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Spatialization of chemical attributes, penetration resistance and magnetic susceptibility of the soil in a Cerrado area

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ABSTRACT: Knowledge on the spatial variability of chemical and physical attributes and magnetic susceptibility of the soil is important for precision agriculture, especially in Cerrado areas, which have limitations due to low natural fertility and acidity. The objective was to analyze the spatial variability of chemical attributes, penetration resistance, and magnetic susceptibility in a Cerrado area. The experiment was carried out in the municipality of Corrente-PI. A sampling grid was defined, with points spaced every 20 m, totaling 50 points, and soil was collected at a depth of 0.00-0.20 m. pH in water, phosphorus (P), organic matter (OM), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), H + Al (potential acidity), and aluminum (Al^{3+}), sand, silt, clay (Texture), penetration resistance (PR) and magnetic susceptibility (MS) were analyzed and the sum of bases (SB), cation exchange capacity (CEC) and percentage of base saturation (V%) were calculated. The values of chemical attributes had positive and negative relationships with pH. Penetration resistance showed that the area is under adequate management conditions and the magnetic susceptibility was considered low, reflecting the parent material, sandy rock. The Cerrado area has more than 50% of its extension with medium to high acidity and low fertility levels. The Cerrado area, in all aspects, has adequate values of soil penetration resistance and low magnetic susceptibility, probably resulting from the sandy soil, proven by the textural analysis.

Key words: precision agriculture; soil conservation; soil fertility; spatial variability

Espacialização dos atributos químicos, resistência a penetração e susceptibilidade magnética do solo em área de cerrado

RESUMO: O conhecimento da variabilidade espacial dos atributos químicos, físicos e susceptibilidade magnética do solo é importante para a agricultura de precisão, principalmente em áreas do cerrado que apresentam limitações, devido à baixa fertilidade natural e acidez. O objetivo foi analisar a variabilidade espacial dos atributos químicos, resistência a penetração e susceptibilidade magnética em área de cerrado. O experimento foi realizado no município de Corrente-PI. Foi definida uma malha amostral, com pontos espaçados a cada 20 m, totalizando 50 pontos, sendo coletada solo em uma profundidade de 0,00-0,20 m. Foram analisados pH em água, Fósforo (P), Matéria orgânica (MO), Potássio (K^+), Cálcio (Ca^{2+}), Magnésio (Mg^{2+}), H + Al (acidez potencial) e Alumínio (Al^{3+}), Areia, Silte, Argila (Textura), Resistência a penetração (RP) e Susceptibilidade magnética (SM), sendo calculado a soma de bases (SB), capacidade de troca de cátions (CTC) e percentagem de saturação por bases (V%). Os resultados indicaram que existe distribuição normal dos valores. Os valores dos atributos químicos seguem a relação positiva e negativas com o pH. A resistência a penetração mostrou que a área está em condições de manejo adequado e a susceptibilidade magnética foi considerada baixa, refletindo o material de origem, rocha arenosa. A área de cerrado possui mais de 50% de média a elevada acidez e níveis de fertilidade baixos. A área de cerrado avaliada, possui valores de resistência do solo em níveis adequados e baixa susceptibilidade magnética, provavelmente, decorrente do solo arenoso, comprovado pela análise de textura.

Palavras-chave: agricultura de precisão; conservação do solo; fertilidade do solo; variabilidade espacial

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Introduction

The Brazilian Cerrado has become one of the main areas of agricultural production in the country in recent years, and the opening and cultivation in this region, mainly in the central part of the country and recently in the Northeast of Brazil, have contributed to a substantial increase in national food production, but the intensification of soil tillage in conventional planting systems causes changes in physical, chemical and biological properties of the soil (Fernandes et al., 2017; Matias et al., 2019).

However, soils in this region are considered to have low fertility, due to the high degree of weathering and their parent material, limiting the growth of cultivated plants (Resende et al., 2014). The management of these soils should consider the capacity for absorption and availability of nutrients at the time of application, avoiding their lack and excess (Matias et al., 2019).

In this context, the study of soil variability combined with geostatistics has been a promising technique that can enable fertilizer management, providing the basis for applying the correct quantity, with no losses to the producer and to the environment, when in excess. In addition, soil chemical attributes play essential functions in plant morphogenesis, since these indicators, such as P, K^+, Ca^{2+} and Mg^{2+}, can limit plant development when found in low quantities in the soil (Gazola et al., 2017). Thus, mapping these attributes in agricultural areas is important for fertilizer recommendations, to indicate with greater precision and accuracy the fertility limit of the outlined areas.

