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Mapping of soil chemical attributes in pasture areas in the Cerrado of Piauí, Brazil

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Abstract

The low natural fertility and compaction of agricultural soils in the Cerrado are the main limitations for agricultural production. Changes in management systems are necessary to optimize the use of natural resources. The objective of this study was to map and evaluate the presence of penetration resistance and its relationship with soil chemical attributes in pasture areas in the Cerrado of Piauí. The experiment was carried out in the municipality of Corrente-PI, Brazil. The area was divided into two sub-areas of 0.5 ha each: the first is remaining vegetation and the second is pasture. Fifty soil samples were collected in the 0.00-0.20 and 0.20-0.40 m layers, with a sampling grid of 10 x 10 m. The pH in water, organic matter, calcium, magnesium, and soil penetration resistance were analyzed. The introduction of animals in the pasture area increased soil compaction by 2%. Chemical attributes, pH, organic matter, calcium and magnesium vary according to soil compaction by 2%. The native forest area has soil penetration resistance at acceptable levels (<2 MPa) and availability of nutrients at adequate levels. The maps of variability of organic matter, calcium, magnesium and penetration resistance showed the heterogeneity of the areas, allowing decisions based on specific management zones, localized application of nutrients and decompaction, and recovery of areas with inefficient management.

Keywords: geostatistics; variability; soil management; soil penetration resistance.

Mapeamento dos atributos químicos do solo em áreas de pastagens no cerrado piauiense

Resumo

A baixa fertilidade natural e a compactação dos solos agrícolas do cerrado são as principais limitações para produção agropecuária. Mudanças nos sistemas de manejo são necessárias para otimização do uso de recursos naturais. O objetivo do estudo foi mapear e avaliar a presença da resistência a penetração e sua relação com os atributos químicos do solo em áreas de pastagens no cerrado piauiense. O experimento foi realizado no município de Corrente-PI. A área foi dividida em duas subáreas de 0,5 ha cada: a primeira é de vegetação remanescente, e a segunda de pastagem. Foram retiradas 50 amostras de solos nas camadas: 0.00-0.20 e 0.20-0.40 m, com malha amostral de 10 x 10 m. Foram analisados, pH em água, matéria orgânica, cálcio, magnésio e resistência do solo a penetração. A introdução de animais na área de pastagem, aumentou a compactação do solo em 2%. Os atributos químicos, pH, matéria orgânica, cálcio e magnésio, variam de conforme a compactação do solo em 2%. A área de mata nativa apresenta resistência do solo à penetração em níveis aceitáveis (<2 MPa) e disponibilidade de nutrientes em níveis adequados. Os mapas de variabilidade espacial mostraram a heterogeneidade das áreas, permitindo decisões baseadas em zonas específicas de manejo, aplicação de nutrientes e descompactação localizada e recuperação das áreas com manejo ineficiente.

Palavras-chave: geoestatística; variabilidade; manejo do solo; resistência do solo à penetração.

1. Introduction

The increase in agricultural yield in Brazil is linked to the adoption of new technologies aimed at environmental sustainability, which is one of the necessary conditions for the growth of the sector so as to excel in the correct management of crops (BERNARDI *et al.,* 2017). In this context, detailed knowledge on soil compaction and fertility is indispensable for decision-making aimed at the best development and yield of crops.

Compaction interferes in soil physical, chemical and biological quality (CARLESSO *et al.,* 2019), and its mapping is challenging due to the heterogeneity of the areas and the diverse causes that may be related to increased bulk density and resistance to root penetration (ALAOUI; DISSERENS, 2018).

Compaction is the main indicator of low physical quality of arable soil, which limits the yield of most crops (VOGEL *et al.,* 2017; CARLESSO *et al.,* 2019). In compacted soils, the volume of macropores is reduced with increasing density, conferring greater physical resistance to the roots (FARIAS *et al.,* 2013; CHAI *et al.,* 2019). This compaction process can be assessed and measured through soil penetration resistance (SPR) and bulk density, since SPR is inversely related to root growth and consequently to crop yield (VOGEL *et al.,* 2017), also being associated with soil moisture.

