ISSN 2175-6813

Revista Engenharia na Agricultura

Viçosa, MG, DEA/UFV - DOI: 10.13083/reveng.v30i1.15695 v.31, p.127-139, 2023

SPATIAL VARIABILITY OF SOIL PHYSICAL ATTRIBUTES UNDER CONSERVATION MANAGEMENT SYSTEMS FOR SUGARCANE CULTIVATION

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Keywords:
Soil density
Spatial dependence
Geostatistics
Kriging

ABSTRACT

Conservation systems for soil management are increasing for sugarcane cultivation. However, there is still little information about the effects of this management on soil physical quality at different scales, fundamental to agricultural activity sustainability. The objective was to evaluate the variability and spatial dependence of Oxisol physical attributes under no-tillage and reduced-tillage in sugarcane cultivation. Undeformed soil samples were collected 45 days after sugarcane planting, using a regular mesh with intervals of 7.5 m, totaling 32 points in each tillage system. Soil density, resistance to penetration, total porosity, macroporosity, and microporosity were determined in two depths (0-0.10 and 0.10-0.20 m). Using geostatistical methods was verified in both tillage systems that spatial dependence in the two depths, prevailing in the layer 0.00-0.10 m, in no-tillage, strong dependence with the adjusted spherical model reduced preparation, moderate dependence, with exponential adjustment. In the 0.10-0.20 m layer, spatial dependence was an inversion and adjusted model, i.e., in no-tillage, there was moderate dependence, exponential adjustment, reduced preparation, strong dependence, and spherical adjustment. Linear correlations demonstrate how much soil physical attributes are related to management conditions and present behaviors like isoline cartogram.

Palavras-chave:
Densidade do solo
Dependência espacial
Geoestatística
Krigagem

VARIABILIDADE ESPACIAL DE ATRIBUTOS FÍSICOS DO SOLO SOB SISTEMAS DE MANEJO CONSERVACIONISTAS PARA CULTIVO DE CANA-DE-AÇÚCAR

RESUMO

Sistemas conservacionistas para o manejo do solo estão se tornando mais comuns para o cultivo de cana-de-açúcar. No entanto, ainda há poucas informações acerca dos efeitos destes manejos sobre a qualidade física do solo, em diferentes escalas, as quais são fundamentais à sustentabilidade da atividade agrícola. Objetivou-se avaliar a variabilidade e a dependência espacial dos atributos físicos de Latossolo Vermelho Distroférrico sob plantio direto e preparo reduzido em cultivo de cana. Aos 45 dias após o plantio de cana, realizou-se a coleta de amostras indeformadas de solo, em uma malha com intervalos regulares de 7,5 m, perfazendo o total de 32 pontos em cada sistema de manejo, nas camadas de 0-0,10 e 0,10-0,20 m para determinar a densidade, a resistência do solo à penetração, a porosidade total, a macroporosidade e a microporosidade. Utilizando-se de métodos geoestatísticos verificou-se que, tanto no plantio direto quanto no preparo reduzido, houve dependência espacial nas duas camadas estudadas; prevalecendo na camada 0,00-0,10 m, no plantio direto, forte dependência com o modelo ajustado esférico e no preparo reduzido, moderada dependência, com ajuste exponencial. Na camada de 0,10-0,20 m ocorreu inversão da dependência espacial e modelo ajustado, ou seja, no plantio direto houve moderada dependência, com ajuste exponencial e no preparo reduzido, com forte dependência, e ajuste esférico. As correlações lineares demonstram o quanto os atributos físicos do solo se relacionam sob as condições de manejo e apresentam comportamentos semelhantes aos cartogramas de isolinhas.

Received 21 Apr, 2023 • Accepted 14 Jul, 2023 • Published 15 Ago, 2023

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SECTION EDITOR IN CHARGE
Michael Silveira Thebaldi

INTRODUCTION

The use and the soil management to implement farm systems can negatively impact them due to adopting an agricultural model that does not prioritize natural resources' rational use (ARCOVERDE *et al*., 2019a). These impact changes in properties and physical processes in chemical and biological order (ARCOVERDE *et al*., 2015). Thus, a sustainable farm must be known about the soils' properties and techniques so that it is possible to effectively use managements that will provide continuously good productivity without degrading this resource (ARAÚJO *et al*., 2014).

The soil knowledge in an area destined for sugarcane production is fundamental for properly planning mechanized agricultural operations, including soil preparation. Since this operation is crucial for sugarcane cultivation, it is carried out only when planting and renewing sugarcane (CARVALHO *et al*., 2011).

Soil tillage aims to improve some soil physical characteristics, giving these adequate plant growth and development conditions. However, soil structural degradation has been observed when sugarcane is grown in conventional tillage systems. Thus, there is a general reduction in its quality due to soil mobilization (SILVA JUNIOR *et al*., 2013).