However, inadequate management, associated with increased use of machines for soil tillage, can increase soil compaction, a process characterized by the reduction in the porous space of the soil, consequently increasing its density and penetration resistance (PR), reducing permeability and water infiltration, besides impairing root system development (Valente et al., 2019; Silva et al., 2017).

PR evaluation is based on the use of a penetrometer, with a conical tip, which exerts pressure on the soil, simulating the resistance offered by the soil to the penetration of roots (Lima et al., 2013). According to Collares et al. (2008), PR values between 1.5 and 3.0 MPa are considered critical for root growth and development.

The study of chemical attributes and PR through spatial variability assisted by geostatistics has been spreading in agricultural research, because it allows the analysis of spatial and temporal variability of soil attributes, through yield and fertility maps, making it possible to combine the use of technologies for input and crop management with the interest in maximizing yield (Dalchiavon et al., 2017; Silva et al., 2017).

However, this technique entails a volume of soil sample that may make its use impossible. In this context, the use of magnetic susceptibility (MS), defined as the measure of how much a material will be magnetized in the presence of a magnetic field, thus being an intrinsic characteristic of the minerals present in rocks, sediments and soil, allows indirect evaluation of soil attributes (Fernandes et al., 2017; Santos et al., 2011). According to Oliveira et al. (2015), MS can be correlated with several mineralogical, physical and chemical attributes in different soil classes. During the process of soil formation, natural magnetism is usually originated, requiring a time of continuous action of soil factors, so MS varies with the degree of weathering (Fernandes et al., 2017; Oliveira et al., 2015).

In addition, the search for indirect techniques that minimize environmental impacts has become frequent in soil science research, and indirect alternatives to quantify soil attributes with magnetic susceptibility have gained great prominence, as it consists of a property of magnetic minerals, detected in rocks and soil, and can be correlated with other attributes (Ramos et al., 2017). According to Siqueira et al. (2014), the MS technique has stood out for meeting the need to characterize soil attributes in large areas for detailed-scale surveys, mainly as sustainable management practices.

According to Siqueira et al. (2010), MS depends on the concentration of magnetic minerals present in the soil, originated from the electron rotation properties of minerals present in the rock or soil, measured as the ease with which a mineral is magnetized in the presence of a magnetic field. For Siqueira et al. (2010), MS together with geostatistics can identify sites with different production potentials, being used in pedotransfer functions. In this context, the present study aimed to analyze the spatial variability of chemical attributes, penetration resistance and magnetic susceptibility in a Cerrado area.

Materials and Methods

The study was carried out in the municipality of Corrente-PI, located in southeastern Piauí state, Brazil, with the following geographical coordinates: 10° 26’ South latitude, 45° 9’ West longitude, with an average altitude of 451 m. The climate of the region is classified, according to Köppen, as Aw (tropical climate with winter dry season), with average temperature of 24.9 °C and average annual rainfall of 1035 mm. The area where the experiment was conducted has a predominance of *Argissolo Amarelo* (Ultisol) (Santos et al., 2018), with 50% of forest characteristic of Cerrado, in addition to the presence of animals and slope ranging from 0.1 to 10%.

Soil samples were collected manually with the aid of a closed-cylinder soil sampler, at 0.00-0.20 m depth, at points spaced every 20 m, totaling 50 single samples, in an area of 0.5 hectare. All sampled points were georeferenced with a GPS. The area is used for pasture and sheep farming, and the animals are removed when the pasture quantity is around 20% of the total area.

Soil attributes were analyzed at the Soil and Plant Analysis Center of the State University of Piauí - UESPI, and the following chemical attributes were determined: pH, phosphorus (P), organic matter (OM), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), H+Al (potential acidity) and aluminum (Al^{3+}), with calculation of the sum of bases (SB), cation exchange capacity (CEC) and percentage of base saturation (V%). The pipette method was used to determine particle size (sand, silt and clay), based on the dispersion of samples by chemical agents and mechanical shaking according to recommendations proposed by Teixeira et al. (2017).

