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ORIGINAL ARTICLE

Using geostatistics to evaluate the physical attributes of a soil cultivated with sugarcane

Uso da geoestatística para avaliação de atributos físicos do solo cultivado com cana-de-açúcar

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ABSTRACT: Intensive farming leads to change in soil physical properties, thus modifying the arrangement of soil structure. The aim of this study was to evaluate the spatial variability of soil under sugarcane crop through its physical attributes using geostatistics. The experiment was conducted in an area cultivated with sugarcane in the municipality of Maracanaú, Ceara state, in an Ultisol that had been under tillage without plowing for five years. In an area of one hectare, we set up a grid with 100 points spaced every 10 m. Samples of disturbed and undisturbed soil were collected from the middle layer of 0-0.20 m. The samples collected were used to determine water dispersible clay, particle size, degree of flocculation, soil density and geometric mean diameter of aggregates. The following soil physical attributes obtained spatial dependence: water dispersible clay, clay, total sand, silt, degree of flocculation, soil density and geometric mean diameter. The spatial variability maps allowed identification of specific areas of management, which can improve the planning of sugarcane cultivation.

RESUMO: *O cultivo intensivo acarreta modificação nos atributos físicos do solo e, consequentemente, altera o arranjo estrutural deste. O objetivo deste trabalho foi avaliar a variabilidade espacial dos atributos físicos do solo cultivado com cana-de-açúcar por meio da geoestatística, visando a gerar informações que permitam orientar melhor o manejo nas áreas agrícolas. O experimento foi montado em julho de 2004, em uma área cultivada comercialmente com cana-de-açúcar havia mais de 20 anos, no município de Maracanaú-CE, em um Argissolo Vermelho-Amarelo sob manejo sem revolvimento por cinco anos. Em uma área de um hectare, foi montado um grid com 100 pontos, distanciados a cada 10 m, sendo, em cada ponto, coletadas amostras de solo com estrutura deformada e indeformada na camada média de 0-0,20 m. Essas amostras foram utilizadas para determinação de argila dispersa em água, granulometria, grau de floculação, densidade do solo e diâmetro médio geométrico de agregados. Os atributos físicos – argila dispersa em água, argila, areia total, silte, grau de floculação, densidade do solo e diâmetro médio geométrico de agregados – apresentaram dependência espacial. Os mapas de variabilidade espacial permitiram identificar áreas específicas de manejo, o que possibilita a melhoria no planejamento do cultivo da cana-de-açúcar.*

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1 Introduction

Brazil occupies a prominent position in the international sugarcane market - the country is the world's largest producer and exporter of this crop. In this context, Campos et al. (2008) emphasize that technological innovation to achieve gains in productivity, quality improvement and cost reduction is essential for the development of the Brazilian sugarcane sector. Geostatistical techniques are used as a strategy for monitoring and better understanding the spatial distribution of soil attributes.

Geostatistics is a useful tool in this process. It enables verification of these changes using dependence or spatial correlations as parameters, because samples collected near each other tend to present closer values than those collected at greater distances, thus enabling the formation of spatial variability maps using the kriging method and, consequently, a more adequate management of the area (MENDES; FONTES; OLIVEIRA, 2008; CAJAZEIRA; ASSIS JÚNIOR, 2011).

In addition, knowledge of the spatial distribution of soil attributes is extremely important for determining the factors responsible for crop yield, and it is essential to achieve sustainable agriculture (WEIRICH NETO et al., 2006). According to Campos et al. (2008), the spatial distribution of particle size and chemical attributes of soil allows for accurate allocation of sugarcane culture using kriging maps, indicating the areas with greater or smaller necessity of management practices for fertilization, culminating in a better accuracy of restrictions imposed by soil attributes (MENDES; FONTES; OLIVEIRA, 2008).

Studies have demonstrated that the physical attributes of soil are influenced in space and time (AMARO FILHO et al., 2007; CAMPOS et al., 2007, 2008, 2009; LEMOS FILHO et al., 2008; MENDES; FONTES; OLIVEIRA, 2008; CAJAZEIRA; ASSIS JÚNIOR, 2011). These authors observed spatial dependence for water dispersible clay, degree of flocculation, geometric mean diameter and particle size. According to Cajazeira and Assis Júnior (2011), knowledge about the spatial variability of water dispersible clay and degree of flocculation is essential for conservation studies, because the first contributes to the formation of densely compacted layers and the latter is associated with the aggregation of soil particles.