Soil physical quality is related to the sustainability of agricultural systems, and its evaluation should be carried out by indicators that reflect their behavior. Among the main soil physical indicators used for studies involving sugarcane crop management systems, the following stand out: soil density, total porosity, and soil resistance to penetration (SILVA JUNIOR *et al*., 2013; ARCOVERDE *et al*., 2019b); who have changed with the increased density and resistance of soil to penetration (CARVALHO *et al*., 2011; MARASCA *et al*., 2015).

Conservation practices have been increasingly used in production systems that bring agricultural and environmental benefits and highlight the cost reduction due to the decrease in tillage operations (ARCOVERDE *et al*., 2019b). However, the no-tillage can also increase these attributes' values in the soil surface layer due to their non-revolving and traffic of agricultural machines (ARCOVERDE *et al*., 2019c). However, the no-tillage could be a feasible strategy to reduce soil mobilization and its negative implications on several ecosystem services without compromising sugarcane yield (BARBOSA *et al*., 2019).

The physical attributes behave dynamically according to the soil, management conditions, and over time, so there is a need for immediate follow-up over the years (Laurindo *et al.*, 2009). To better understand these soil dynamics, geostatistic technics have been used as a tool that allows obtaining essential information for agricultural management from the spatial variability of soil characteristics (GREGO and VIEIRA, 2005).

Thus, the objective was to evaluate the variability and spatial dependence of the Oxisol physical attributes under no-tillage and reduced-tillage for sugarcane cultivation.

MATERIAL AND METHODS

The work was conducted on the Experimental Farm of the Federal University of Grande Dourados, located in Dourados, MS (22º13'58" South latitude, 54° 59'57" West longitude). According to Köppen's climatic classification, the climate is Cwa (FIETZ *et al*., 2017). The soil is classified as a clayey Oxisol (SANTOS *et al*., 2018), having in the depth of 0.30 m 603 g kg^{-1} of clay, 147 g kg^{-1} of silt, and 250 g kg^{-1} of sand (ARCOVERDE *et al*., 2019b).

A completely randomized design was used in the 8x2 factorial scheme (eight sugarcane cultivars and two conservation tillage systems), with four replications. Each experimental unit consisted of 5 rows of sugarcane 5-meters long, spaced 1.50 m, with a total area of 37.5 m^2. On July 21, 2016, manual planting was carried out.

The experiment area was in 2-years fallow, and after 14 years in succession system (soybean-corn) without soil revolving was submitted to no-tillage and reduced-tillage for sugarcane crop. The reduced-tillage consisted of heavy harrowing, while the no-tillage consisted of weeds mechanical control, and after, furrowing for soil preparation only in the planting row.

The following types of equipment were used for soil preparation: a straw grinder equipped with a steel curved blade rotor and weight 1.2 Mg, a two-row furrower, an offset disk harrow with 32 discs of diameter 0.76 m (30”) and weight 2.0 Mg, operating down to 0.15 m deep. A New Holland model 8030, 4x2 AFT tractor was used for soil tillage and furrowing operations, with 89.8 kW engine power, 14.9-58 front tires, and 23.1-30 rear tires, a weight of 4.51 Mg. A Massey Fergusson model MF292, 4x2 AFT tractor, with 68.74 kW engine power, 7.50-18 front tires, 18.4-34 rear tires, and 3.40 Mg of weight was used for covering the furrows and crop management.

Forty-five days after sugarcane planting, undeformed soil samples were collected in the center of the experimental unit and the interspersed tractor, in a mesh with regular intervals of 7.5 m, totaling 32 points each area (Figure 1), in the depth of 0-0.10 and 0.10-0.20 m.

Soil density (SD), resistance to penetration (SRP), total porosity (TP), macroporosity (Ma), and microporosity (Mi) were determined using metallic cylinders (5.57 cm of diameter and 4.41 cm of height). TP was obtained by the difference between saturated and dry soil mass at 110°C for 24 h. Mi was determined by the suction table method with a water column 60 cm in height. From the difference between TP and Mi, the Ma was calculated. The SRP was determined utilizing an electronic penetrometer model MA-933, with a rod diameter of 4 mm and conical tip at 30º semi-angle, set to operate a constant penetration velocity of 10 mm min^{-1} (ARCOVERDE *et al*., 2019b).

Soil physical attributes data were analyzed using descriptive statistics to allow general visualization of data behavior, in addition to Pearson’s correlation, and normality was verified using the Shapiro-Wilk test.

The results of soil attributes were subjected to spatial dependence analysis. The spatial dependence was evaluated using variogram adjustments, assuming the intrinsic hypothesis’s stationarity, as Bottega *et al*. (2017) defined. The models were selected based on the best coefficient of determination (R^2) and the lowest residue sum of squares. The following variogram models were tested: the spherical and exponential models. The following parameters were defined: nugget effect (C0), sill (C0 + C1), and range (A) (CORTEZ *et al*., 2018).

The spatial dependence of the soil attributes (SPD) was determined (Seidel and Oliveira, 2016) and classified (ZIMBACK, 2001) as the following intervals: weak spatial dependence for SPD < 25%, moderate spatial dependence between 25 and 75%, and strong spatial

A

B

Figure 1. Sampling grid size in no-tillage (A) and reduced-tillage (B)

dependence for SPD > 75%.

