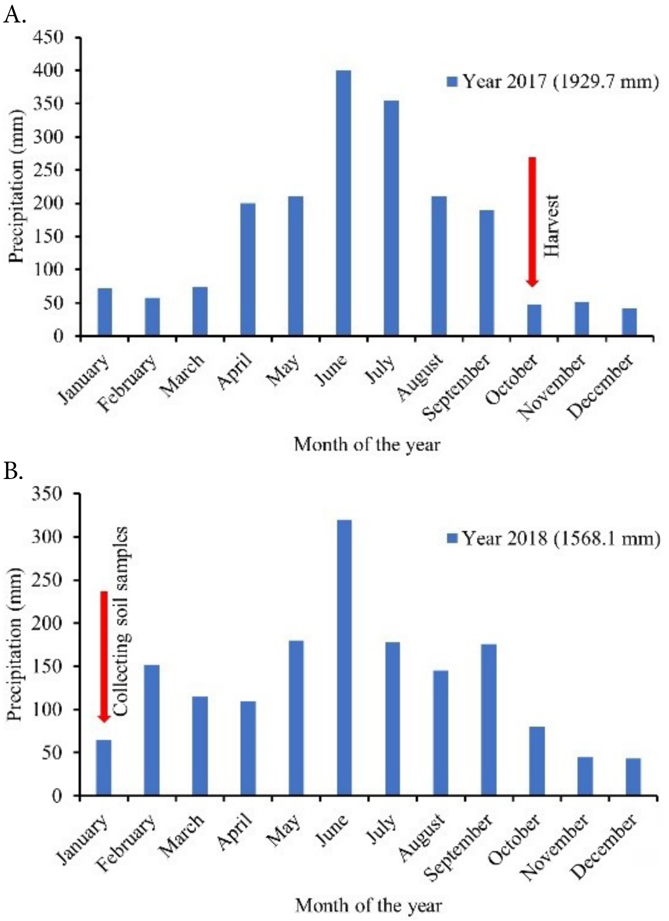


Figure 2. Precipitation in the municipality of Goiana, PE, Brazil, during the sugarcane harvesting period (A) and soil sampling (B)

The climate of the region is humid tropical of the As’ type, according to Köppen’s climate classification, which is characterized by being hot and humid, with annual rainfall of approximately 2000 mm from autumn to winter, concentrated between the months of May to July (Figure 2), and with average annual temperatures around 24 °C.

In the last 30 years, the studied area has been managed with the sugarcane crop (*Saccharum officinarum* L.) of the RB86 7515 variety, cultivated under rainfed conditions, with burning of the straw carried out for harvesting. Therefore, it is an area of great importance in the regional context. The planting of this crop was done with spacing of 1 m between rows.

The soil in the area is classified as Spodosol (United States, 2014), which corresponds to a Espodossolo in Brazil (Siqueira et al., 2015b), and its physical characterization and organic matter content are shown in Table 1.

The sugarcane harvest was carried out in October 2017 and the soil sampling in January 2018; this period followed the availability schedule of Santa Teresa Sugar Mill. Soil and plant sampling (biometry and harvest) were carried out at 90 georeferenced points, randomly chosen in the experimental area (Figure 3). This sampling scheme was chosen because it satisfactorily covered a large set of distances between the

Table 1. Physical characterization and organic matter content for the Spodosol, in Goiana, Pernambuco state, Brazil, after collecting soil samples

Soil layer (m)	Particle size ($g\ kg^{-1}$)			Organic matter ($g\ kg^{-1}$)
	Clay	Silt	Sand	
0.0-0.20	253.20	33.91	712.89	17.50
0.20-0.40	253.38	26.87	719.76	7.50

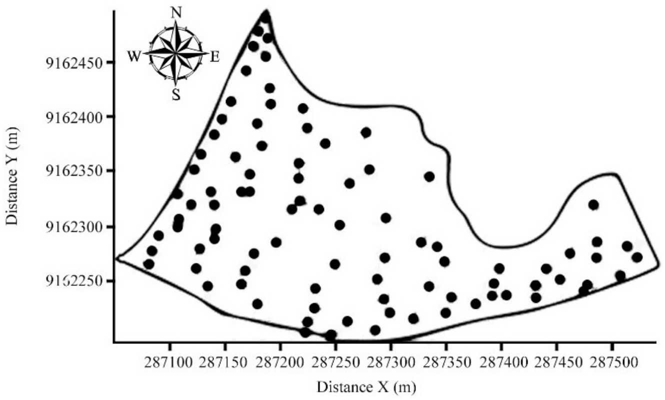


Figure 3. Location of sampling points in the study area

samples and because of the practicality of operationalizing soil sampling in the field, since there is no need to locate the georeferenced point defined by the sampling grid.

At each point, disturbed and undisturbed soil samples were collected in the 0.00-0.20 and 0.20-0.40 m soil layers, and samples of sugarcane stalks were also collected. Undisturbed soil samples were collected using a sampler with a stainless-steel volumetric cylinder, with diameter and height measuring 5 cm, and a volume of approximately 98 cm^3. The dimensions of the volumetric cylinders were measured using a caliper to ensure the accuracy of the analysis.