The pH was determined in water in the proportion of 1:2.5, using 10 cm^3 of soil and 25 ml of water, with subsequent reading in a potentiometer with combined glass electrode. Ca^{2+} and Mg^{2+} contents were extracted with 1 mol L^{-1} KCl solution, and reading was performed using an atomic absorption spectrophotometer. K^+ content was determined using a Mehlich-1 solution, with subsequent determination by flame spectrophotometry according to the methodology proposed by Teixeira et al. (2017).

Based on the results obtained in the chemical analyses, CEC and V% were calculated. CEC was determined by the sum of the bases, and H+Al was determined using calcium acetate buffered at pH 7.0, with volumetric determination by means of NaOH solution, using phenolphthalein as indicator. V% was determined by dividing the sum of the exchangeable bases by CEC and multiplying the result by 100. The obtained value indicates the percentage of negative charges occupied by the bases (Teixeira et al., 2017).

The magnetic susceptibility (MS) of the samples was determined according to the methodology of Siqueira et al. (2010). This technique comprises an analytical scale, a magnet, a magnet holder and a sample holder, promoting an interaction between the magnet and the magnetic minerals within the soil samples, generating a weight force on the scale, which is then converted into MS using a standard curve.

Soil penetration resistance (PR) was determined using a IAA/Planalsucar impact penetrometer with 30º cone angle. The penetration of the device's rod into the soil (cm/impact) was transformed into penetration resistance through the equation proposed by Stolf (1991) (Equation 1).

$$\mathrm{PR} = \frac{\left[\mathrm{Mg} + \mathrm{mg}\left(\frac{\mathrm{M}}{\mathrm{M}+\mathrm{m}} \cdot \frac{\mathrm{Mg}\cdot\mathrm{h}}{\mathrm{x}}\right)\right]}{\mathrm{A}} \qquad (1)$$

where: PR - soil penetration resistance, kgf cm^{-2} (kgf cm^{-2} * 0.098 = MPa); M - mass of the hammer, 4 kg (Mg - 4 kgf); m - mass of the device without hammer, 3.2 kg (Mg - 3.2 kgf); h - hammer fall height, 40 cm; x - penetration of the device's rod, cm/impact; and A - cone area, 1.29 cm^2.

PR was analyzed at 0-0.20 m depth, and there were no soil moisture analyses.

The data were subjected to descriptive statistical analysis, by initially performing an exploratory study, with Minitab 14 software (Minitab Release, 2000), calculating measures of location (mean, median, minimum and maximum), variability (coefficient of variation) and central tendency (skewness and kurtosis), to check the normality of the attributes evaluated. The coefficient of variation (CV) was classified according to Warrick & Nielsen (1980) as with low variability for values lower than 12%, medium variability for values between 12 and 60% and high variability for values greater than 60%.

Correlations between the variables analyzed by Pearson's correlation ($p < 0.05$) were determined using Minitab 14 statistical software (Minitab Release , 2000), adopting the classification proposed by Figueiredo Filho & Silva Júnior (2009): weak (0.1 > and ≤ 0.3), moderate (0.4 > and ≤ 0.6) and strong (0.7 > and ≤ 1.0). Thus, a good linear correlation between two variables should have a correlation coefficient with values at least higher than +0.60 (positive correlation) or lower than -0.60 (negative correlation).

The semivariograms were obtained through the GS+ program (Robertson, 2008), and the following models were fitted to the data: (a) spherical, (b) exponential and (c) Gaussian. These models were then used to predict each attribute at unsampled points by kriging, represented in contour maps, using the Surfer program (Golden Software, 2000).

The theoretical models were chosen based on the residual sum of squares (RSS), coefficient of determination (R^2) and, later, the correlation coefficient obtained by the cross-validation technique. The degree of spatial dependence (DSD) was classified based on the ratio between the nugget effect and the sill (C_0/C_0+C_1) as follows: weak for ratio higher than 75%; moderate for ratio between 25% and 75%; and strong for ratio lower than 25% (Cambardella et al., 1994).

Results and Discussion

The results obtained by the descriptive statistical analysis are described in Table 1, which shows that the mean and median values remained similar for the variables pH, K^+, Al^{3+}, PR, MS and Clay, indicating normal distribution. Silva et al. (2017) state that the expected normality in descriptive statistics is not a required parameter in geostatistics, as variation among the data is necessary and required.