After the confirmation of spatial dependence, inferences were performed by ordinary kriging, which allowed for the estimation of values at locations not measured. For ordinary kriging, non-biased estimates, with minimum deviation from the known values, are interpolated, considering the spatial variability structure of the attribute (PASINI *et al*., 2014). The thematic cartogram (two-dimensional) of the soil attributes was obtained by performing ordinary kriging (BOTTEGA *et al*., 2017; CORTEZ *et al*., 2018).

The semivariogram model was selected according cross-validation technique. That cross-validation allows comparing the impact of interpolators among the real estimated values, in which the model with more accurate predictions is chosen. The cross-validation criterion as the most adequate for choosing the best semivariogram adjustment. Linear regression was used as a first indicator of cross-validation, in which the estimated values (dependent variable) were crossed with the sampled values (independent variable). The best adjustments are obtained when the estimation of the intercept a approaches zero, and the linear b and determination R^2 coefficients approach 1 (PASINI *et al*., 2014).

For the experience of the existence or not of the spatial dependence, we used the semivariogram exam, through the GS+ 7.0 program (GAMMA DESIGN SOFTWARE, 2004). To prepare the spatial distribution cartograms of the variables, the SURFER 9.0 (GOLDEN SOFTWARE, 2010) program was used.

RESULTS AND DISCUSSION

The descriptive statistics of soil physical attributes under no-tillage and reduced-tillage, for the depth of 0.00 to 0.10 and 0.10 to 0.20 m, are present in Table 1. The mean and median values for all attributes are close, except for SRP. Soil attributes approach a normal distribution, indicating that their data follow symmetrical distributions, the same pattern observed in a study conducted by Oliveira *et al*. (2013).

The results referring to the Shapiro-Wilk test indicated normality for all attributes, except for Ma under no-tillage (0.10-0.20 m) and in reduced preparation, for SRP, in the layer of 0.00-0.10 m, as well as TP, Ma, Mi, and SD, in the layer of 0.10-0.20 m. Even if it is not an assumption for applying geostatistics, normality allows for greater accuracy of kriging estimates (ISAAKS and SRIVASTAVA, 1989).

The results of skewness and shortness are within the range of -2 and 2, indicating that the data tend to a normal distribution; therefore, there was no normality, mainly for TP, Ma, Mi, and SD under reduced preparation, in the layer of 0.00-0.10 m.

In the reduced preparation, the SRP variation was 3.17 MPa, in the 0.00-0.10 m layer, at 5.83 MPa, in the 0.10-0.20 m layer. According to Sá *et al*. (2016), SRP values higher than 3.8 MPa represent a limitation to sugarcane root growth. The negative correlation between SRP and sugarcane roots mass and 25 to 30% are located in the interline - 0.6 m away from the row (CURY *et al*., 2014); and according to Barbosa *et al*. (2018), the root systems of the plant cane get concentrated into the first 0.40 m in deep (70%) and around the stools (area of planting).

Variation coefficients (VC) obtained in the no-tillage area were from 3.7 to 56% at a depth of 0.00-0.10 m, while down of 0.10-0.20 m deep was from 4.0 to 37%. Under reduced-tillage, the soil attributes VC was from 4.7 to 58.6% (depth of 0.00-0.10 m) and 5.26 to 44.34% (0.10-0.20 m). According to the classification proposed by Warrick and Nielsen (1980), VC values for TP, Mi and SD are classified as low (VC < 12%), while for the other attributes are classified as high (12% < VC < 60%).

As VC values are indicators of data heterogeneity, there is a higher variation in the soil surface layer, whose effects are more significant due to management practices (ARCOVERDE *et al*., 2019b) and machine traffic (ARCOVERDE *et al*., 2019c). However, there was a greater variation in VC values in the reduced-tillage at a depth of 0.10-0.20 m, resulting from the tillage's physical changes. Cavalcante *et al*. (2011) and Araújo *et al*. (2014) also observed a high VC for SRP and low for SD.

SD values ranged from 1.3 to 1.4 Mg m^{-3} in both soil tillage systems. The highest value in no-tillage was observed at a depth of 0.00-0.10 m

Table 1. Descriptive statistics of soil physical attributes under no-tillage and reduced-tillage at a depth of 0.00-0.10 and 0.10-0.20 m