Soil physical analyses followed methodologies described by Teixeira et al. (2017). Soil granulometric analysis was performed to determine the texture. The disturbed soil samples were placed to dry in the air. Subsequently, they were crushed (ADE), and then sieved using a 2.00 mm mesh sieve, obtaining air-dried fine earth (ADFE). The following attributes of the undisturbed soil samples were determined: bulk density, total porosity, macroporosity, microporosity and field capacity.

The granulometric fractions of the soil (sand, clay and silt) were determined using the Boyoucos hydrometer method, and bulk density measurements were performed using the volumetric ring method. Field capacity was quantified with the aid of a Richards' pressure plate apparatus, based on the ratio between the weight of water in the sample after water equilibrium at a tension of 10 kPa and the volume of the soil.

The calculation of the total porosity of the soil was based on the weight of the saturated sample. Soil microporosity was determined with the aid of a tension table, based on the ratio between the weight of water in the sample after water balance at a tension of 0.60 m.w.g and the volume of the soil, and macroporosity was determined by the difference between total porosity and microporosity of the soil. Sugarcane yield was determined using the method proposed by Gheller et al. (1999), who estimated the total weight of the plot by multiplying the number of culms in the sampled area by the average weight of ten culms. At each sampling point, three rows of sugarcane measuring ten meters were chosen. In each row, the numbers of stems were counted to calculate the average weight. Subsequently, ten culms were randomly picked from the three rows at each point for weighing.

The estimate of average sugarcane yield was based on the methodology proposed by Gheller et al. (1999), according to Eqs. 1 and 2:

Average weight per culm (awpc):

$$\text{awpc} = \frac{\text{wb}}{10} \tag{1}$$

Estimated weight at the sampling point (ws):

$$\text{ws} = \text{awpc} \times \text{tculms} \tag{2}$$

where:

awpc - average weight per culm (kg);
wb - weight of the bundle with 10 culms (kg);
ws - estimated weight at the sampling point (kg); and,
tculms - total of culms counted in the three rows.

From the average weight estimated at each sampling point, the yield per hectare ($Mg\ ha^{-1}$) can be calculated. The descriptive statistical moments such as mean, median, standard deviation, skewness coefficient, kurtosis and variation were determined for the attributes studied. Coefficient of variation values (CV, %) were used to determine data variability according to the classification of Warrick & Nielsen (1980). Statistical analyses used the Statistica 10.0 software (StatSoft, 2011).

By means of semivariogram fitting, geostatistics was used for the analysis of spatial dependence, based on the assumption of stationarity of the intrinsic hypothesis. The GS+ program was used to obtain the semivariance pairs, and the Excel spreadsheet was used to construct and fit the semivariograms.

The premise proposed by Vieira et al. (2011), according to which if a trend is observed, it must then be removed from the data and the semivariogram fitted for residuals, was met. Trend analysis was performed, and a first- and/or second-degree polynomial was later fitted using an electronic spreadsheet. This polynomial was fitted as a function of the coordinates for the property values, and the residual was obtained by the difference between the measured value and the value of the polynomial at each point. However, none of the variables showed a trend in the area of this study. After obtaining the experimental semivariogram, a theoretical model was fitted to the data, testing the spherical, Gaussian and exponential models, choosing the one with the highest R^2. From the fit of a mathematical model to the data, the semivariogram parameters were defined: a) nugget effect (C_0), which is the value of γ when $h = 0$; b) range of spatial dependence (α), which is the distance at which $\gamma(h)$ remains approximately constant, after increasing with increasing h; c) sill ($C_0 + C_1$), which is the value of $\gamma(h)$ from the range and which approximates the variance of the data, if it exists.

The degree of spatial dependence (DSD) was analyzed according to Cambardella et al. (1994), in which the percentage proportion of the nugget effect (C_0) in relation to the sill (C_0

+ C$_1$) is recommended, presenting: (a) strong dependence < 25%; (b) moderate dependence between 25 and 75%; and (c) weak dependence > 75%.

Using the Surfer 11.0 program (Golden Software, 2014), the isoline maps were constructed, allowing the visualization of the distribution and spatial distribution of the studied attributes. For the purpose of spatial comparison between the attributes under study, whenever the presence of a pure nugget effect was detected, isoline maps were constructed using the default parameters of the Surfer program, which is based on a linear interpolation model by simple kriging. In the case of a pure nugget effect, the standard IDW method in Surfer was used.

Results and Discussion

According to the mean and median values of the descriptive statistics results (Table 2), most of the variables followed the normal distribution of frequencies, with results confirmed by the Kolmogorov-Smirnov test at $p \leq 0.05$, except for the moisture at field capacity (θfc), which showed a Lognormal (Ln) frequency distribution for the two soil layers studied.

The variance of sugarcane yield in the studied area was 188.50 Mg ha^{-1} (Table 2). In an analysis performed by Siqueira et al. (2015a) in the same irregular-looking area, the variance of sugarcane yield (2012/2013 harvest) was 241.94 Mg ha^{-1}, showing that yield varied considerably with soil changes over the course of the year of the landscape. This variation in sugarcane yield can be explained by the higher rainfall in the year 2013 compared to the year 2017, in the Zona da Mata Norte of Pernambuco, associated with the age of the sugarcane crops, which had not been renovated in this area since the 2016/2017 harvest.

