CHARACTERIZATION OF THE SOIL COMPACTION BASED ON THE MAPPING OF THE APPARENT ELECTRICAL CONDUCTIVITY

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ABSTRACT

Based on the measurement of soil penetration resistance (PR), it is possible to identify compacted soil layers, where root growth may be harmed, affecting crop development and yield. The objective of this work was to analyze the use of management zones (MZ), delimited on the basis of mapping of the spatial variability of the soil apparent electrical conductivity (ECa), in the differentiation of soil compaction levels. The work was carried out in a 25.8-ha no-tillage area, cultivated under a center pivot. The ECa was measured under two soil moisture conditions (13.7 and 16.45%), using the Terram® equipment. Soil penetration resistance (PR) was measured using the SoloStar PLG5500 penetrograph. Based on the spatial variability ECa mapping, management zones (2, 3, and 4 zones) were delimited. The mean PR values of each MZ were compared by the t-test of means. It was possible to differentiate mean values of penetration resistance (PR), which vary from 0.9 to 2.10 MPa, from the characterization of management classes generated on the basis of the ECa spatial variability. The highest stratification of PR values was obtained as a function of sampling directed at delimited management zones when the soil had lower moisture content (13.7%). The highest mean PR values were obtained for the split of the ECa map into at least three classes. It was identified that for the study area there is no need to perform any mechanical decompaction operation.

CARACTERIZAÇÃO DA COMPACTAÇÃO DO SOLO COM BASE NO MAPEAMENTO DA CONDUTIVIDADE ELÉTRICA APARENTE

RESUMO

A partir da medição da resistência do solo à penetração (RP) é possível identificar camadas de solo compactadas, onde o crescimento radicular poderá ser prejudicado, afetando o desenvolvimento e produtividade da cultura. Este trabalho objetivou analisar o uso de zonas de manejo (ZM), delimitadas com base no mapeamento da variabilidade espacial da condutividade elétrica aparente do solo (CEa), na diferenciação de níveis de compactação do solo. O trabalho foi realizado em uma área de plantio direto, cultivada sob pivô central, com 25,8 hectares. A CEa foi medida em duas condições de umidade do solo (13,7 e 16,45%), utilizando o equipamento Terram®. A resistência do solo à penetração (RP) foi medida utilizando o penetrógrafo SoloStar PLG5500. A partir do mapeamento da variabilidade espacial da CEa foram delimitadas zonas de manejo (2, 3 e 4 zonas). Os valores médios de RP de cada ZM foram comparados pelo teste de médias t. Foi possível diferenciar valores médios de resistência à penetração (RP), que variam entre 0,9 e 2,10 Mpa, a partir da caracterização de classes de manejo geradas com base na variabilidade espacial da CEa. A maior estratificação de valores de RP foi obtida em função da amostragem direcionada em zonas de manejo delimitadas quando o solo apresentava menor teor de umidade (13,7%). Os maiores valores médios de RP foram obtidos para a divisão do mapa de CEa em, no mínimo, três classes. Identificou-se que para a área do estudo não há necessidade de realizar nenhuma operação de descompactação mecânica.

SECTION EDITOR IN CHARGE
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INTRODUCTION

The diffusion of technologies in the field, especially the geospatial ones, allowed the mapping of the spatial variability of soil attributes capable of influencing the productive performance of crops, highlighting, in this context, the characteristics associated with the physical quality of the soil. Knowledge of the physical quality of the soil is essential to ensure that farming is being sustainably and profitably carried out. In addition, such knowledge allows adapting soil and water management systems, in order to ensure improvements in plant development (SPLIETHOFF *et al.*, 2020) and, consequently, in crop yield.

One of the physical characteristics of the soil that can be mapped is the soil penetration resistance (PR) which has been widely studied due to its potential to reduce the crop yield. Tavares Filho *et al.* (2012) highlight that PR is influenced by a series of soil properties, such as density, moisture content, texture, aggregation, cementation, organic matter content, and mineralogy. Because it is directly linked to soil compaction, PR has been used as an indicator of physical quality, as it describes the resistance that the soil exerts on the roots of plants that try to move through it, being directly influenced by density and porosity (MAZURANA *et al.*, 2013).

In this scenario, the mapping of the spatial variability of soil compaction can help in more assertive management, as it allows interventions to be applied in a localized manner. The localized treatment of soil compaction tends to be more effective, as it reduces the costs of mechanized agricultural operations since they are no longer carried out in a total area. However, its success depends on an accurate and reliable survey of this soil characteristic.