Still according to Cajazeira and Assis Júnior (2011), soil aggregation plays an important role in agricultural land use, once it is associated with soil aeration, root development, nutrient supply, soil resistance to penetration, retention and storage of water. On the other hand, particle size variation is a function of sediment deposition environment, vegetation and relief, which regulate the exposure time of materials to weathering (YOUNG; HAMMER, 2000), and mainly of parent material (CAMPOS et al., 2007).

The purpose of this study was to assess the spatial variability of the physical attributes of a soil cultivated with sugarcane by means of geostatistics, aiming to generate information to better guide the management of agricultural areas.

2 Materials and Methods

The study was carried out at the farm "Fazenda Jaçanaú" in the municipality of Maracanaú, Ceará state. The area is located at 03° 49' S and 38° 38' W, 47 m above sea level on average. The climate in the region is AW according to Köppen classification, hot and humid with temperatures above 18 °C in the coldest month and average annual precipitation of 1200 mm, with rainfall concentrated between February and April. The area presents gently undulating relief with slopes ranging from 2 to 5%.

The experiment was conducted in a sugarcane commercial area cultivated under conventional tillage for over 20 years and under no-tillage, fertirrigated, with manual harvesting without fire for the past five years. The soil studied was classified as dystrophic Ultisol of sandy texture (EMBRAPA, 2006), with 810, 100 and 90 g kg^{-1} average contents of sand, silt and clay, respectively. A regular grid of 100 × 100 m was established in this area and ten soil samples were collected every 10 m (Figure 1).

In July 2004, samples of disturbed soil were collected at the depth of 0-0.20 m at each point; the crop was at the tillering stage (V4) at that time. The samples collected were taken to the Laboratory of Soil Physics, Federal University of Ceará (UFC), for particle size analysis determined by the pipette method, with 1 mol L^{-1} sodium hydroxide solution, agitated for 10 minutes in a shaker at a speed of 1500 rpm. Clay was separated by sedimentation according to Stokes law, while silt was separated by difference between clay and sand. Water dispersible clay and degree of flocculation were determined according to the methodology by Embrapa (1997).

Soil density (Sd) was determined from undisturbed samples collected by an Uhland sampler; they were dried at 105 °C to constant weight. For determination of aggregate stability in water, 50 g of soil passed through a 7.93 mm sieve and retained on a 4.00 mm sieve were used; the retained soil was pre-wetted with alcohol according to the slow wetting principle. Next, this sample was placed in a vertical oscillation device on a set of sieves of 4.00; 2.00; 1.00; 0.50; 0.25 and 0.125 mm mesh size diameters, as described by Embrapa (1997). After 15 min, the portions retained on each sieve were transferred to aluminum cans with the aid of water spray and dried at 105 °C for 24 h for subsequent weighing. Based on the values of these masses, the geometric mean diameter (GMD) of aggregates was calculated as in the following equation:

$$DMG = \exp\left(\sum (MA_i \, ln\, (d_i) / MAT) \right)$$

where: MA_i = mass of aggregates of the i class; MA_T =total mass of aggregates subtracted from the inert fraction: $d_{i=}$ mean diameter of the i class.

For statistical analysis, an exploratory study of data was initially conducted using Statistica software (STATSOFT, 2010), calculating measures of location (mean, median, minimum and maximum), variability (coefficient of variation - CV), and central tendency (asymmetry and kurtosis) by the Kolmogorov-Smirnov (K-S) test at $p<0.05$. This way, normality was evaluated, providing better predictions especially when associated with geostatistical techniques (DIGGLE; RIBEIRO-JÚNIOR, 2007).