Soil bulk density (Ds) values (Table 2) were 1.68 and 1.70 Mg m^{-3} for soil layers between depths of 0.00-0.20 and 0.20-0.40 m, respectively. Reichert et al. (2003) proposed that for sandy soils, such as the one in the study, soil bulk density values in the range between 1.70 to 1.80 Mg m^{-3} may limit crop root growth. Batista et al. (2019) point out that Ds is one of the physical properties that characterize the state of soil compaction. In this context, it was possible to characterize in the area of this study the behavior of spatial distribution of soil bulk density and the influence of compaction on sugarcane yield.

With the increase in soil bulk density in the 0.20-0.40 m layer, there was a reduction in total porosity, macroporosity and microporosity (Table 2). The lowest value of soil bulk density in the 0.00-0.20 m layer (Table 2) may be associated with the influence of the higher organic matter content in this superficial layer (Table 1), since the density of organic matter is lower than that of the mineral soil (Mangiere & Tavares Filho, 2019).

The average values of microporosity in both soil layers (38.03 and 36.72%) were higher than those of macroporosity (3.70 and 3.30%). Due to the increase in the proportion of micropores in relation to macropores, it is common to have greater water retention in denser soils. The reduction of macroporosity and the increase of microporosity may show greater limitations regarding the arrangement of pores in the soil. The low macroporosity value may be linked to the effect of organic matter on the soil, and to the fact that the study area is one of sediment deposition (Carter, 1990; Lima et al., 2022).

A soil has ideal aeration conditions for the development of most crops when the macroporosity is greater than 10% (Suzuki et al., 2007; Barbosa et al., 2019). Therefore, the macroporosity values for the two soil layers under study were below these ideal conditions, which suggests that this soil could not have satisfactory aeration conditions for the development of sugarcane. However, it is worth mentioning that this observation is not valid for all crops, since there are plants that are tolerant to low levels of soil aeration, as is the case of sugarcane.

Table 2. Statistical parameters of sugarcane yield data and soil physical attributes

Variables	Soil layer (m)	Mean	Median	Variance	SD[6]	Skewness	Kurtosis	CV[7]	D[8]
Yield (Mg ha^{-1})		99.73	98.24	188.50	13.73	-0.26	0.09	13.77	0.09 n
Ds[1] (Mg m^{-3})	0.00-0.20	1.68	1.67	0.007	0.08	0.13	-0.35	4.91	0.07 n
	0.20-0.40	1.70	1.69	0.005	0.07	0.16	-0.41	4.07	0.07 n
PT[2] (%)	0.00-0.20	41.87	41.52	22.49	4.74	0.43	-0.26	11.33	0.06 n
	0.20-0.40	39.91	40.16	34.40	5.87	-0.07	-0.14	14.7	0.08 n
Mi[3] (%)	0.00-0.20	38.03	37.51	18.80	4.33	0.4	-0.27	11.4	0.05 n
	0.20-0.40	36.72	36.41	32.00	5.66	-0.07	-0.15	15.41	0.08 n
Ma[4] (%)	0.00-0.20	3.70	3.88	2.33	1.53	0.14	-0.82	41.24	0.09 n
	0.20-0.40	3.30	3.29	0.63	0.80	0.45	0.05	23.94	0.07 n
θ_{fc}[5] (%)	0.00-0.20	20.06	19.94	20.86	4.57	0.21	2.14	22.77	0.10 Ln
	0.20-0.40	17.15	18.35	35.78	5.99	-0.9	0.86	34.88	0.14 Ln
Total sand (g kg^{-1})	0.00-0.20	712.80	716.8	1384.42	37.21	-0.23	-0.18	5.22	0.11 n
	0.20-0.40	722.80	724.00	768.94	27.73	-0.17	-0.26	3.84	0.09 n
Fine sand (g kg^{-1})	0.00-0.20	293.73	296.50	863.85	29.39	-0.47	-0.33	10.01	0.09 n
	0.20-0.40	249.98	253.70	1772.66	42.10	-0.21	-0.49	16.84	0.05 n
Coarse sand (g kg^{-1})	0.00-0.20	423.56	421.77	2021.44	44.96	0.02	-0.20	10.62	0.06 n
	0.20-0.40	467.31	468.20	1798.81	42.41	0.04	0.01	9.08	0.05 n
Clay (g kg^{-1})	0.00-0.20	254.62	256.00	727.74	26.98	-0.32	0.21	10.60	0.11 n
	0.20-0.40	253.18	256.00	443.81	18.13	-0.18	-0.50	7.16	0.13 n
Silt (g kg^{-1})	0.00-0.20	32.58	20.00	960.76	30.99	0.92	-0.15	95.15	0.18 n
	0.20-0.40	25.60	20.00	504.71	22.47	0.80	-0.05	87.76	0.15 n

[1] Soil bulk density; [2] Total porosity; [3] Microporosity; [4] Macroporosity; [5] Volumetric moisture at field capacity; [6] Standard deviation; [7] Coefficient of variation; [8] Maximum deviation from the normal distribution; n - Data that showed normal distribution by the Kolmogorov-Smirnov test at $p \leq 0.05$; Ln - Data that showed Lognormal distribution by the Kolmogorov-Smirnov test at $p \leq 0.05$

The θfc data from the study area showed similar mean and variance values (Table 2), especially in the 0.00-0.20 m layer with the highest organic matter content (Table 1).