	Average		Median		VC		Skewness		Kurtosis		W[1]	
	NT	RT	NT	RT	NT	RT	NT	RT	NT	RT	NT	RT
						0 to 0.10 m						
TP	42.7	44	42.5	44	5.4	5.9	0.3	-	0.2	-1	0.3*	0.5*
Ma	8.0	8.7	7.6	8.3	35	31.4	0.8	0.3	0.2	-0.7	0.1*	0.4*
Mi	34.6	35.3	34.6	35.4	3.7	4.7	0.5	-0.2	0.3	-0.2	0.6*	1*
SD	1.4	1.3	1.4	1.3	5.2	5.7	-0.2	0.5	-0.1	-0.2	0.9*	0.2*
SRP	3.3	3.2	2.9	2.3	56.1	58.6	1.3	0.8	2.5	-0.5	0.1*	0
						0.10 to 0.20 m						
TP	42.8	41.4	42.5	41.3	4.1	5.3	0.9	0.8	1.2	4.6	0.5*	0
Ma	6.4	6.1	6.2	5.5	19.8	45.5	0.4	3.3	-0.1	12.6	0	0
Mi	36.4	35.4	36.1	36	5.0	5.3	1.2	-1.8	1.5	3.2	1*	0
SD	1.4	1.4	1.4	1.4	4.0	6.6	0.2	-1	-0.1	3.1	1*	0
SRP	5.3	5.8	5.2	5.7	37.0	44.3	0.2	0.2	-0.1	-0.2	1*	0.9*

NT – no-till; RT – reduced-tillage; VC – variation coefficient; W[1] – Shapiro-Wilk test ($p<0,05$); TP – total porosity (%); Ma – macroporosity (%); Mi – microporosity (%); SD: soil density (Mg m^{-3}); SRP: soil resistance to penetration (MPa)

and 0.10-0.20 m in reduced-tillage. Baquero *et al*. (2012) highlighted that values of 1.48 Mg m^{-3} indicate compaction in a very clayey latosol, which may restrict the growth of sugarcane roots. Sá *et al*. (2016) and Oliveira *et al*. (2012) found in clayey to very clayey latosols with sugarcane, limiting values between 1.51 and 1.59 Mg m^{-3}, respectively.

Ma values were less than 0.10 m^3 m^{-3}, which has been indicated as the appropriate minimum value for liquid and gaseous exchanges between the external environment and the soil, and it is considered a critical attribute for the growth of the roots of most crops (SANTOS *et al*., 2012). TP and Mi means were similar for the two soil tillage systems, which can be explained by the influence of the clay fraction's mineralogical composition in Oxisol, according to Ferreira *et al*. (1999).

The geostatistical analysis (Table 3) indicated that all soil attributes presented spatial dependence (Table 2). The pure nugget effect was observed for the following soil attributes: Ma at a soil depth of 0.00-0.10 m under reduced-tillage; SRP and SD at a soil depth of 0.10-0.20 m, and TP at 0.00-0.10 m under no-tillage.

The pure nugget effect is a parameter that indicates the unexplained variability because of the sampling distance used, i.e., there is no continuity of the phenomenon (OLIVEIRA *et al*., 2013). The intensive use of soil has caused alterations in spatial dependence structure, causing the randomness of physic attribute data (TAVARES *et al*., 2012).

The soil attributes presented a moderate to a strong spatial dependence. The predominance of strong dependence in no-tillage was at a depth of 0.00-0.10 m. When analyzing the reduced-tillage, the SPD occurred from moderate to strong, with a predominance of strong dependence at 0.10-0.20 m. According to Cambardella *et al*. (1994), attributes with strong spatial dependence are most influenced by intrinsic soil properties.

In this sense, due to the recent implementation of soil management systems, there were no significant changes in its structure, and the physical properties were more dependent on texture. And the greater heterogeneity in the other soil layers is due to the mechanical mobilization and the history of heavy machine traffic in the area under no-tillage systems, which caused changes in the soil surface layer's attributes.

The range values were from 3.17 to 101.0 m, with greater ranges observed in the reduced-tillage, except for SD in the depth of 0.00-0.10 m and Mi of 0.10-0.20 m. Contrary to Cavalcante *et al*. (2011), when observed the lower ranges for SD (5 m) and SRP (7 m), in conventional tillage, while in no-tillage, these were 9.5 and

Table 2. Adjustment parameters of the semivariogram models and respective degrees of spatial dependence for the soil physical attributes obtain at a depth of 0.0-0.10 and 0.10-0.20 m under no-tillage and reduced-tillage for sugarcane cultivation

Tillage	Model	Co	Co + C	A (m)	R^2	SQR	SPD	Class
				0 to 0.10 m				
				Soil density				
NT	Spherical	0.0013	0.0055	12.96	0.82	10^{-8}	0.76	Strong
RT	Exponential	0.0016	0.0056	3.17	0.96	10^{-9}	0.71	Moderate
				Soil resistance to penetration				
NT				***				
RT	Exponential	1.0370	3.6490	5.06	0.54	0.086	0.72	Moderate
				Soil macroporosity				
NT	Spherical	2.0400	8.3500	11.49	0.97	10^{-3}	0.76	Strong
RT				***				
				Soil microporosity				
NT	Spherical	0.442	1.796	13.42	1	10^{-6}	0.75	Strong
RT	Spherical	1.43	5.309	101.0	0.91	0.173	0.73	Moderate
				Total soil porosity				
NT	Exponential	1.80	5.533	4.53	0.86	0.039	0.67	Moderate
RT	Exponential	2.15	6.522	4.95	0.86	0.072	0.67	Moderate
				0.10 to 0.20 m				
				Soil density				
NT				***				
RT	Spherical	0.0024	0.0097	14.88	1	10^{-12}	0.75	Strong
				Soil resistance to penetration				
NT	Spherical	0.9620	3.846	9.50	0.85	10^{-3}	0.74	Moderate
RT	Spherical	1.6800	6.833	12.90	0.99	10^{-3}	0.75	Strong
				Soil macroporosity				
NT	Exponential	0.9060	1.8130	14.87	0.88	0.015	0.50	Moderate
RT	Spherical	1.88	8.77	16.97	0.92	0.237	0.79	Strong
				Soil microporosity				
NT	Exponential	0.731	3.0650	9.51	0.58	0.010	0.76	Strong
RT	Exponential	1.2080	4.0020	6.34	0.90	0.023	0.70	Moderateyourself
				Total soil porosity				
NT				***				
RT	Spherical	1.11	5.298	13.93	0.71	0.144	0.79	Strong