Analysis of spatial dependence was performed based on the calculation of the anisotropic semivariogram and the assumption of stationarity of the intrinsic hypothesis using the software package *Gamma Design Software 7.0 - GS+* (ROBERTSON, 2008). Analysis of evaluation of spatial

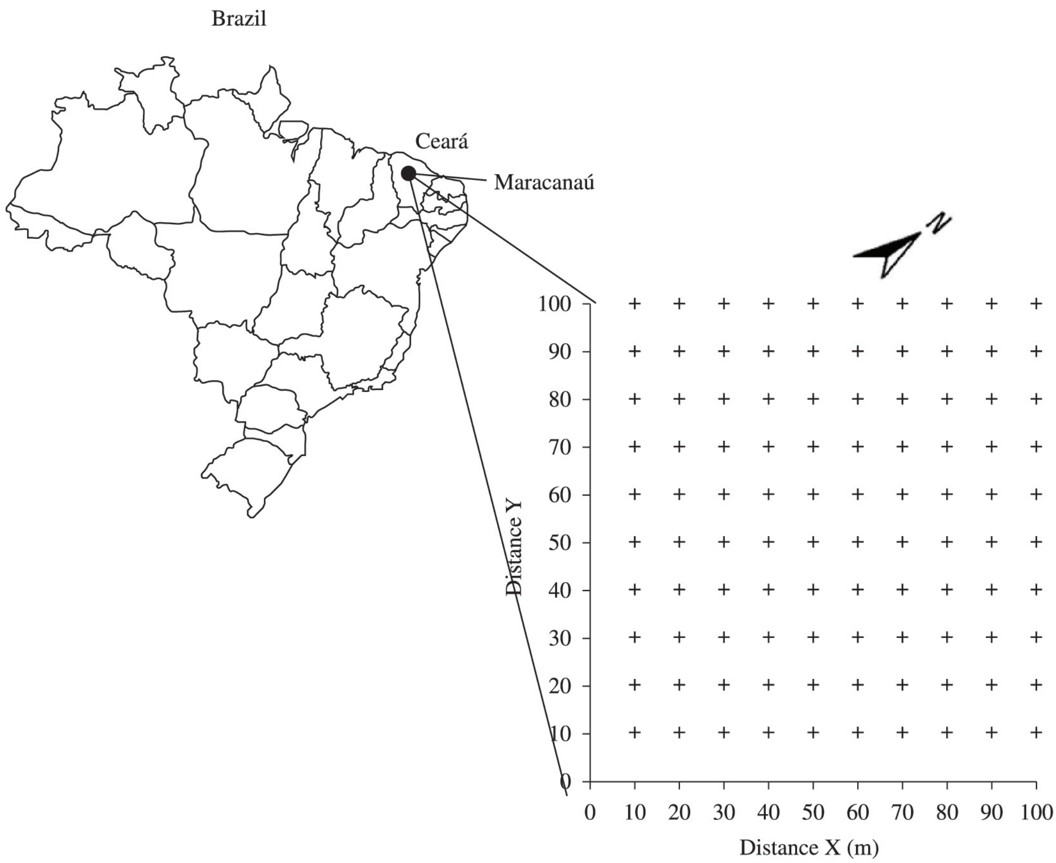

Figure 1. Location of the experimental area and the grid used for soil sampling. The signs (+) indicate the sampled points.

dependence (ESD) (CAMBARDELLA et al., 1994) was performed according to Equation 1:

$$ESD = [C/(C + C_0)] \times 100 \quad (1)$$

where:

ESD, evaluation of spatial dependence; C, structural variance; and $C + C_0$, baseline.

The following interpretation is proposed for ESD: a) ESD < 20% = spatial variance of very low dependence (VL); b) 20% < ESD < 40% = low dependence (L); c) 40% < ESD < 60% = medium dependence (ME); d) 60% < ESD < 80% = high dependence (H); and e) 80% < ESD < 100% = very high dependence (VH). Using these models, a prediction of each soil attribute in non-sampled areas was performed by ordinary kriging, represented in contour maps using the software Surfer (GOLDEN SOFTWARE, 2010), together with the maps and Pearson's correlation analysis.