In the Cerrado of Piauí, the low natural fertility of soils causes changes in the form of management in this region, when compared to traditional agriculture (MATIAS *et al.,* 2019), so the intensive use of land has caused physical, chemical and biological degradation of the soil, which leads to reduced crop yield and subsequent loss for the producer. Knowing the characteristics and spatial variability of the areas aiming at reducing soil degradation is indispensable for the implementation of sustainable agriculture from an environmental and economic point of view.

To identify the spatial dependence structure of attributes that indicate soil quality such as chemical, physical and biological, authors report in the literature the importance of geostatistics combined with kriging for digital mapping, in order to facilitate decision-making through modeling (ROSALEN *et al.,* 2011; MATIAS *et al.,* 2019; NÁJERA *et al.,* 2020; DUAN *et al.,* 2020).

The wide diversity of the results of studies on spatial variability of soil physical attributes is partly associated with the management system adopted (SIQUEIRA *et al.,* 2012; CARLESSO *et al*., 2019). Thus, studying the spatial variability of soil penetration resistance on the soil surface favors the understanding of how the management adopted in pasture areas affects the soil and, from this, of which techniques should be adopted for the best yield of pastures (MATIAS *et al.,* 2019).

The use of geostatistical tools allows constant evaluation of a large number of variables, with the capacity to determine specific management zones, evaluating variables that vary vertically and horizontally throughout the landscape, for the correct and safe use of water without degrading the environment (MOREIRA *et al.,* 2020), and their association with other statistical analyses, for example, correlation and descriptive.

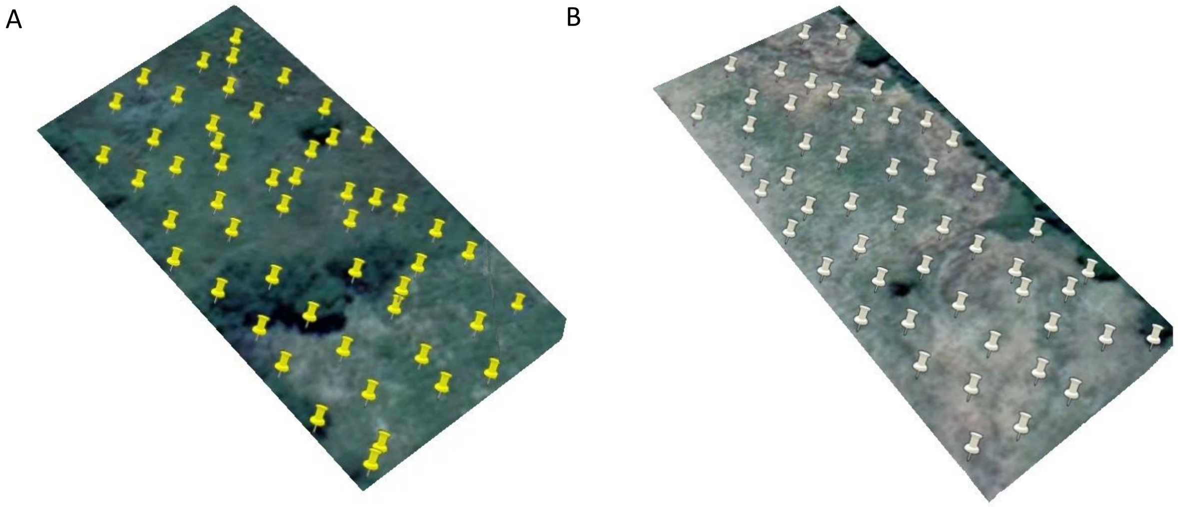
Faced with the challenge of modeling with geostatistics to ration the management of agricultural crops associated with the identification of specific management area, the present study aimed to map and evaluate the presence of penetration resistance and its relationship with soil chemical attributes in pasture areas in the Cerrado, aiming at improving agricultural management.

2. Material and methods

The experiment was conducted in the locality of Caxingó, in the municipality of Corrente-PI, Brazil, whose geographic coordinates are 10°26’ South latitude and 45°09’ West longitude, with an average altitude of 438 m. The slope varies from 1 to 10 %. The climate of the region, according to Köppen’s classification, is Aw’ type, characterized by being hot and semi-humid and with average annual temperature of 27 °C and average annual precipitation around 900 mm, concentrated in the period from November to April (ALVARES *et al.,* 2013).