NT: No-tillage; RT: Reduced-tillage; Co: nugget effect; Co+C: Sill; A: range; R^2: Coefficient of determination of the semivariogram; SQR: Residual sum of squares; SPD: Spatial dependence of the soil attribute. ***: Pure nugget effect

10 m, respectively. For these authors, the more extensive ranges in no-tillage are due to excessive soil mechanical stabilization over time, unlike conventional tillage, which promotes heavy machine traffic and higher soil mobilization. However, in this study, the uniform soil tillage in the area may have generated a temporary stabilization of the arable layer, which did not occur in no-tillage due to excessive machine traffic for years.

The spherical and exponential semivariogram models were the best adjustments to represent all soil attributes, agreeing with Oliveira *et al*. (2013), Tavares *et al*. (2012) and Souza *et al*. (2009). However, the spherical model better adjusted the SD and Mi attributes, in no-tillage at a depth of 0.00-0.10 m and SRP at 0.10-0.20 m. In the no-tillage, there was a better fit for Mi in-depth of 0.00-0.10 m and 0.10-0.20 m. To the reduced-tillage, there was a better fit for SD, SRP, Ma, and TP in-depth 0.10-0.20 m. Regarding the exponential model for no-tillage, there was a better adjustment for SD and SRP, and TP in two soil managements at 0.00-0.10 m deep. In the reduced-tillage up 0.10-0.20 m deep, Ma obtained exponential tendency, while in both conservationist systems was Mi.

Cortez *et al*. (2018), working with a Dystrophic Red Latosol under no-tillage, observed the spherical model's adjustment for SRP, while Oliveira *et al*. (2013) studied a Cambisol found exponential and spherical models for SD, Ma, Mi, and TP. According to these authors, the adjusted exponential model explains a more abrupt change in the attribute variability. In contrast, the spherical model shows a smoother shift and a transition between the estimated variability values.

There are similar linear correlations between physical attributes of soil under reduced-tillage in two soil depths (Table 3). There are positive correlations between TP and Ma, SD and SRP, negative correlations between TP and SD, and SRP, and between Ma and Mi, SD and SRP. The mobilization effect on soil structure is perceived similarly in both depths, increasing Ma and reducing SD, SRP, and Mi.

On the other hand, the no-tillage influenced the two soil depths (Table 3). In the 0.00-0.10 m depth, a positive correlation was observed between TP and Ma, and negative correlations between SD and SRP with TP attributed to a positive correlation with the Ma. This result is possibly attributed to previous managements effects, given the recent implementation of the sugarcane cultivation system (ARCOVERDE *et al*., 2019c).

In the depth of 0.10-0.20 m, a positive correlation between TP and Mi was observed, a negative correlation between Ma and Mi. Yet, it is verified that the relationship between attributes is higher in the soil surface layer. A positive correlation between SD and SRP confirms the direct relationship between these attributes. The correlation coefficients of soil attributes obtained at a depth of 0.00-0.10 m were higher than those obtained at 0.10-0.20 m. The machines' continuous traffic has fewer influences on the depth of 0.10-0.20 m and factors intrinsic to the soil, such as clay content, conditions Mi, and, consequently, TP.

The linear correlations that present the greatest significance, either in no-tillage or reduced-tillage, can be highlighted SD and SRP, which in the two depths indicate positive and significant linear correlation (<0.01), with coefficients greater than 0.7. Thus, the DS and SRP data can select mathematical models that explain the relationship between the two attributes. Ma had similar behavior concerning TP, except in the soil depth of 0.10-0.20 m under no-tillage.

Observing the thematic cartograms for the depth of 0.0 to 0.10 m (Figure 2), the SD values (Figure 2A and 2B) ranged from 1.26 to 1.46 Mg m^{-3}, with lower values evaluated in reduced-tillage due to surface soil mobilization.