3 Results and Discussion

The values of mean, median, asymmetry and kurtosis obtained for the soil physical attributes confirmed the normal distribution of these data (Table 1). The variables total sand, degree of flocculation, soil density and geometric mean diameter showed no significant effect by the Kolmogorov-Smirnov (K-S) test. Contrary to other variables (water dispersible clay, silt and clay) evaluated in this study, which showed significant response. Several studies have shown that the distribution of data does not significantly improve the results obtained by geostatistics, that is, data normality is not the central point, but the fact that the results of variables do not present very elongated tails, which may impair the assessment by the kriging method (CAMPOS et al., 2008; RAMIREZ-LÓPEZ; REINA-SÁNCHEZ; CAMACHO-TAMAYO, 2008; CAJAZEIRA; ASSIS JÚNIOR, 2011).

The average results for DF, WDC and Sd obtained in this study correspond to a soil with medium texture, greater aggregation, lower density and with less traffic of agricultural machinery according to Ribeiro et al. (2007), Lemos Filho et al. (2008), Cruz et al. (2010) and Cajazeira and Assis Júnior (2011). It is emphasized that mean values for Sd indicate that the no-tillage system applied in the area allowed the soil to maintain its physical characteristics at acceptable levels for the development of sugarcane culture (CRUZ et al., 2010).

Another important aspect in determining the use of geostatistics to assess spatial variability are the coefficients of variation (CV) that, according to Campos et al. (2009), are dimensionless and allow comparison of values between different soil attributes. High CV values can be considered the first indicators of heterogeneity of data. Changes in soil properties, in turn, can be classified according to their CVs as low (CV < 10%), medium (10% < CV < 20%), high (20% < CV < 30%) and very high (CV > 30%), according to Pimentel Gomes (2009).

Based on CV classification, the variables TS, Sd and DF were described as of low (< 10%), GMD as of medium (10% < CV < 20%) and WDC, C and silt, as of high (20% < CV <

30%) variability. When characterizing spatial variability of physical attributes using CV as parameter, Muñoz, Martínez and Giraldo (2006), Ribeiro et al. (2007), Amaro Filho et al. (2007), Cruz et al. (2010) and Cajazeira and Assis Júnior (2011) obtained similar results for the same variables in Oxisol and Ultisol.

All variables showed spatial dependence with predominance of the spherical model, except for silt and GMD, which presented the exponential model (Table 2 and Figure 2). These results indicate, based on several studies (SANCHEZ; MARQUES JÚNIOR; SOUZA, 2009; SIQUEIRA; MARQUES JÚNIOR; PEREIRA, 2010; CRUZ et al., 2010; SANTOS et al., 2011), that the spherical and exponential models are the most suitable for studies of variability of soil attributes. The results for physical attributes are consistent with those obtained by Campos et al. (2008, 2009) and Cruz et al. (2010).

It is worth mentioning that the use of geostatistical techniques enables accurate planning of sugarcane cultivation based on the separation of environments, adequacy of fertilization practices and allocation of varieties adapted to the restrictions imposed by soil attributes (CAMPOS et al., 2009). According to Cruz et al. (2010), conventional tillage does not take soil variability into account. Campos et al. (2009) report that the lack of this knowledge implies the use of inadequate management practices, leading to reduced crop yield and increased soil degradation.

The variables C, TS, silt and DF obtained high values by the nugget effect (Table 2), indicating a probable discontinuity of the variability of these attributes in the soil. Similar results were reported by Mendes, Fontes and Oliveira (2008), Campos et al. (2009) and Cajazeira and Assis Júnior (2011). According to Campos et al. (2009) and Siqueira, Marques Júnior and Pereira (2010), the function of the nugget effect (C_0) is to explain the non-variance of data, possibly caused by measurement errors or variances in attributes that cannot be detected in the sample scale.

Concerning the baseline ($C_0 + C_1$), the same results of the nugget effect (C_0) are verified, that is, the highest values were found in the same attributes, indicating that these results reflect the stationarity and distribution of variability of soil attributes (Table 2 and Figure 2).

The baseline is a reflection of the adjusted models; it allows us to indicate the limits between the distances of samples, that is, spatial dependence no longer exists as from a certain distance, allowing us to identify the stationarity of sampled points between pairs of data, becoming constant values (SANCHEZ; MARQUES JÚNIOR; SOUZA, 2009; SIQUEIRA; MARQUES JÚNIOR; PEREIRA, 2010; SANTOS et al., 2011).