The main area where the study was conducted was divided into two sub-areas of 0.5 ha each: area (A) has soil covered by vegetation, at the beginning of opening for pasture and cattle introduction, and area (B) has soil cultivated with pasture (Figure 1), at the beginning of degradation. The soil was classified as *Argissolo Amarelo* (Ultisol) (SANTOS *et al.,* 2018).

Figure 1. Sampling grid of the area under native vegetation (A) and at the beginning of opening for pasture introduction, and pasture (B), in beginning of degradation, located in the municipality of Corrente-PI, Brazil.



In area A, there is anthropic action, an area that has been prepared for the introduction of pasture and cattle for 3 years, with capoeira-type vegetation. In area B, there is no application of inputs, the cultivated species has been *Brachiaria brizantha* for 13 years, 3 animal units (AU) are placed in the area, and the animals stay as long as there is pasture. Then, they are moved to another location. After removing the animals, fire is set to improve the pasture and regrowth. Conservation practices are not used in the area. In addition, the two areas are located in a depression (valley), which receives sediments from other sites, due to inadequate management of higher areas, with little vegetation cover.

In each area, a regular internal sampling grid of 10 x 10 m was defined, and soil was collected at 50 points in the 0.00-0.20 and 0.20-0.40 m layers, in a total area of 1.0 ha, totaling 200 soil samples. At each point sampled, penetration resistance was evaluated to identify soil penetration resistance and chemical attributes were evaluated to characterize soil fertility. All the sampled points were georeferenced (Figure 1), and the points were marked with a tape measure, to better separate the area and the distance between the points.

Soil penetration resistance was determined using a IAA/Planalsucar impact penetrometer with cone angle of 30°, with 3 (three) replicates per sampling point, calculating the average at the end. The penetration of the penetrometer rod into the soil (cm/impact) was transformed into penetration resistance by means of the following formula (STOLF *et al.,* 2014):

$$SPR = \frac{\left[Mg + mg\left(\frac{M}{M+m}\ X\ \frac{Mg\ .h}{x}\right)\right]}{A}$$

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

The chemical attributes analyzed were: hydrogen potential (pH), calcium (Ca^{2+}), magnesium (Mg^{2+}) and organic matter. The pH in water was determined in water in the proportion of 1:2.5, using 10 cm^3 of soil and 25 ml of water. Ca^{2+} and Mg^{2+} contents were extracted with 1 mol L^{-1} KCl extracting solution and reading was performed in an atomic absorption spectrophotometer. Organic matter (OM) was determined by wet oxidation according to the methodology proposed by Teixeira *et al.* (2017).

The data were subjected to descriptive statistics analysis to observe the centralization of the data and the variations around the mean. The software program used was MINITAB®, and the measures of location (mean and median), variability (coefficient of variation) and central tendency (skewness and kurtosis) were calculated to check the normality of the attributes evaluated. The coefficient of variation (CV) was classified according to Warrick and Nielsen (1980), which consider variability as low for CV values below 12%, medium for CV between 12 and 60%, and high for CV values greater than 60%.

The semivariograms were obtained through the GS+ program. The following models were fitted to the data: spherical, exponential and Gaussian. Through these models, each attribute was predicted in unsampled areas by kriging, represented in contour maps created with SURFER® software.

The theoretical models were chosen by observing the residual sum of squares (RSS), coefficient of determination (R^2) and then 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), being considered weak for ratio higher than 75%, moderate for ratio between 25% and 75%, and strong for ratio below 25% (CAMBARDELLA *et al.,* 1994).

3. Results and discussion

By the exploratory analysis of descriptive statistics, it is observed that the mean and median values for the variables studied in areas A and B, in the two layers (0.00-20 and 0.20-0.40 m), with the exception of organic matter (OM), are similar (Table 1). Very similar values of mean and median indicate a normal, symmetrical distribution (OLIVEIRA JUNIOR *et al.,* 2011), showing that the values have central tendency measures and are not dominated by atypical values in the distribution (CAMBARDELLA *et al.,* 1994), so geostatistics can be applied (ARTUR *et al.,* 2014).

Table 1. Descriptive statistics of soil resistance to soil penetration and chemical attributes in areas under pasture and native forest in the 0.00-0.20 and 0.20-0.40 m layers.