In cartograms of both the soil conservationist

Table 3. Matrix of linear correlation between the soil's physical attributes under no-tillage and reduced-tillage in the depths of 0.00-0.10 and 0.10-0.20 m

0.0-0.10 m					0.10-0.20 m				
No-tillage									
	TP	Ma	Mi	SD		TP	Ma	Mi	SD
Ma	0.9**				Ma	0.3			
Mi	-0.2	-0.6**			Mi	0.8**	-0.4*		
SD	-0.6**	-0.6**	0.3		SD	0.1	-0.3	0.3	
SRP	-0.6**	-0.6**	0.3	0.7**	SRP	-0.1	-0.3	0.1	0.7**
Reduced-tillage									
	TP	Ma	Mi	SD		TP	Ma	Mi	SD
Ma	0.8*				Ma	0.7**			
Mi	0.2	-0.4*			Mi	0.2	-0.5**		
SD	-0.5**	-0.6**	0.2		SD	-0.6**	-0.8**	0.3	
SRP	-0.4*	-0.5**	0.2	0.7**	SRP	-0.4	-0.6**	0.3	0.8**

**= (p<0,01); *= (p<0,05); TP - total porosity; Ma - macroporosity; Mi - microporosity; SD: density; SRP: soil resistance to penetration tillage systems, SD values above 1.36 Mg m^{-3} are observed in the area's central and northwest regions. Furthermore, in the reduced-tillage, there is, especially in the southeast region, the prevalence area of SD ranging between 1.26 and 1.31 Mg m^{-3}.

SRP (Figure 2C) ranged from 1.0 to 5.4 MPa, with values of the order of 2.1 to 5.4 MPa covering most of the area. It is also observed that the SRP follows the same pattern as the SD. The linear correlation analysis confirmed that zones with high SD would have high SRP. The relationship between RP and SD is observed by examining the Ma cartogram (Figure 2D). The higher the macropore values are expected, the lower resistance the soil offers to penetration and the existence of a compacted layer. Barbosa *et al*. (2018) observed a correlation between SRP and SD with the development of sugarcane roots in clay soil, pointing out the values of 2.5 MPa and 1.25 kg m^{-3} as restrictive to root growth.

Macroporosity values ranged from 4.5 to 12.5%, overall values between 6.5 and 10.5%. There are also values of 4.5% in the northwest region with higher SD and SRP. Santos *et al*. (2012) observed Ma's linear correlations with plant growth, and values below 0.10 m^3 m^{-3} impair the excellent root growth, the water infiltration, and the soil aeration.

The Mi values (Figure 2E and 2F) varied from 32.8 to 36.8%, obtaining the lowest values in no-tillage, probably preserving the soil surface layer. It was also observed that the highest Mi value was precisely in the region where the highest Ma values occurred. In the reduced-tillage was obtained values of Mi from 34 to 36.4%. However, the cartogram central region showed a higher range of intermediate values (34.6 to 35.8%).

The TP cartograms (Figure 2G and 2H) showed no-tillage variation from 39.5 to 45.1%, relatively lower than the reduced-tillage, ranging from 40.5 to 46.5%. According to Rosa Filho *et al*. (2009), although the machine traffic is more down in no-tillage, there is no revolving of the soil surface layer, causing an increase in surface density and a decrease in total porosity.

The thematic cartograms for the 0.10-0.20 m soil layer (Figure 3) bring SD values (Figure 3A) ranging from 1.20 to 1.52 Mg m^{-3} in the reduced-tillage. However, overall values are between 1.36 and 1.52 Mg m^{-3} in most cartogram areas.

There are SRP values (Figures 3B and 3C) ranging from 2 to 8 MPa in no-tillage and between 1.5 and 9.5 MPa in reduced-tillage, which prevailed in most of the area (northwest direction).

Ma data (Figure 3D and 3E) are between 5.3 and 7.3% in no-tillage and 3.5 and 13.5% in the other tillage system. Under the reduced-tillage, most Ma values are located in the range of 3.5%. The Mi (Figure 3F and 3G) in no-tillage is between 34 and 40%, and the reduced-tillage values are between 32 and 36%. Mi was generally higher in most of the cartogram area in no-tillage.

There were TP (Figure 3H) values between 37.5 and 45.5%, with predominance in the area of intermediate variation between 39.5 and 43.5%. Barros *et al*. (2016) and Ribeiro *et al*. (2016) observed that the soil pore space has a relationship with SD, which increased with TP reduction.

When analyzing the mean values of soil physical attributes and their spatialization in areas with soil management systems in sugarcane plants, it was observed for SRP that most of them have values within or above the range of 2.5 MPa (BARBOSA *et al*., 2018) to 3.8 MPa (SÁ *et al*., 2016) as limiting the root growth of plants in clay soils to very clayey. This result can also be attributed to high SD values, with most above 1.25 Mg m^{-3}, which is pointed out as preventing the growth of sugarcane roots in clay soil (BARBOSA *et al*., 2018).

Despite this, sugarcane is a species that seems to be more tolerant to soil compaction than other crops (SÁ *et al*., 2016) and, according to Arcoverde *et al*. (2019d), even if cultivation in soil with some restriction or physical impediment, such effects are mitigated when it is subjected to no-tillage, instead of reduced tillage, since the improvement of its physical quality and preservation of soil moisture is reflected in the productivity of cultivars, in sugarcane plant (ARCOVERDE *et al*., 2019a; ARCOVERDE *et al*., 2019d).