Regarding spatial dependence (ESD), the physical attributes (Table 2) were classified as follows: Silt and GMD, very low; WDC, C, DF and Sd, low; and TS, medium; these results were similar to those obtained by Amaro Filho et al. (2007),

Table 1. Descriptive measures for water dispersible clay (WDC), clay (C), total sand (TS), silt, degree of flocculation (DF), soil density (Sd) and geometric mean diameter (GMD) of aggregates.

Descriptive measures	WDC	C	Silt	TS	DF	Sd	GMD
		(g kg^{-1})			(%)	(Mg m^{-3})	(mm)
Mean	24.2	89	102	809	72.76	1.29	1.02
Median	22.4	88	101	811	73.07	1.30	1.00
SD	0.76	20.62	23.46	31.22	6.87	0.10	0.16
Minimum	12.9	50	54	735	57.59	1.05	0.72
Maximum	42.2	145	166	862	88.89	1.30	1.40
Asymmetry	0.70	0.76	0.65	–0.38	–0.02	–0.02	0.24
Kurtosis	–0.41	0.34	0.46	–0.43	–0.56	–0.21	–0.58
CV (%)	31.71	22.98	23.15	3.86	9.44	8.06	15.97
K-S	1.78*	1.18*	0.72*	0.55	0.37	0.53	0.38

(*) significant at 5% probability (p<0.05) by the Kolmogorov-Smirnov (K-S) test; SD = standard deviation; CV (%) = coefficient of variation.

Table 2. Parameters of adjusted semivariogram models of water dispersible clay (WDC), clay (C), total sand (TS), silt, degree of flocculation (DF), soil density (Sd) and geometric mean diameter (GMD) of aggregates.

Attribute	Model	C_0	$C_0 + C$	DSD	ESD	Range (m)	R^2	CVRC	
								a	b
WDC	Spherical	0.18	0.46	39.13	L	50.60	0.86	0.29	0.87
C	Spherical	113.70	321.00	35.42	L	75.50	0.98	–0.93	1.00
TS	Spherical	364.00	869.80	41.84	AV	54.90	0.92	–12.88	1.01
Silt	Exponential	24.00	340.90	7.04	VL	31.50	0.95	3.25	0.96
DF	Spherical	12.62	41.22	30.61	L	36.10	0.96	11.35	0.84
Sd	Spherical	0.004	0.011	36.36	L	86.60	0.76	0.09	0.92
GMD	Exponential	0.001	0.025	4.00	VL	16.80	0.51	0.19	0.81

C_0 = nugget effect; C_0+C_1 = baseline; R^2 = determination coefficient; DSD (C_0/(C_0 + C) *100) = degree of spatial dependence; ESD = evaluation of spatial dependence , where VL = very low, L = low, ME = medium. CVRC = cross-validated regression coefficient; a = intercept; b = angular coefficient.

Cruz et al. (2010) and Cajazeira and Assis Júnior (2011). Some studies use different criteria to identify the degree of spatial dependence, such as Sanchez, Marques Júnior and Souza (2009); Siqueira, Marques Júnior and Pereira (2010), and Santos et al. (2011) for areas of sugarcane cultivation in Oxisol in the state of Sao Paulo, with the same purpose - to confirm the theory of stationarity, that is, that the distribution of soil attributes in space does not occur randomly (Figure 2).

According to the adjustment of the semivariograms, regarding the coefficients of spatial determination (R^2), most