Area A (Native forest)						**Area B (Pasture)**				
					0.00-0.20 m layer					
S.P.	**pH**	**OM**	**Ca^{2+}**	**Mg^{2+}**	**SPR**	**pH**	**OM**	**Ca^{2+}**	**Mg^{2+}**	**SPR**
	H_2O	**g kg^{-1}**	**$cmol_c$ dm^{-3}**		**MPa**	**H_2O**	**g kg^{-1}**	**$cmol_c$ dm^{-3}**		**MPa**
Mea.	5.6	9.5	2.2	0.9	1.50	5.5	8.4	1.5	2.0	1.64
Med.	5.6	9.9	2.2	1.0	1.43	5.5	8.5	1.5	2.0	1.51
Max.	6.8	15.9	4.8	1.9	2.73	7.4	9.2	2.9	4.2	3.58
Min.	4.9	2.1	0.4	0.1	0.47	4.7	7.5	0.5	0.1	0.52
Skw.	0.9	-0.2	0.4	0.4	0.21	1.1	-0.3	0.3	0.0	0.93
Kurt.	1.1	-0.3	-0.1	0.2	-0.59	2.2	-1.0	-0.9	-0.2	0.52
CV (%)	7.2	45.6	43.8	39.3	35.78	9.6	7.0	39.9	48.6	42.9
					0.20-0.40 m layer					
P.E.	**pH**	**OM**	**Ca^{2+}**	**Mg^{2+}**	**SPR**	**pH**	**OM**	**Ca^{2+}**	**Mg^{2+}**	**SPR**
Mea.	5.9	8.1	1.1	0.6	0.90	5.6	4.8	1.5	0.8	1.10
Med.	5.8	5.4	1.1	0.5	0.85	5.5	2.3	1.5	0.9	1.00
Max.	6.8	18.1	3.4	1.8	1.70	6.6	8.8	4.0	3.0	2.36
Min.	5.2	2.1	0.3	0.0	0.38	4.7	1.4	0.4	0.1	0.30
Skw.	0.2	0.9	1.3	0.7	0.43	0.2	0.1	0.9	1.3	0.80
Kurt.	-0.4	-0.9	3.5	0.3	-0.61	-0.5	-1.9	2.0	2.9	0.01
CV (%)	7.0	77.3	47.7	72.0	35.3	8.0	65.4	46.2	65.9	43.6

*S.P. = statistical parameters; Mea. = mean; Med. = median; Max. = maximum; Min. = minimum; Skw. = skewness; Kurt. = kurtosis; CV = coefficient of variation; SPR= soil penetration resistance.

Although the variability of chemical attributes can be classified according to their coefficient of variation (CV) (ARTUR *et al.,* 2014), this parameter is quantified relatively by percentage when the values are distancing themselves from the mean (OLIVEIRA JUNIOR *et al.,* 2011). In area A and B, in the 0.00-0.20 and 0.20-0.40 m layers, the CV was classified as low for pH and as medium for calcium (Ca^{2+}).

Considering the classification proposed by Warrick and Nielsen (1980), the CV of organic matter (OM) in the 0.00-0.20 m layer was the only attribute that showed different classification for the different areas, medium for vegetation and low for pasture, while in the 0.20-0.40 m layer the classification was equal (high). The CV for magnesium (Mg^{2+}) was medium in the 0.00-0.20 m layer and high in the 0.20-0.40 m layer, showing that the variability for most variables is medium. According to Vanni (1998), when the coefficient of variation is greater than 35% the series is heterogeneous, so the values found for the variables show heterogeneity, except for pH in the areas and in the two layers, as well as OM in area B in the 0.00-0.20 m layer. This heterogeneity in most of the attributes analyzed may have occurred due to the processes of soil formation, and in the pasture area this variation from medium to high may be related to the variations in management.

Regarding the geostatistical parameters, spatial dependence structure was identified for all attributes studied in the different areas and layers (Table 2). The best fitted models were spherical and exponential. The identification of semivariogram models leads to the function of semivariance, through the distances between the sampling points (SIQUEIRA *et al.,* 2012).

Table 2. Models and estimated parameters of the semivariograms for soil penetration resistance and chemical attributes of soil in areas under pasture and native forest, in a sample grid of 10 x 10 m.