Higher water retention was identified in the 0.00-0.20 m layer, justified by the higher organic matter content in this surface layer than in the deeper layers (Table 2). Organic matter has a larger specific surface area than sand, resulting in a superior water holding capacity. Thus, the water added to the soil is concentrated close to the organic particles, making it difficult to form water films on the surface of the sand grains (Martins et al., 2021).

The mean values for the textural attributes (total sand, silt and clay – g kg^{-1}) confirmed that the soil in the study area can be classified as having a sandy texture. Although Spodosols normally have parent materials very poor in clay, resulting in soil with a sandy texture along the profile, the value of the clay fraction in the 0.20-0.40 m layer was higher than that of fine sand (Table 2); this result may be associated with the intense turning of the soil during its preparation, which is common in this study area, where the conventional system is used for planting sugarcane. In both soil layers, there was a higher proportion of coarse sand compared to the proportion of fine sand.

The CV values for θfc of the soil in the two layers (Table 2) were classified as median (12% < CV < 62%). Corwin & Lesch (2005) emphasize that θfc is a dynamic soil attribute, which varies with depth and with the positioning in the landscape, generally showing medium to high variability. Siqueira et al. (2015b) in a study in the same area, in 2013, found high CV values, 106.99 and 98.40% for the soil layers of 0.00-0.20 and 0.20-0.40 m, respectively.

The results of the geostatistical analysis (Table 3) allow observing that the data of most attributes showed a pure nugget effect (PNE), indicating that the sampling was not sufficient to detect spatial variability for the distances presented by the random sampling scheme used in this study.

The geostatistical analysis identified spatial dependence for sugarcane yield, which can be indicated by fitting the spherical model to the semivariogram. It was observed that the distribution of data did not occur randomly in space. It is important to note that the semivariograms of the variables analyzed were mostly described by the spherical model, which confirms the predominance of this model in studies in the field of soil science (Siqueira et al., 2015b).

The degree of spatial dependence (DSD) (Table 3) showed strong or moderate dependence for most variables, with the exception of sugarcane yield. Soil Ds in the 0.00-0.20 m layer and the clay fraction in the 0.20-0.40 m layer were the only attributes that showed a strong degree of dependence (< 25%).

Variables that show a strong degree of spatial dependence are more influenced by intrinsic soil properties, that is, factors related to soil formation (mineralogy, granulometry). Thus, moderate and weak spatial dependences may be related to human action on the soil, such as plowing and harrowing (Cambardella et al., 1994). The highest range values were observed for the physical attributes of the soil that showed a strong degree of dependence, soil Ds in the 0.00-0.20 m layer (a = 73 m) and clay in the 0.20-0.40 m layer (a = 70 m) (Table 3). Among the attributes that make up soil texture, clay was the one that showed the lowest variability and greatest spatial continuity, ensuring better accuracy in estimates in non-sampled locations. These results were also expected for sand and silt; however, it was not possible to identify spatial dependence behavior for these granulometric fractions. One of the possible causes of this continuity is associated with the parent material of the soil and the action of the weathering process. The same phenomenon was observed by Campos et al. (2007), who highlighted soil disturbance as a possible particle homogenizer, thus contributing to higher range values.

The contents of total sand, fine sand, coarse sand, silt and clay (Figures 4 and 5) varied in the soil, although there was a predominance of sand contents over the other granulometric

Table 3. Fitting parameters of semivariograms for sugarcane yield and soil physical attributes

Variables	Soil layer (m)	(C_0)[6]	(C_1)[7]	Range - a (m)	Model	(R^2)[8]	DSD (%)[9]
Yield (Mg ha^{-1})		168.00	30.00	70.00	Spherical	0.65	84.85
Ds[1] (Mg m^{-3})	0.00-0.20	0.002	0.01	73.00	Spherical	0.77	16.86
	0.20-0.40	0.006	0.003	35.00	Gaussian	0.70	74.68
PT[2] (%)	0.00-0.20	*	*	*	PNE	*	*
	0.20-0.40	25.00	22.00	57.00	Spherical	0.28	53.19
Mi[3] (%)	0.00-0.20	*	*	*	PNE	*	*
	0.20-0.40	21.00	27.00	55.00	Spherical	0.25	43.75
Ma[4] (%)	0.00-0.20	*	*	*	PNE	*	*
	0.20-0.40	0.008	0.004	25.00	Gaussian	0.44	65.57
Θfc[5] (%)	0.00-0.20	9.80	20.00	56.00	Spherical	0.35	32.89
	0.20-0.40	22.00	16.00	42.00	Spherical	0.17	57.90
Total sand (g kg^{-1})	0.00-0.20	*	*	*	PNE	*	*
	0.20-0.40	*	*	*	PNE	*	*
Fine 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	*	*
Clay (g kg^{-1})	0.00-0.20	*	*	*	PNE	*	*
	0.20-0.40	0.69	3.79	70.00	Exponential	0.85	15.40
Silt (g kg^{-1})	0.00-0.20	*	*	*	PNE	*	*
	0.20-0.40	*	*	*	PNE	*	*