The mean values of soil chemical attributes for the Cerrado area were classified as low for P (5.12 mg dm^{-3}), OM (0.43%), Ca^{2+} (0.48 $cmol_c$ dm^{-3}), Al^{3+} (0.10 $cmol_c$ dm^{-3}), SB (1.48 $cmol_c$ dm^{-3}), CEC_{pH7} (4.48 $cmol_{cd}$ dm^{-3}) and V% (35.01%), and medium for pH (5.51), K^+ (0.12 $cmol_c$ dm^{-3}), Mg^{2+} (0.87 $cmol_c$ dm^{-3}) and H+Al (3.00 $cmol_c$ dm^{-3}), according to soil fertility interpretation classes (Sobral et al., 2015).

The low and medium values can be justified by the predominant soil class, *Argissolo* (Ultisol), which from the physical point of view has low clay content (4%) and high sand content (91%) in the A horizon, resulting in a lower amount of charges for adsorption of chemical elements (Campos et al., 2011).

The result of PR (0.91 MPa) was considered low (Beutler et al., 2001) and, according to Valente et al. (2019), PR values above 2 MPa lead to impeding conditions for root system growth and development due to the higher degree

Table 1. Descriptive analysis of chemical attributes, physical attributes and magnetic susceptibility of the soil in a Cerrado area.

Attributes	M	Med	SD	Min	Max	Coefficients		
						Skew	Kurt	CV (%)
0-0.20 m depth								
pH (H_2O)	5.51	5.50	0.37	4.66	6.49	-0.03	0.31	6.75
OM %	0.43	0.38	0.32	0.00	1.22	0.38	-0.67	75.00
P (mg dm^{-3})	5.12	3.27	5.86	0.00	28.28	2.96	8.36	114.4
K^+ (cmol$_c$ dm^{-3})	0.12	0.09	0.07	0.04	0.37	1.68	2.69	59.96
Ca^{2+} (cmol$_c$ dm^{-3})	0.48	0.45	0.31	0.03	1.50	1.04	1.40	64.93
Mg^{2+} (cmol$_c$ dm^{-3})	0.87	0.80	0.40	0.10	2.30	0.90	2.32	45.97
H+Al (cmol$_c$ dm^{-3})	3.00	2.39	1.43	0.83	6.68	0.77	-0.30	47.67
Al^{3+} (cmol$_c$ dm^{-3})	0.10	0.08	0.09	0.00	0.38	1.20	1.08	87.18
SB (cmol$_c$ dm^{-3})	1.48	1.43	0.60	0.27	3.48	0.77	1.34	40.67
CEC (cmol$_c$ dm^{-3})	4.48	4.07	1.50	2.17	8.18	0.73	-0.24	33.54
V%	35.01	30.9	14.68	11.24	73.76	0.57	-0.34	41.93
PR (MPa)	0.91	0.92	0.13	0.67	1.27	0.62	0.72	14.34
Sand (g kg^{-1})	910.3	912.3	19.92	861.0	91.0	-0.79	0.21	2.19
Clay (g kg^{-1})	40.41	39.2	19.30	8.40	114.0	1.36	3.70	47.76
Silt (g kg^{-1})	49.28	45.55	23.20	10.90	104.6	0.70	0.05	47.08
MS (10^{-6} m^3 kg^{-1})	0.05	0.05	0.0005	0.04	0.07	2.15	6.71	9.03

CV - Coefficient of Variation [CV% = (Standard Deviation/Mean) x 100]; OM - Organic matter; K - Potassium; Ca - Calcium; Mg - Magnesium; SB - Sum of bases; ECE - Cation exchange capacity; V% - Base saturation; MS - Magnetic susceptibility; PR - Penetration resistance; M - Mean; Med - Median; Max - Maximum values; Min - Minimum values; SD - Standard deviation; Skew - Skewness; Kurt - Kurtosis.

of compaction. Different results were reported by Silva et al. (2017), who found 4.01, 5.18 and 5.12 MPa at depths of 0-0.10, 0.10-0.20 and 0.20-0.30 m, respectively, in a *Latossolo* (Oxisol) cultivated with maize.