Area A (Native forest)						**Area B (Pasture)**				
0.0-0.20 m layer										
G.P.	**pH**	**OM**	**Ca^{2+}**	**Mg^{2+}**	**SPR**	**pH**	**OM**	**Ca^{2+}**	**Mg^{2+}**	**SPR**
Mod.	Gau.	Gau.	Exp.	Exp.	Gau.	Exp.	Gau.	Exp.	Exp.	Sph.
Co	0.0	0.0	0.2	0.0	0.0	0.0	2.3	0.3	0.1	0.1
$Co+C_1$	0.3	0.5	0.5	0.9	0.3	0.1	24.2	1.2	0.3	0.6
Ran	16.2	59.4	161.1	19.5	13.6	19.5	40.8	47.1	632	41.7
R^2	0.8	0.9	0.7	0.8	0.8	0.7	0.9	0.9	0.5	0.9
DSD	0.0	8.9	42.0	27.8	1.9	9.9	9.7	26.3	27.7	28.2
CR(b)	1.0	0.9	0.9	0.4	0.9	0.9	0.9	0.9	0.7	0.7
Int(a)	-0.0	0.1	0.0	1.0	0.0	0.2	0.2	-0.0	0.2	0.3
0.20-0.40 m layer										
G.P.	**pH**	**OM**	**Ca^{2+}**	**Mg^{2+}**	**SPR**	**pH**	**OM**	**Ca^{2+}**	**Mg^{2+}**	**SPR**
Mod.	Exp.	Exp.	Sph.	Sph.	Sph.	Sph.	Exp.	Exp.	Sph.	Sph.
Co	0.1	6.1	0.1	0.0	0.0	0.1	2.6	0.03	0.01	0.2
$Co+C_1$	0.4	14.2	0.4	0.3	0.1	0.2	39.5	0.34	0.19	0.4
Alca.	354.9	207.3	36.5	14.5	18.9	48.4	13.2	24.6	14.0	92.6
R^2	0.7	0.6	0.9	0.5	0.7	0.9	0.31	0.88	0.58	0.8
DSD	32.8	43.3	27.7	0.2	5.4	26.6	6.6	8.52	2.63	42.1
RC(b)	0.9	1.0	0.9	0.9	0.9	1.0	1.0	0.60	0.33	0.9
Int(a)	0.5	-0.0	0.0	0.0	0.0	-0.2	-0.4	0.48	0.40	0.0

*G.P. = geostatistical parameters, Mod = model, Co = nugget effect, C_o+C_1 = sill, Ran = range, DSD = *degree of spatial dependence, RC = regression coefficient, INT = Intercept.

According to the classification of Cambardella *et al.* (1994), in the vegetation area in the 0.00-0.20 m layer the attributes pH (H_2O), OM and SPR showed strong spatial variability and for the same area in the 0.20-0.40 m layer, only Mg^{2+} and SPR did; the spatial variability for other attributes in the two layers was classified as moderate. The strong spatial dependence in the area of native forest can be justified by variations in the general and specific processes of soil formation and interactions with microclimatic processes such as the dynamics of water in the soil, resulting from the geographical position (relief), which leads to displacement of soil particles from one area to another. In this context, Branco *et al.* (2013) state that variables with strong dependence are more influenced by intrinsic soil properties (soil formation factors), while variables that show weak dependence are more influenced by atypical factors such as inadequate soil management. On the other hand, in the pasture area in the surface layer, only pH and OM showed strong spatial variability, and the other attributes showed moderate variability. In the 0.20-0.40 m layer, Ca^{2+} and Mg^{2+} entered the strong classification, which was not expected since their variability was classified as moderate in the surface layer.

The variability of soil pH in the surface layer is possibly associated with the Parnaíba river sedimentary basin, with different materials from the Formosa formation of the Rio Preto Group. In addition, in the pasture area, variations in management, sediments from other sites together with soil formation processes may have interfered with this variability. OM in the surface layer is very variable in space, since the roots (living organic matter) occupy a large volume of the soil and the process of decomposition of dead organic matter varies as a function of microbial activity and anthropic action. Oliveira *et al.* (2021) state that there was a greater input of organic matter in the surface layer, resulting from the low mineralization in banana planting area.