*Pure nugget effect, not allowing fitting (PNE); [1]Soil bulk density; [2]Total porosity; [3]Microporosity; [4]Macroporosity; [5]Volumetric moisture at field capacity; [6]Nugget effect; [7]Sill; [8]Coefficient of determination; [9]Degree of spatial dependence

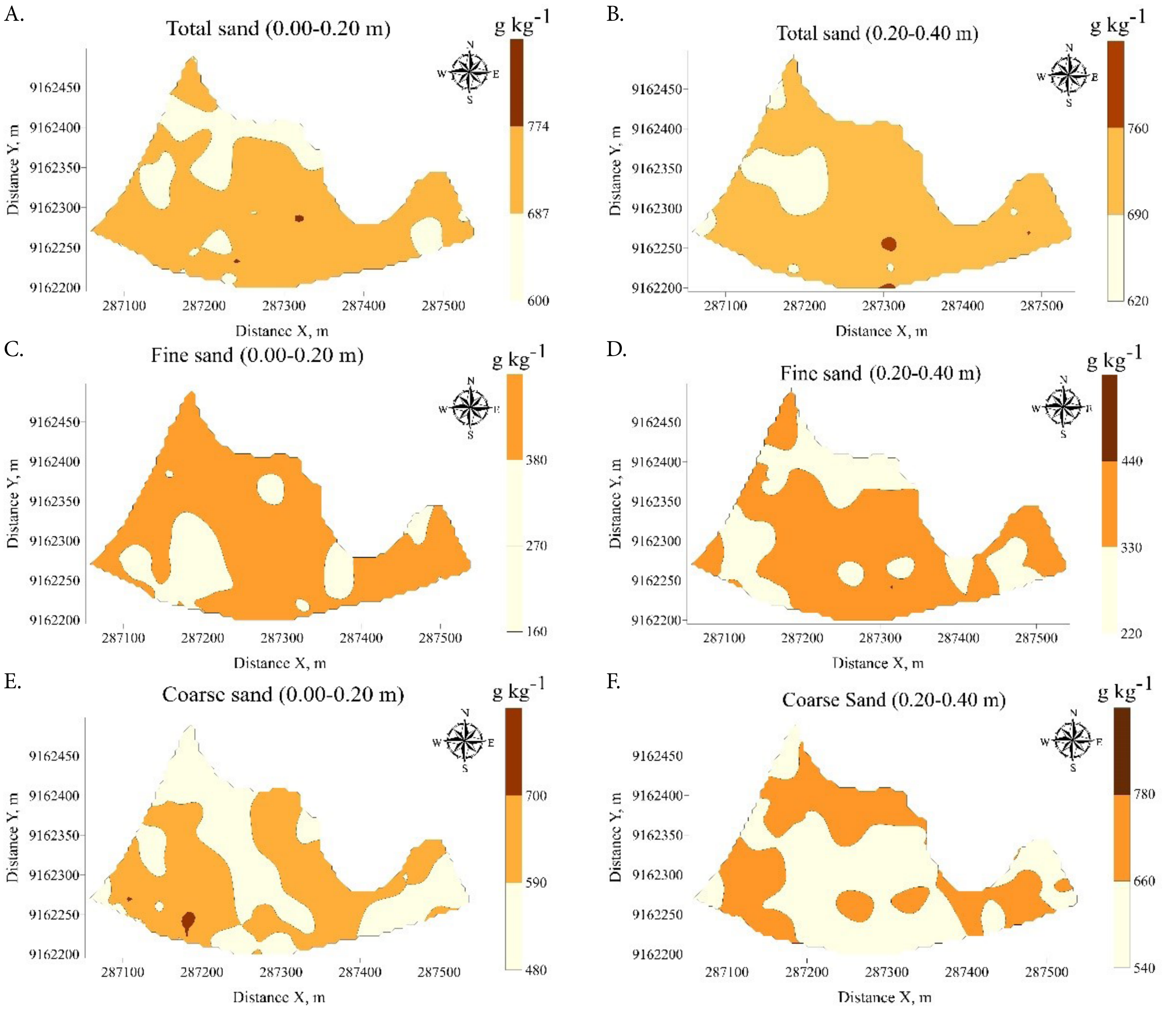


Figure 4. Isoline maps for total sand (A) (0.00-0.20 m) and (B) (0.20-0.40 m), fine sand (C) (0.00-0.20 m) and (D) (0.20-0.40 m), and coarse sand (E) (0.00-0.20 m) and (F) (0.20-0.40 m)

fractions, which can be justified by the lithology developed from sandstones and clay eluviation caused by the characteristic weathering of the soil under study (Campos et al., 2007).