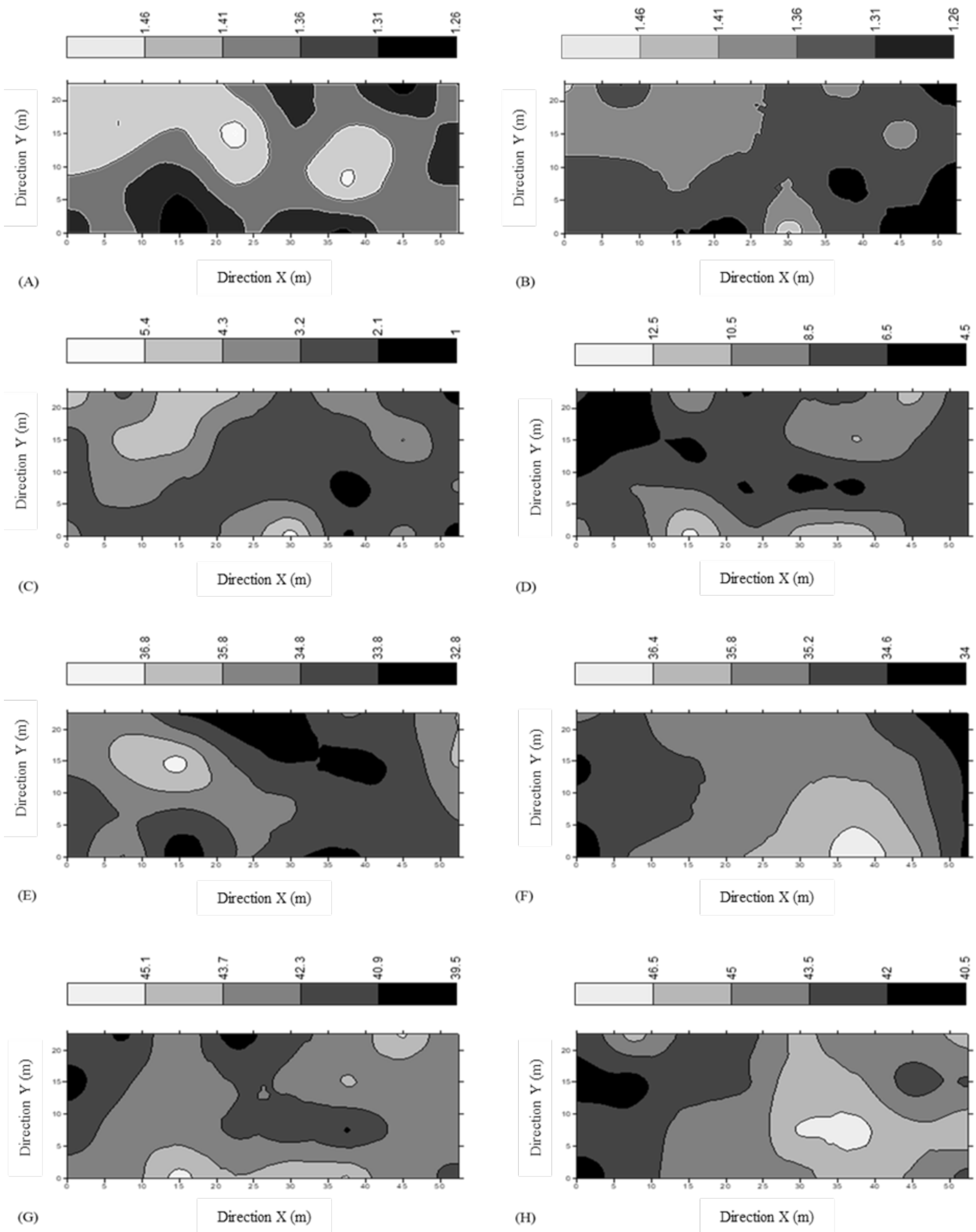

Figure 2. Isoline cartograms of soil physical attributes, in the depth of 0.0 to 0.10 m: (A) Soil density (Mg m^{-3}) - No-tillage, (B) Soil density (Mg m^{-3}) - Reduced-tillage, (C) Resistance penetration (MPa) - Reduced-tillage, (D) Macroporosity (%) - No-tillage, (E) Microporosity (%) - No-tillage, (F) Microporosity (%) - Reduced-tillage, (G) Total porosity (%) - No-tillage, and (H) Total porosity (%) - Reduced preparation