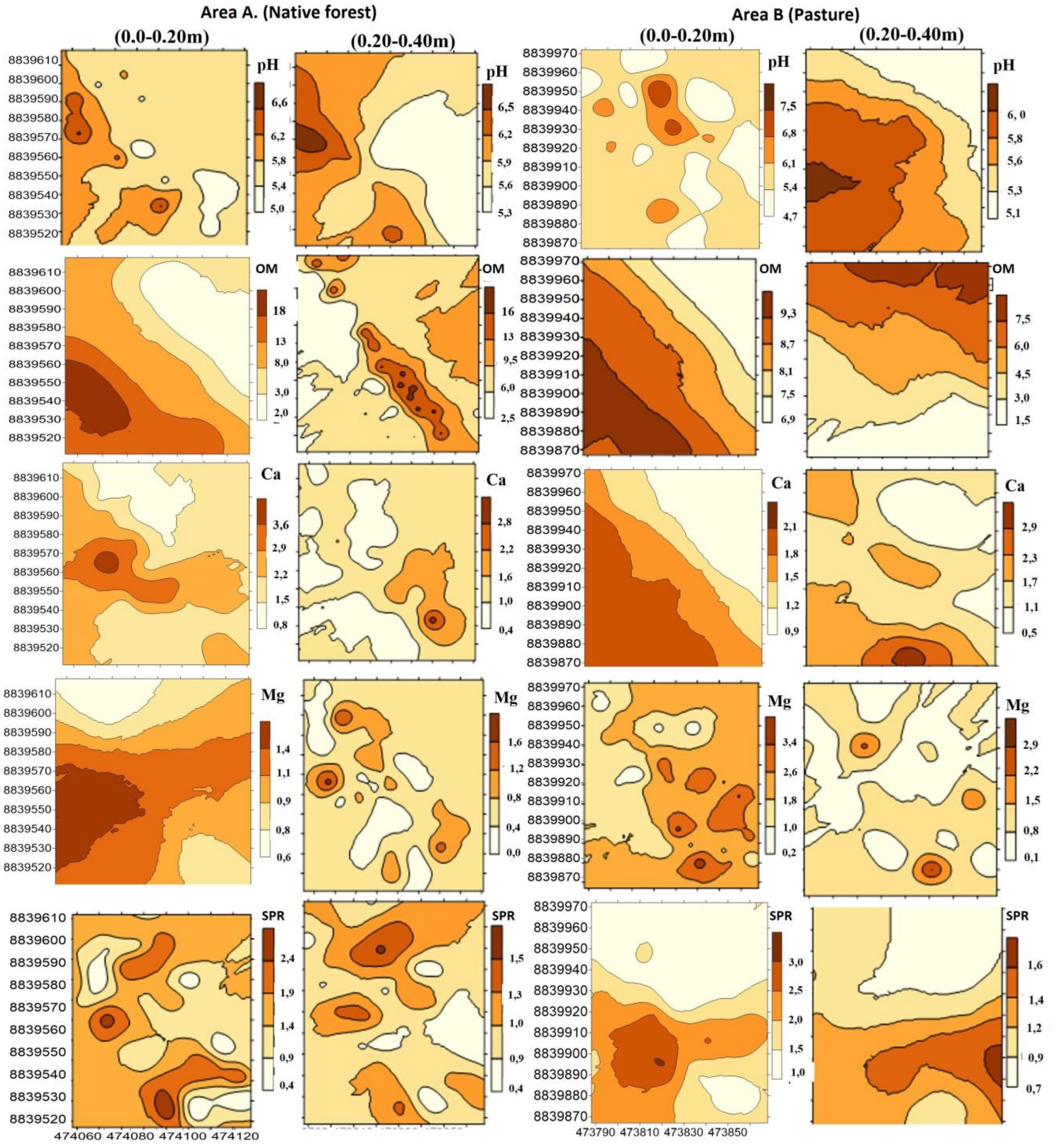
The variability of the degree of spatial dependence (DSD) was classified as strong for Ca^{2+} and Mg^{2+} in the 0.20-0.40 m layer, indicating that the sampling grid was sufficient to identify the variation. Moreover, this strong connection between the sampling points can be justified by the absorption of nutrients by thinner roots that are deeper, justified by the variability of OM, which is in the same classification in the pasture area, a result that was not observed in the native forest.