When observing the map of clay in the 0.20-0.40 m layer (Figure 5B), which was the only granulometric fraction that showed spatial dependence, a similar spatial behavior was not verified with that of sugarcane yield (Figure 6C). These results corroborate those obtained by Siqueira et al. (2015a), in the evaluative study of the spatial correlation between textural fractions and sugarcane yield (2012/2013 harvest) in the same area of this study.

Higher clay content was identified in the 0.00-0.20 m soil layer (Figure 5A), and higher organic matter content was also observed for this layer (Table 1). Clay is the most active mineral fraction for the formation of organo-mineral complexes due to its charge and specific surface area. The accumulation of organic matter, due to physical protection, occurs due to the positive influence of aggregation on the formation of a barrier between it and the microorganisms (Martins et al., 2021).

Higher clay contents were found in areas with lower sand contents (Figures 4A, B, 5A and B). These results were similar to those obtained by Cornélio et al. (2021), who stated that the water flow, as it is dependent on the relief, easily mobilizes clay and silt through preferential flow areas. Therefore, in the surface layer of the soil, the spatial distribution of clay (Figure 5A) showed a slight similarity with the distribution of θfc (Figure 6A).

The silt distributions in the area occurred in different ways than those of clay in the two soil layers. A smaller amount of silt was found in the lower parts of the area, and this may be linked to its greater mobility in the soil (Figures 5C and D).

Based on the distribution of the soil bulk density maps (Figures 7A and B), it was found that in the 0.00-0.20 m layer soil bulk density showed lower values (1.3 Mg dm^{-3}) when compared to the layer 0.20-0.40 m (1.6 Mg dm^{-3}). It was possible to highlight that soil management by conventional tillage, which seeks to turn and unpack the soil in the arable layer causes compaction of the deepest layer of soil, due to the weight of the tractor (Cavalcanti et al., 2020; Silva et al., 2020).

Soil bulk density and total porosity showed inverse spatial distribution, as expected. This behavior was evidenced in the 0.00-0.20 m layer, where the highest values of soil bulk density

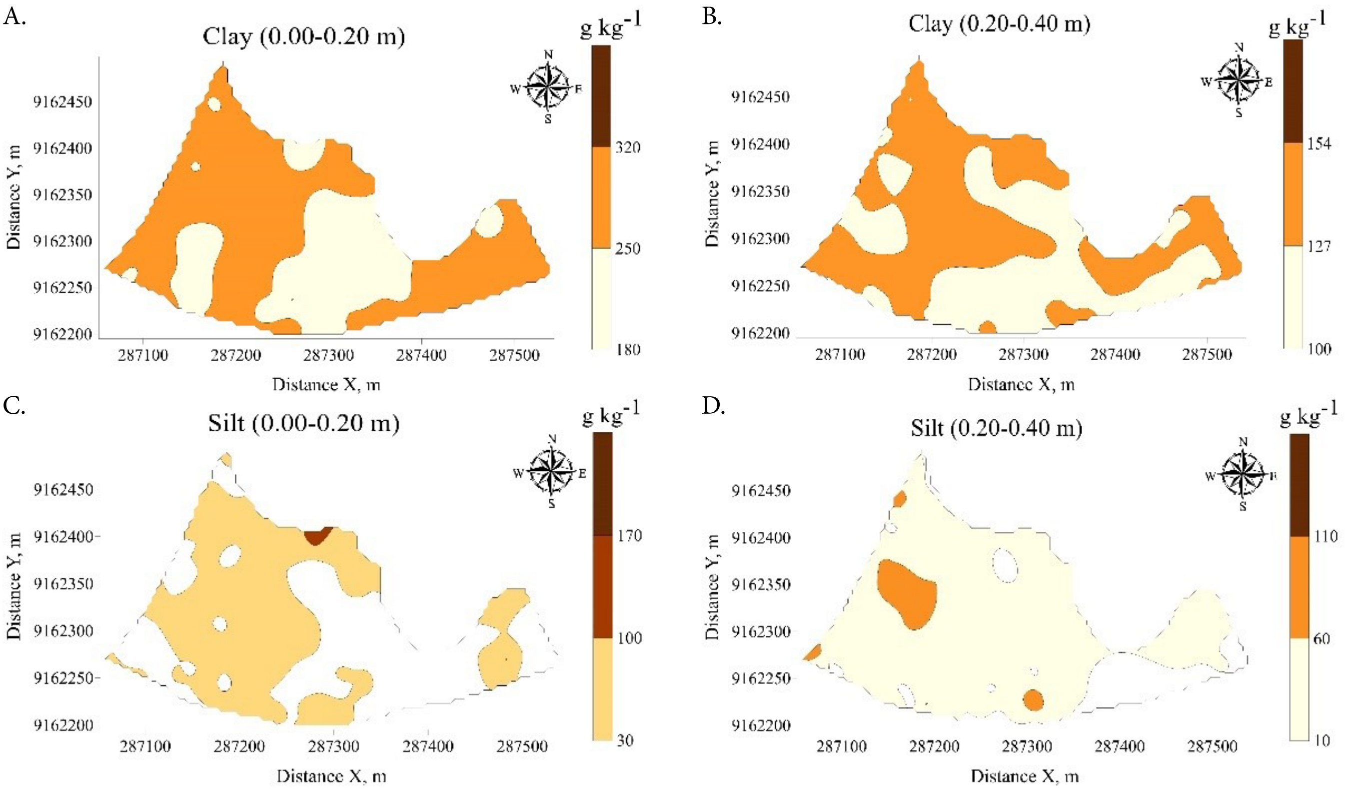


Figure 5. Isoline maps for clay (A) (0.00-0.20 m) and (B) (0.20-0.40 m), and silt (C) (0.00-0.20 m) and (D) (0.20-0.40 m)