MS ranged from 0.04 to 0.07 x 10^{-6} m^3 kg^{-1}, with an average of 0.05x 10^{-6} m^3 kg^{-1}, and these values are considered low (Siqueira et al., 2010, 2014). Similar results were obtained by Fernandes et al. (2017), who evaluated MS in soils of the Cerrado of Goiás and obtained values of 0.08 and 0.02 x 10^{-6} m^3 kg^{-1}, in *Latossolo* (Oxisol) and *Cambissolo* (Inceptisol) at a depth of 0-25 cm, respectively. According to these authors, soils with higher MS derive from igneous rocks because they have more ferromagnetic minerals, while lower values are related to soils derived from metamorphic and sedimentary rocks.

When studying samples from the 0.0-0.20 m depth in *Neossolo Regolítico* (Psamment) in the municipality of Gilbués-PI, Santos et al. (2011) found values of 0.6 x 10^{-6} m^3 kg^{-1} for MS, reporting that in soils originated from sandstone-basalt transitions the values vary from 1 to 10^{-6} m^3 kg^{-1}, so the behavior of MS occurs in response to the sandstone origin of the local soil and to the pedogenetic processes.

The pH and Sand attributes showed negative skewness coefficient (Table 1), with a trend of values greater than the arithmetic mean. The other chemical and physical attributes of the soil showed positively skewed distribution, with values lower than the mean.

According to Betzek et al. (2017), kurtosis coefficients are used to evaluate the flattening degree of a distribution compared to the normal curve. Kurtosis was classified as leptokurtic for H+Al, OM, CEC, V% and Sand and as platykurtic for the other attributes.

Considering the classification proposed by Warrick & Nielsen (1980), the CV of pH, MS and Sand showed homogeneous spatial dependence for values lower than 12%, heterogeneous for values between 12 and 60% for K^+, Mg^{2+}, H+Al, SB, CEC, V%, PR, Clay and Silt and very heterogeneous for results above 60% in the attributes P, Ca^{2+} and Al^{3+}, evidencing that most of the attributes showed medium values of variability, which can be associated with the soil formation processes and variations of management in the area.

An analysis of Pearson's linear correlation for the chemical attributes, physical attributes and magnetic susceptibility of the soil (Table 2) showed that most variables obtained significant values, with positive interaction at $p<0.01$ probability level.

It can be observed that Al^{3+} was the attribute that most obtained negative correlations at $p<0.01$ probability level, with pH (-0.8), Ca^{2+} (-0.6) and Mg^{2+} (-0.4). Regarding the positive correlations at $p<0.01$ probability level, SB was the attribute that most obtained correlations with pH (0.6), K^+ (0.4), Ca^{2+} (0.7) and Mg^{2+} (0.9). According to Moreira et al. (2020), for variables that show a negative correlation the results tend to have inverse positions, so as one increases the other decreases; for positive correlations, when one increases the value of the other variable tends to increase as well.

According to the classification proposed by Figueiredo Filho & Silva Júnior (2009), the correlations between pH and K^+, pH and H+Al, OM and H+Al, OM and SB, OM and PR, K^+ and Al^{3+}, SB and CEC, and Sand and Clay are considered weak, with values ranging from -0.3 to 0.3 at $p<0.05$ probability level. On the other hand, the correlations between pH and Mg^{2+}, SB, V%; OM and Mg^{2+}; K^+ and Mg^{2+}, SB; Ca^{2+} and Al^{3+}, V%; Mg^{2+} and Al^{3+}; CEC and V%; H+Al and Al^{3+}; Al^{3+} and SB; CEC and V%; Sand and Silt; and Clay and Silt are considered moderate (0.4 > and ≤ 0.6) at $p<0.01$ probability level, except

Table 2. Pearson's linear correlation between chemical attributes, physical attributes and magnetic susceptibility of the soil in a Cerrado area.