The results are reliable as more than 90% of the models showed R^2 above 50%, and this is more evident by the RC (b) with values close to 1 and intercepts (a) close to zero. Therefore, the sampling grid was sufficient, allowing accuracy of the data based on the previously mentioned variables. Matias *et al.* (2019) and Nájera *et al.* (2019) obtained similar results in their studies.

For RC (b) and intercept (a) in the 0.00-0.20 m and 0.20-0.40 m layers, the values were higher in the native forest area than in the pasture area, except for Ca^{2+} and Mg^{2+}, for which the values were higher in the pasture area than in the native forest area. This may have occurred due to the processes and factors of soil formation and possibly due to the decomposition of SOM, resulting in the availability of this nutrient, since there is no soil correction in this location. Figure 2 shows that the variation of soil penetration resistance in the pasture area is greater than in the vegetation area, evidencing animal trampling associated with the absence of conservation practices.

For the SPR attribute, values above 2 MPa are considered critical and begin to severely compromise plant development (GAO *et al.,* 2012; STEFANOSK *et al.,* 2013; VOGEL *et al.,* 2017). Gao *et al.* (2012) obtained excellent production with values of 3 MPa. In vegetation areas such as pasture, there are dark spots on the maps indicating soil compaction, with values above 2 MPa. Regarding the layers, higher SPR values in the surface layer are probably related to animal trampling in the pasture area, besides being a consequence of the absence of conservation practices.

Figure 2. Spatialization maps of soil penetration resistance and chemical attributes in areas under vegetation (A) and pasture (B), in a sampling grid of 10 x 10 m.



Although higher concentrations of nutrients are found in the sites with higher soil penetration resistance, this is not indicative of fertile and/or productive soil. Nutrients are retained in compacted soils because macropores are reduced, which compromises their movement by mass flow and diffusion and consequently limits their absorption by plants. In compacted areas, absorption by root interception is also compromised, since the roots face resistance of the soil to penetration, so they do not come into contact with chemical elements.

Compaction is the main physical constraint of the soil and, in pasture areas, it is related to the inadequate management systems adopted, especially in areas of continuous grazing without rotation (STEFANOSKI *et al.,* 2013). The main nutrients affected by compaction were calcium and magnesium, and these are the basis for the availability of the others, due to their power to neutralize aluminum, which causes high levels of acidity in the soil, compromising the absorption of the other nutrients by the plant or making them unavailable (MATIAS *et al.,* 2019). This situation is evident in sites where the level of compaction is higher, shown by the concentrations of these nutrients (Figure 2).

With regard to soil OM content, it follows the same behavior with regard to compaction. In this case, OM may have physical protection, which limits the access of microorganisms. Cui and Holdem (2015) observed a decrease in microbial communities in compacted soils, because soil microorganisms need good conditions of aeration and moisture to be active in the processes of decomposition and mineralization. Hargreaves *et al.* (2019), working with compacted soils, observed a significant reduction in water volume in soils with higher density and resistance to root penetration, with compromised movement of nutrients and biological activity. These results are in accordance with Carlesso *et al.* (2019), who investigated the influence of soil compaction on the decomposition of organic matter.

In addition, soil is a complex natural body and just as formation processes and factors interact in its genesis, chemical attributes are interconnected in surface and cannot be studied separately for an efficient management. It is observed that soil compaction interferes in the distribution and dynamics of chemical attributes and possibly in microbiology, which compromises the decomposition of organic matter. Studies that consider all attributes (physical, chemical, mineralogical and biological) tend to be more complete. Soil compaction is an evident problem, which impairs plant development and consequently the availability of nutrients.

4. Conclusions

The introduction of animals in the pasture area causes a 2% variation in soil compaction. Chemical attributes, pH, organic matter, Ca and Mg, vary according to soil compaction by 2%. The native forest area has soil penetration resistance at acceptable levels (<2 MPa) and nutrient availability at adequate levels. The variability maps of organic matter, calcium, magnesium and penetration resistance highlighted the heterogeneity of the areas, allowing decisions based on specific management zones, localized application of these nutrients and decompaction, and recovery of areas with inefficient management.

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