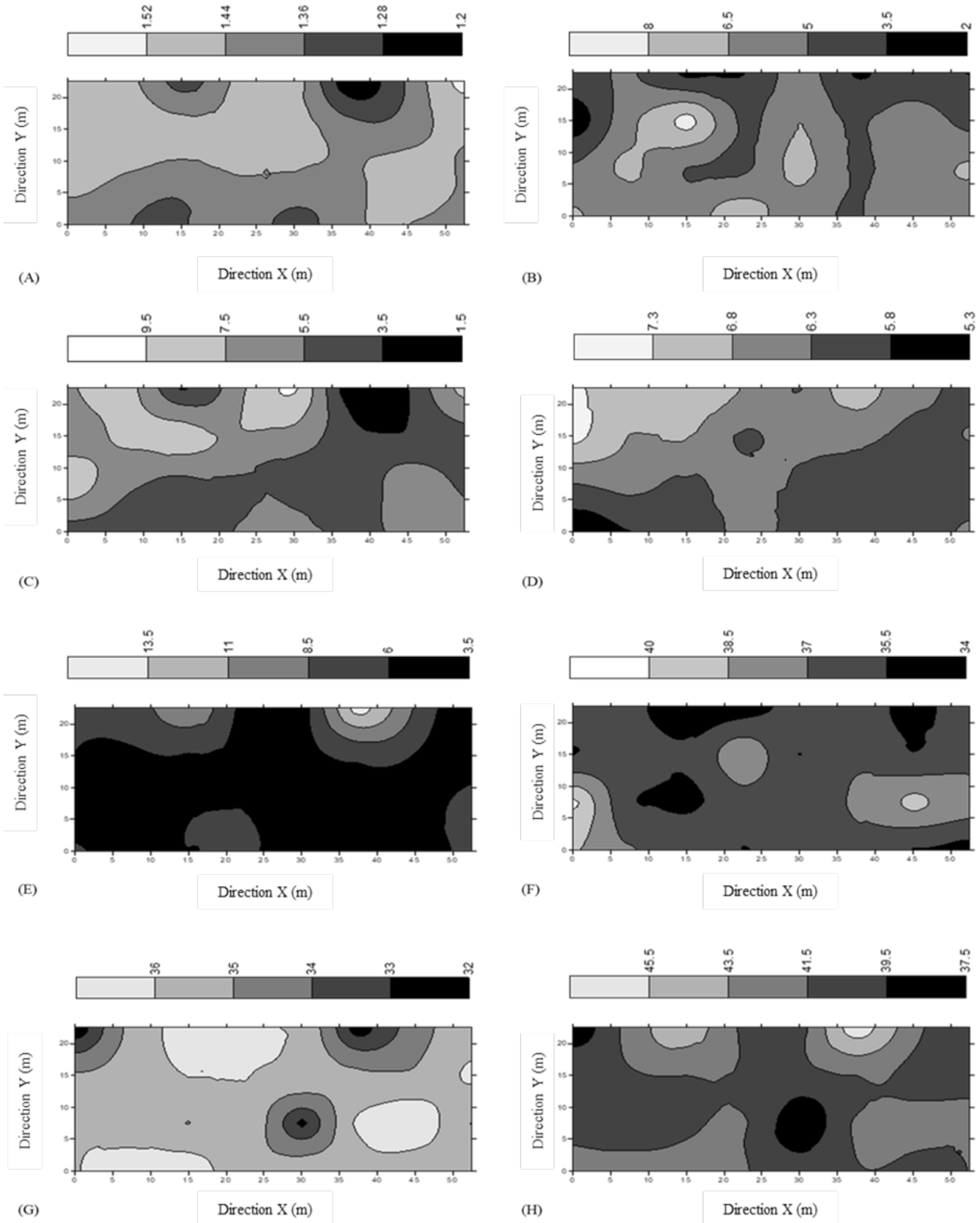

Figure 3. Thematic cartograms of soil physical attributes, in the 0.10-0.20 m layer. (A) Soil density (Mg m^{-3}) - Reduced-tillage, (B) Penetration Resistance (MPa) - No-tillage, (C) Resistance penetration (MPa) - Reduced preparation, (D) Macroporosity (%) - No-tillage, (E) Macroporosity (%) - Reduced preparation, (F) Microporosity (%) - No-tillage, (G) Microporosity (%) - Reduced preparation and (H) Total porosity (%) - Reduced preparation

CONCLUSIONS

- In the 0 to 0.10 m soil layer, there are lower soil densities and higher macroporosities and total porosities in most of the area under reduced-tillage. In the no-tillage area, there is more presence of micropores.
- In no-tillage (0.00-0.10 m), moderate to strong spatial dependence occurs, and this dependence is strong in reduced-tillage (0.10-0.20 m).

AUTHORSHIP CONTRIBUTION STATEMENT

ARCOVERDE, S. N. S.: Conceptualization, Formal Analysis, Methodology, Writing – original draft; **SOUZA, C. M. A.:** Data curation, Funding acquisition, Supervision, Validation, Writing – original draft; **NAGAHAMA, H. J.:** Formal Analysis, Software, Visualization, Writing – original draft, Writing – review & editing; **CORTEZ, J. W.:** Investigation, Resources, Software, Visualization, Writing – review & editing; **NASCIMENTO, J. M.:** Software, Writing – review & editing.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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