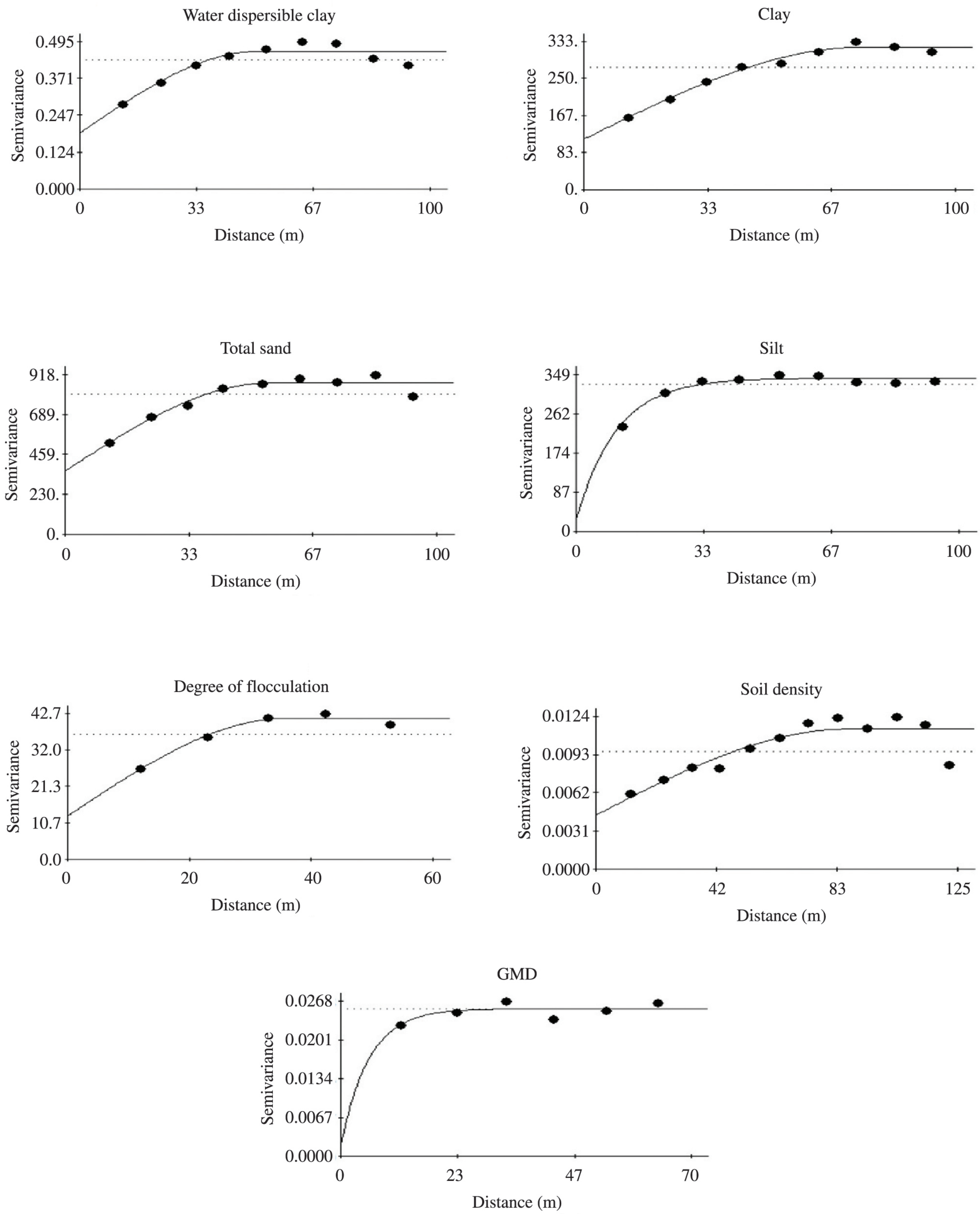

Figure 2. Semivariograms for soil physical attributes: water dispersible clay, clay, total sand, silt, degree of flocculation, soil density, geometric mean diameter.

attributes presented values above 0.92, except for GMD, Sd and WDC, which showed values below 0.86 (Table 3). The spatial dependence of the attributes evaluated in this study (WDC; C; TS; Sd; GMD) showed the best adjustments in cross-validation once the cross-validated regression coefficients (CVRC) were close to one and zero (Table 2), except for silt and DF. According to Amaro Filho et al. (2007), Lemos Filho et al. (2008) and Campos et al. (2009), these results indicate that the models of semivariograms obtained are the most suitable.

Regarding range, variation from 16.8 to 86.6 m was observed for the attributes, with the highest value for Sd and the lowest value for GMD. None of the ranges exceeded the limit of the area - 100 m, confirming that the semivariograms were adjusted adequately (Figure 2). Working with the variability of the same attributes in Argisol, Cruz et al. (2010) and Cajazeira and Assis Júnior (2011) obtained results similar to those of the present study.