	pH	OM	P	K^+	Ca^{2+}	Mg^{2+}	H + Al	Al^{3+}	SB	CEC	V%	PR	MS	Sand	Clay
OM	-0.08														
P	0.2	0.0													
K^+	0.3**	0.1	0.8*												
Ca^{2+}	0.7*	-0.1	0.0	0.2											
Mg^{2+}	0.4*	0.5*	0.2	0.4**	0.3										
H + Al	-0.3**	-0.3**	-0.1	-0.0	-0.2	0.0									
Al^{3+}	-0.8*	-0.1	-0.2	-0.3**	-0.6*	-0.4*	0.4*								
SB	0.6*	0.3**	0.3	0.4*	0.7*	0.9*	-0.1	-0.6*							
CEC	-0.1	0.3	0.0	0.2	0.1	0.4*	0.9*	0.2	0.3**						
V%	0.6*	0.1	0.3	0.3	0.6*	0.5*	-0.7*	-0.7*	0.7*	-0.4*					
PE	0.2	0.3**	0.2	0.3	-0.1	-0.0	-0.3	-0.1	-0.0	-0.3	0.1				
MS	-0.0	-0.2	0.1	-0.1	-0.1	-0.2	-0.1	-0.0	-0.1	-0.1	-0.1	-0.0			
Sand	0.1	-0.2	0.1	-0.0	-0.0	0.1	0.1	-0.1	0.0	0.1	-0.0	-0.1	-0.2		
Clay	-0.2	-0.1	-0.2	0.0	-0.1	0.0	0.1	0.2	-0.0	0.0	-0.1	0.2	-0.1	-0.3**	
Silt	0.1	0.2	0.0	0.0	0.1	-0.1	-0.1	-0.1	-0.0	-0.1	0.1	-0.2	0.2	-0.6*	-0.6*

OM - Organic matter; K - Potassium; Ca - Calcium; Mg - Magnesium; SB - Sum of bases; CEC - Cation exchange capacity; V - Base saturation; MS - Magnetic susceptibility; PR - Penetration resistance. * and ** Significant at $p < 0.01$ and $p < 0.05$, respectively, by the F test.

for that between K^+ and Mg^{2+}. The strong correlations (0.7 > and ≤ 1.0) were all obtained at $p<0.01$ probability level, for the attributes pH and Ca^{2+}; P and K^+; Ca^{2+} and SB; Mg^{2+} and SB; H+Al and CEC, V%; Al^{3+} and V%; and SB and V%.

Regarding geostatistical parameters, it was identified that all chemical attributes, physical attributes and MS showed spatial dependence (Table 3). After checking the parameters of the semivariograms, the best fitted model was Gaussian, followed by exponential and spherical. Different results were reported by Santos et al. (2011), who found the best fits with the exponential and spherical models. According to Siqueira et al. (2012), the distances between the sampling points allow the identification of the semivariogram models, leading to the semivariance function.

Nugget effect (C_0) is related to sampling density, representing the unexplained variability, and these values are usually caused by measurement errors. Thus, when there is a pure nugget effect, it is not possible to identify the variability of the attributes (Matias et al., 2019). It can be observed that V% has a higher value (84), indicating low variability.

C_o+C_1 indicates the distance from the samples at which the values become constant, that is, the stationarity of the sampled results (Matias et al., 2019), and variation was observed in the values (4.1^{-05} to 427.7) of MS and Silt, respectively. According to Cambardella et al. (1994), C_o+C_1 is extremely important in the determination of range, informing the limits of dependence and spatial independence, thus being relevant in the choice of the statistical method to define the minimum distance between the sampling points, thus ensuring the independence of the samples.

Table 3. Estimation of the parameters of the semivariogram models fitted for the chemical attributes, physical attributes and magnetic susceptibility of the soil in a Cerrado area.

Attributes	Model	Co	$C_0 + C_1$	DSD	Rng (m)	R^2	CVRC	
							b	a
				0-0.20 m depth				
pH	Gaussian	0.0001	0.1512	0.07	38.79	0.91	0.7	1.62
OM	Gaussian	0.0001	0.1142	0.09	33.08	0.8	0.15	0.38
P	Gaussian	0.01	7.78	0.13	30.65	0.61	-0.32	5.11
K^+	Gaussian	0.00035	0.00544	6.43	46.59	0.98	0.84	0.02
Ca^{2+}	Exponential	0.0155	0.107	14.49	51.3	0.73	0.59	0.19
Mg^{2+}	Spherical	0.0014	0.1218	1.15	33.3	0.82	0.4	0.51
H + Al	Gaussian	0.001	2.424	0.04	34.46	0.85	1.04	-0.32
Al^{3+}	Gaussian	0.00001	0.00949	0.11	33.43	0.95	0.51	0.05
SB	Spherical	0.031	0.42	7.38	49.9	0.96	0.96	0.35
CEC	Exponential	0.0001	2.4	0.00	56.1	0.87	0.94	0.19
V%	Spherical	84	245.7	34.19	201	0.94	0.87	4.12
PR	Gaussian	0.01074	0.02288	46.94	101.33	0.94	0.69	0.28
MS	Exponential	0	4.1E-05	0.00	30.9	0.46	0.8	0.01
Sand	Spherical	0.1	272.2	0.04	17	0	0.93	59.71
Clay	Exponential	10.7	210.5	5.08	21.3	0.05	47.53	-0.26
Silt	Exponential	1	427.7	0.23	15	0.03	0.73	13.97