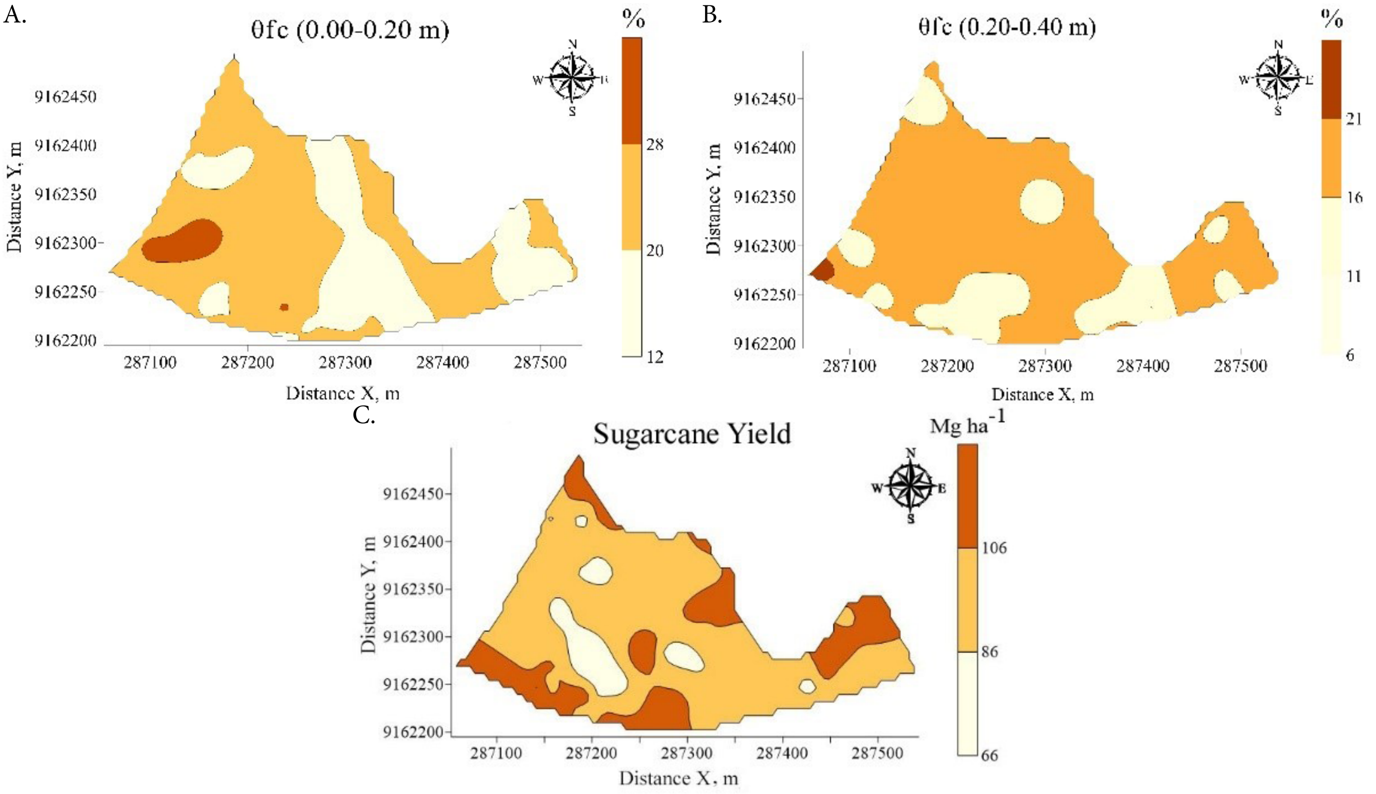


Figure 6. Isoline maps for volumetric soil water content at field capacity - θfc (A) (0.00-0.20 m) and (B) (0.20-0.40 m), and sugarcane yield (C)

coincided with the lowest values of total porosity (Figures 7A, B, C and D). Reichert et al. (2003) point out that, as the total porosity is affected by the arrangement of soil particles, when the soil is subjected to pressure, as occurs in the compaction process, the particles tend to arrange themselves more densely, modifying the quantity, size and orientation of the pores.

The average sugarcane yield was higher than 86 Mg ha^{-1} in almost the entire area, and some points showed yields higher than 106 Mg ha^{-1}, coinciding with higher water content values in the soil when compared to other areas, confirming the influence of water on the crop and its yield (Santos et al., 2020; Ortiz et al., 2022) (Figures 6A, B and C).