Range is the main parameter provided by geostatistics; it represents the distance at which a regionalized variable presents spatial continuity, and from this distance, the spatial behavior of the variable becomes totally random (LEMOS FILHO et al., 2008). The description of the range value obtained by geostatistics may affect the quality of the estimates, because it determines the number of values used in interpolation, delimiting the extent of the spatial correlation between samples (MENDES; FONTES; OLIVEIRA, 2008).

Table 3 shows that WDC obtained positive correlation with C and negative correlation with DF, confirming the theory that the greater the value of WDC, the smaller the value of DF - results confirmed in the studies by Cajazeira and Assis Júnior (2011). Such results can also be observed in the maps of variability of soil physical attributes (Figure 3). Concerning WDC, it is worth adding that dispersion is the hydration of clay, and considering that both clay and water have localized electrical charges, it can be stated that the less active the clay fraction, the smaller the water adsorption, resulting in low values of WDC (JONG VAN LIER, 2010).

We found an inverse relation between C and TS and a direct relation between C and GMD, corroborating Campos et al. (2007, 2009) and Cajazeira and Assis Júnior (2011), who reported that the particle size ratio in soil is always negative, because the value of C is expressed by the ratio between TS and silt. This explanation is also valid to justify the negative relation between TS and silt. Regarding GMD, correlation results were positive for C and negative for TS, both at $p<0.01$. DF showed negative relation with Sd, indicating that the greater the DF of a soil, the smaller its Sd, corroborating Jong Van Lier (2010). In addition, the higher the DF value, the higher the soil aggregation, which indicates the presence of particles less vulnerable to erosion or soil compaction and the presence of trivalent aluminum (CAJAZEIRA; ASSIS JÚNIOR, 2011).

Based on the results of Table 2 and Figure 2, it was possible to obtain maps of spatial variability of the attributes studied using the kriging method (Figure 3), which allowed us to identify and delimit specific areas from the behavior of variables. The distribution maps reflect the results of positive and negative correlations of attributes (Table 3 and Figure 3). It should be emphasized that the near (isolines) and distant lines indicate higher and lower variability of attributes, respectively. The kriging maps of soil attributes provide information to establish production environments and ways of sustainable management (CAMPOS et al., 2009).

In the variability map (Figure 3), concerning Sd, it was possible to observed that 50% of the area presents values (1.31 Mg m^{-3}), but with variation between 1.16 and 1.36 Mg m^{-3}, which are considered moderate by Arshad, Lowery and Grossman (1996), indicating that the management and preparation of soil are not negatively affecting its physical attributes. Another point that should be highlighted concerns the distribution of GMD (Figure 3), which showed specific behavior (above 1.36 mm) rather than on continuous strips. This result can be explained by the behavior of the soil particle size, which is composed of more than 75% of sand, particles considered more stable in relation to their size when compared to clay and silt.

Several authors (CAMPOS et al., 2009; CRUZ et al., 2010; CAJAZEIRA; ASSIS JÚNIOR, 2011) have reported that inadequate management promotes changes in soil physical attributes, impairing the production of sugarcane. In this sense, all these authors emphasize that the knowledge of variability allows for reassessment of soil management, especially in areas of conventional tillage, which should be considered for commercial areas, avoiding decrease in production.

The knowledge of soil variability allows us to understand the causes and effects of the behavior of plants and attributes that can contribute to a better development of the crop, enabling sustainable soil management.

Table 3. Pearson's linear correlation of the attributes water dispersible clay (WDC), clay (C), total sand (TS), silt, degree of flocculation (DF), soil density (Sd) and geometric mean diameter (GMD).

Attribute	WDC	C	TS	Silt	DF	Sd	GMD
C	0.338**	1					
TS	–0.180	–0.637**	1				
Silt	0.078	–0.028	–0.694**	1			
DF	–0.732**	–0.056	–0.012	–0.054	1		
Sd	0.161	0.017	0.049	–0.079	–0.211*	1	
GMD	0.175	0.205*	–0.205*	0.104	–0.125	–0.116	1

* and ** Correlation is significant at 5 and 1% probability ($p<0.05$ and $p<0.01$) by the F test.