Co = nugget effect, $Co+C_1$ = sill, Rng = range, DSD = degree of spatial dependence [DSD% = $(C_0/C_0+C_1) \times 100$]; R^2: Coefficient of determination of the model; CVRC: Cross-validation regression coefficient; b: Angular coefficient; a: Interceptor.

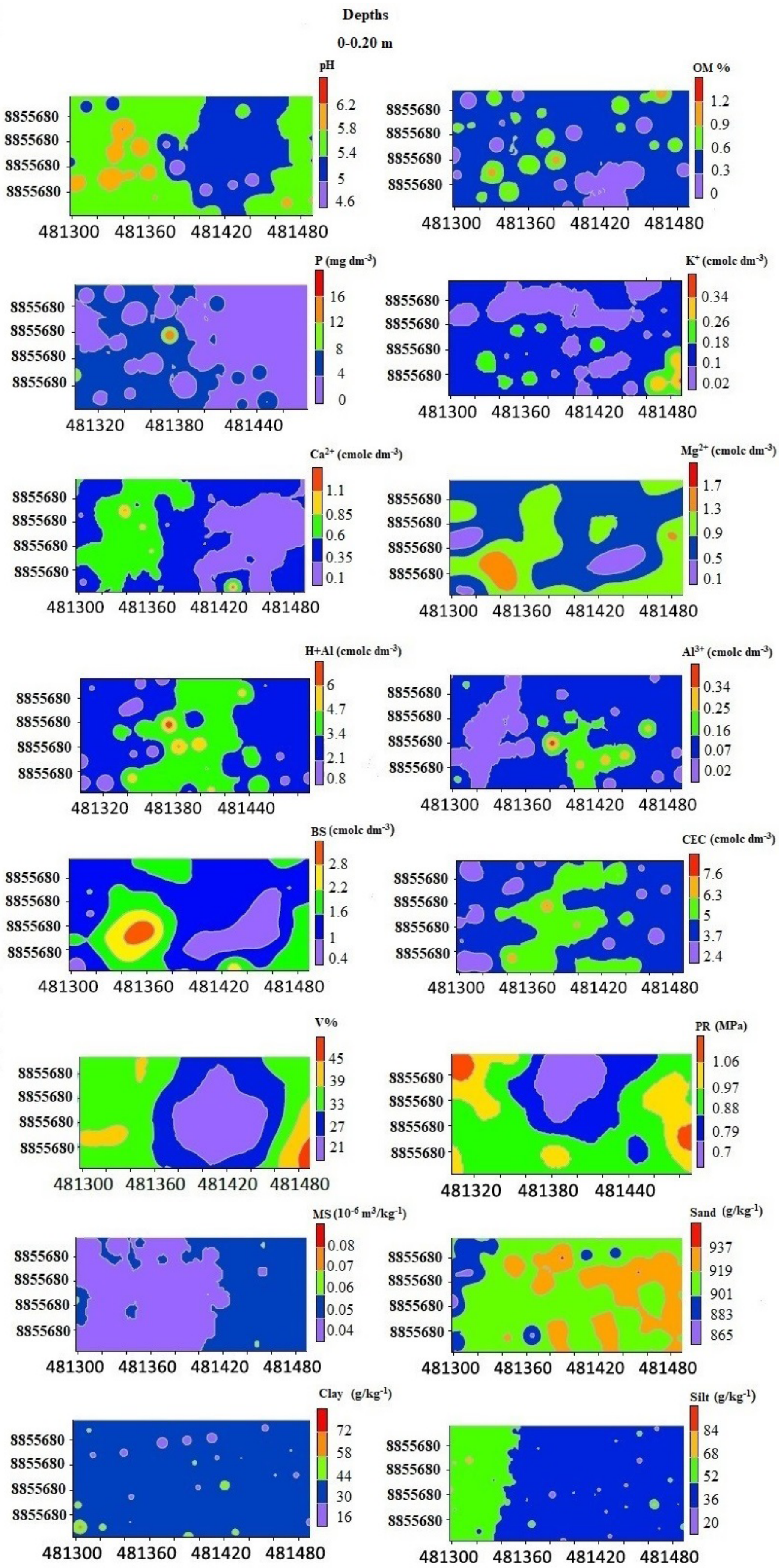

Figure 1. Spatialization maps of chemical attributes, physical attributes and magnetic susceptibility of the soil in a Cerrado area.

The variability in the degree of spatial dependence (DSD) was classified as moderate for V% and PR, and strong for the other attributes (Cambardella et al., 1994). The strong spatial dependence can be highly influenced by the minerals present in the soil, while the weak dependence is influenced by external factors, such as fertilization and soil management (Cambardella et al., 1994; Matias et al., 2019).

The range among the evaluated attributes showed values between 15 m for Silt and 101.33 m for PR, according to Gazola et al. (2017), Matias et al. (2019), Moreira et al. (2020) and Lundgren et al. (2017), range is the distance up to which there is correlation between the sampled points, being one of the main parameters in geostatistics, as it monitors the evolution of the attributes analyzed.

The spatial coefficients of determination (R^2) ranged from 0.03 to 0.98 for the attributes Silt and K^+, respectively. R^2 values closer to 1 indicate a better relationship between the actual value and the one estimated by the equation. The cross-validation regression coefficient (CVRC) indicates whether the model is actually expressing the actual situation of the area, when the values are close to one (b) and zero (a). According to Lundgren et al. (2017), errors are lower when there are higher values of CVRC (b) and lower (a), so the use of the kriging technique is reliable.

With the results of the fitted semivariograms, it was possible to construct the maps of the spatial distribution of the chemical and physical attributes pH, OM, P, K^+, Ca^{2+}, Mg^{2+}, H+Al, Al^{3+}, SB, CEC, V%, PR, MS, Sand, Clay and Silt (Figure 1). The construction of kriging maps makes it possible to evaluate the areas with higher and lower variability in relation to the attributes, enabling the adoption of techniques that assist in soil management (Gazola et al., 2017; Lundgren et al., 2017; Moreira et al., 2020).