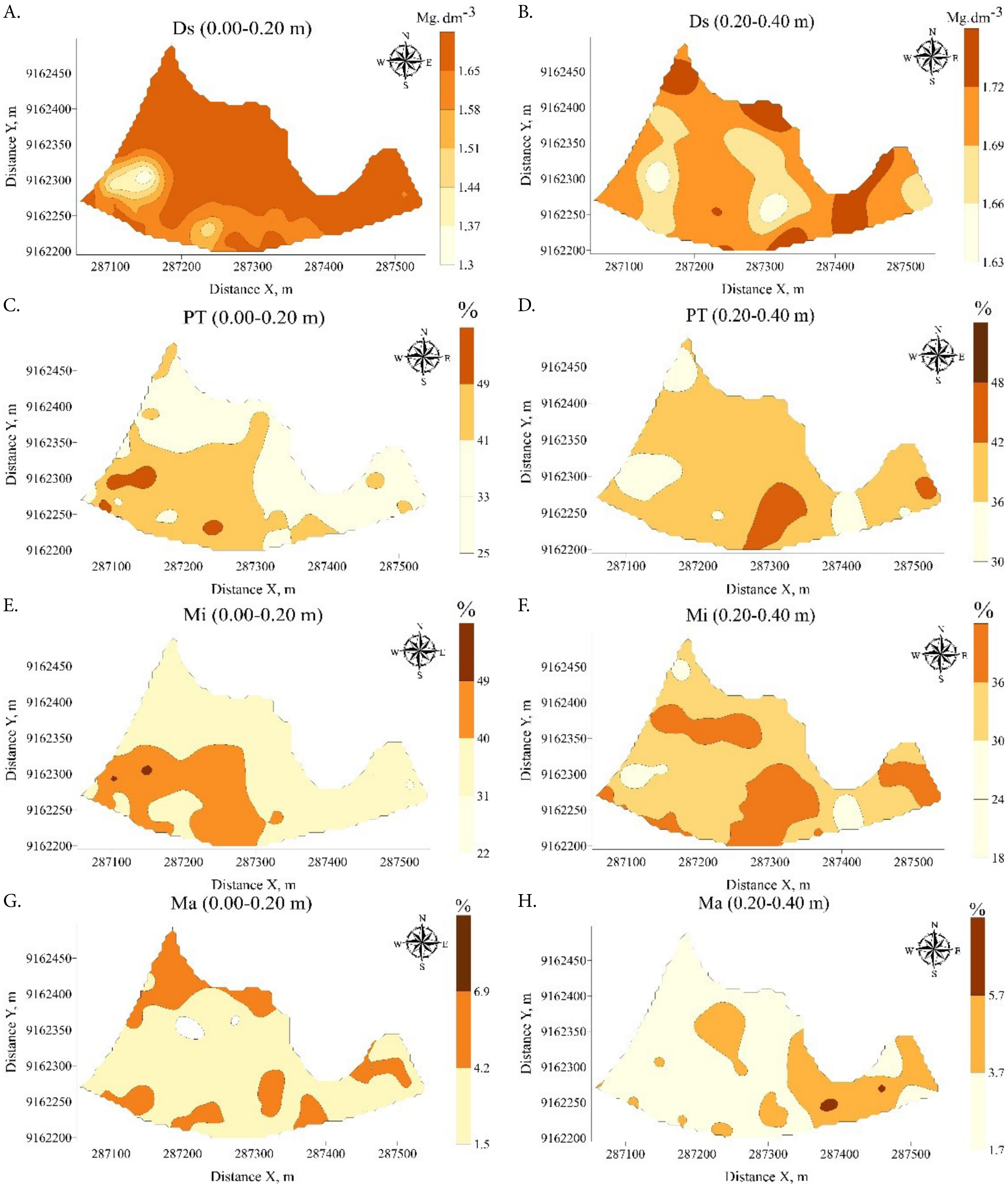


Figure 7. Isoline maps for soil bulk density (A) (0.00-0.20 m) and (B) (0.20-0.40 m), total porosity (C) (0.00-0.20 m) and (D) (0.20-0.40 m), microporosity (E) (0.00-0.20 m) and (F) (0.20-0.40 m), and macroporosity (G) (0.00-0.20 m) and (H) (0.20-0.40 m)

In the narrowest strip of the area and with the highest topographic elevation, there was an increase in macroporosity, a decrease in microporosity, and consequent lower soil moisture, in the layers of 0.00-0.20 and 0.20-0.40 m, leading to lower yield in this range (Figures 7E, F, G and H, 6B and C). These results contribute to describing the water behavior in places where a higher proportion of macropores, responsible for favoring water infiltration, allowing drainage, and a lower proportion of micropores, responsible for retaining water in the soil, predominate.

Conclusions

1. Geostatistical analysis detected spatial dependence of sugarcane yield on soil physical attributes in the studied

area, with the best geostatistical fit being the spherical model.

2. It was not possible to observe the influence of spatial dependence of soil granulometric fractions on sugarcane yield, in the study area, with the sampling scheme used, except for clay in the 0.20-0.40 m layer.

3. The highest sugarcane yields were observed in regions with more aerated soil and with greater water retention capacity in the surface layer.

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