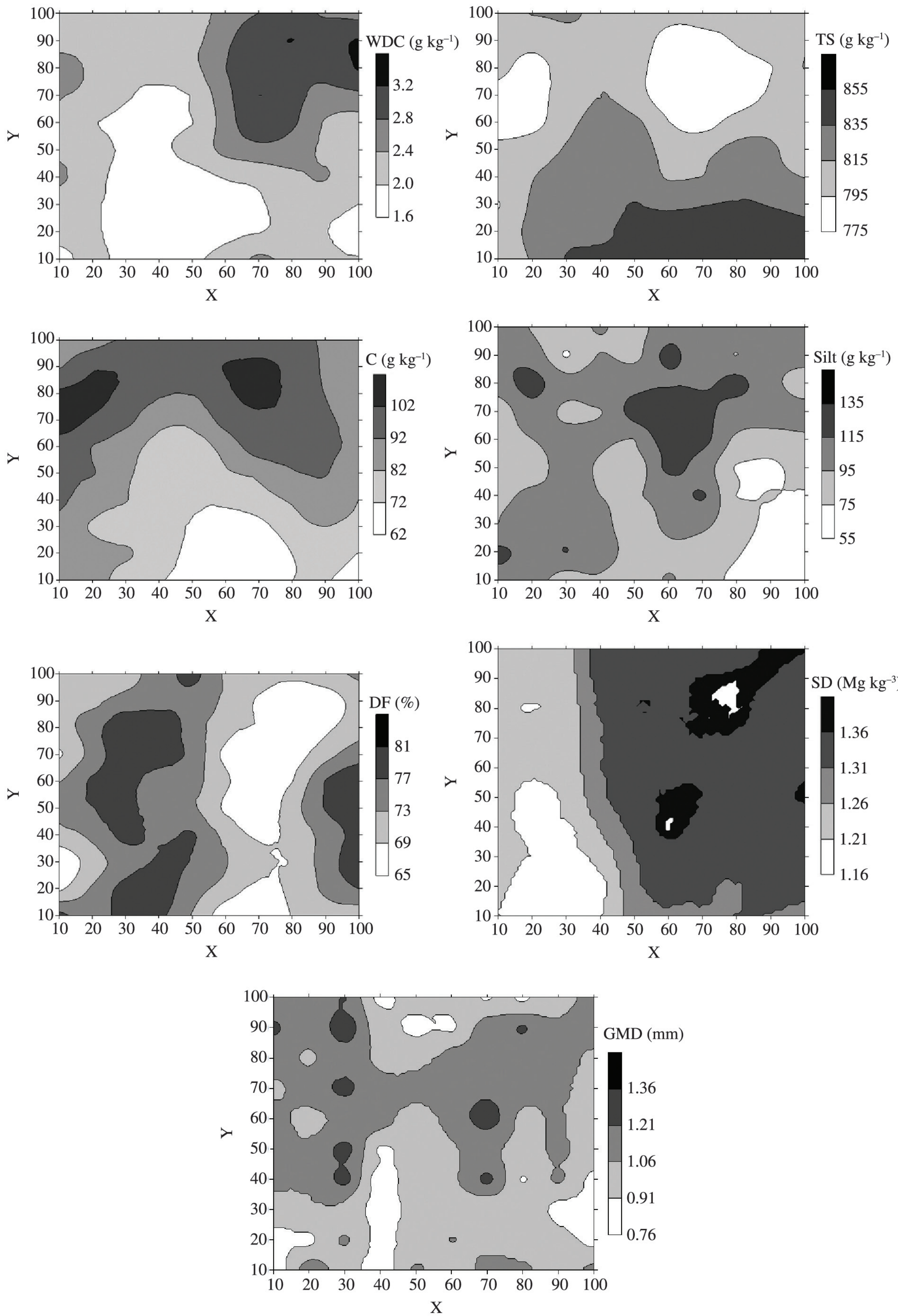

Figure 3. Spatial distribution of the variables studied: water dispersible clay (WDC), clay (C), total sand (TS), silt, degree of flocculation (DF), soil density (Sd) and geometric mean diameter (GMD).

4 Conclusions

The following soil physical attributes obtained spatial dependence: water dispersible clay, clay, total sand, silt, degree of flocculation, soil density and geometric mean diameter.

The spatial variability maps allowed identification of specific areas of management, which can improve the planning of sugarcane cultivation.

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