Figure 1 allows identifying sites with higher and lower variability through interpolation by kriging. According to Matias et al. (2019), maps with closed and close lines identify areas with higher spatial variability and maps with spaced lines identify areas with lower variability.

When evaluating the area as a whole, it was possible to detect the spatial dependence of the chemical attributes, physical attributes and MS of the soil. According to Dalchiavon et al. (2017), soils with acidity ($pH < 5.0$) and low base saturation (< 50.0%) require liming and fertilization to homogenize fertility, as well as promoting better yield responses of agricultural crops.

Low values of the pedoindicator attribute MS were observed in the maps, showing that in the study area it is not possible to estimate the chemical and physical attributes using magnetic susceptibility, with also no significant correlation with the indicators (Table 2). Different results were obtained by Peluco et al. (2015), who found a positive correlation between MS and adsorbed P.

In this context, identifying the variability of the chemical attributes, physical attributes and MS of the soil will contribute in environmental terms to the definition of adequate doses of nutrients to be applied to the soil in a possible correction and fertilization, thus avoiding excessive applications in the soils of the region, hence resulting in less damage to the environment.

Conclusions

The Cerrado area has more than 50% of its extension with medium to high acidity and low fertility levels.

The Cerrado area evaluated has adequate values of soil penetration resistance and low magnetic susceptibility, probably resulting from the sandy soil, proven by the textural analysis.

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Compliance with Ethical Standards

Author contributions: Conceptualization: BAAB, MSN, RCL; Data curation: BAAB, MSN; Formal analysis: GSTF, SSRM, FFO; Investigation: BAAB, MSN; Methodology: GSTF, SSRM, FFO; Project administration: GSTF, SSRM; Supervision: MSN, RCL; Validation: GSTF, SSRM, RCL, FFO; Visualization: BAAB, MSN, RCL; Writing – original draft: BAAB, GSTF, SSRM; Writing – review & editing: GSTF, SSRM, FFO.

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