To map the PR spatial variability, collections are usually carried out at georeferenced points that compose a sampling grid, as shown in several studies (SOUZA *et al.*, 2020; SANTOS *et al.*, 2020; COMPAGNON *et al.*, 2020). According to Lopes *et al.* (2020), adequate sampling should be as small as possible, but with a representative accuracy, in order to produce reliable results. The accuracy of the mapping, in grid sampling, is directly related to the number of sampling points, and the denser the grid, the greater the reliability of the generated map (GELAIN *et al.*, 2021), however, the greater will also be the cost of sampling and laboratory analysis, which may, according to the size of the area, invalidate the use of this technique.

One strategy to reduce costs with grid sampling is the delimitation of management zones (MZ). The MZs can be understood as sub-regions of the production field that have similar characteristics that limit crop yield. This is a simpler approach for managing the spatial variability of crops and soils (DALCHIAVON *et al.*, 2012; RODRIGUES JUNIOR *et al.*, 2011; MORAL *et al.*, 2011), being one of the fundamental principles of precision agriculture (XIAOHU *et al.*, 2016).

The success of management using MZ depends on the relationship of the variable to be mapped to those that will be managed. Studies have shown a correlation between the apparent soil electrical conductivity (CEa) and chemical and physical attributes of the soil (MORAL *et al.*, 2010; RODRÍGUEZ-PÉREZ *et al.*, 2011; CORASSA *et al.*, 2016) that influence the crop yield. The measurement of ECa is faster and cheaper than traditional soil sampling and laboratory analysis (BOTTEGA *et al.*, 2017) which makes it a potential variable in MZ delimitation. In addition, ECa has been used as an indirect estimator of the variability existing in a production field (CORWIN; LESCH, 2003).

Considering the relationship between ECa and soil attributes (MORAL *et al.*, 2010; RODRÍGUEZ-PÉREZ *et al.*, 2011; CORASSA *et al.*, 2016) and its potential as a limiting factor for MZ and considering the scarcity of studies on the relationship of ECa with soil compaction, the objective of this work was to evaluate the use of management zones, delimited on the basis of the mapping of the ECa spatial variability, as a factor of differentiation of soil compaction levels.

MATERIAL AND METHODS

This experiment was conducted in the municipality of Cachoeira do Sul, State of Rio Grande do Sul, in a 25.8-ha commercial area

intended to grain crops in a no-tillage system under central-pivot. The soil in the region is classified as Red Argisol (EMBRAPA, 2013). It was established a sample net made up of 95 points and a 50 x 50-meter regular spacing. These points were used as a base for altitude data collection in relation to sea level, quantification of the soil penetration resistance (PR, MPa). Soil samples were collected in the 25 points for texture and moisture characterization (red-circled points). Figure 1 shows the sample points map (Figure 1A) and the representative map of the digital elevation model of the study area (Figure 1B).

A Garmin GNSS (Global Navigation Satellite System) receiver, model GPSMAP 62sc was used to locate the sampling points in the area, to obtain the altitude value in relation to sea level, and to collect soil samples. Soil collection was carried out using a Dutch-type auger. Representative samples were taken from a 0-20 cm depth. The samples were placed in aluminum capsules and plastic packaging and later sent to the laboratory for moisture quantification and texture classification.

Apparent electrical conductivity was measured under different soil moisture conditions. On the first day of readings (11/13/2018), the soil moisture content was estimated at 13.7% (lower moisture). The second reading was carried out on 11/17/2018, with an estimated humidity of 16.45% (higher humidity). CEa readings were taken in the off-season, containing wheat residue on the soil.

For the CEa readings, the Falker *Automação Agrícola* Terram® equipment was used. The Terram is a piece of equipment consisting of a chassis where four discs equally spaced at 0.25 m are mounted, which guarantees the measurement of ECa up to 0.25 m in depth. Weights were added to the chassis to ensure the cutting of the straw and the contact of the discs with the soil ground. The inner disks act as potential electrodes and the outer ones as current electrodes. The electrical conductivity of the soil represents the inverse of the electrical resistivity of the soil, which is measured through the potential difference between the current emitted and that received.

The PR was measured on November 17, 2018, using a penetrograph, manufactured by the Falker company (Falker Automação Agrícola Ltda, Porto Alegre/RS, Brazil) model SoloStar PLG5500, with an automated measurement system. The equipment performs electronic measurement of penetration resistance along with depth measurement. A type-2 cone was used, with a diameter of 12.83 mm, and the PR was measured at a depth of 0-40 cm, being stratified into four parts, for analysis of the PR in the 0-10; 10-20; 20- 30 and 30-40 cm layers. The collected data were recorded in the Fieldbox system, manufactured by the same company. The Terram and the penetrograph were coupled to a quadricycle for displacement in the study area. After running the area using the set, 95 PR (Figure 1A) and 4485 CEa readings were obtained. Figure 2 shows the quadricycle equipped with the penetrograph and the ECa meter Terram (Figure 2A) and a walking map detailing the ECa reading points on the ground (Figure 2B).

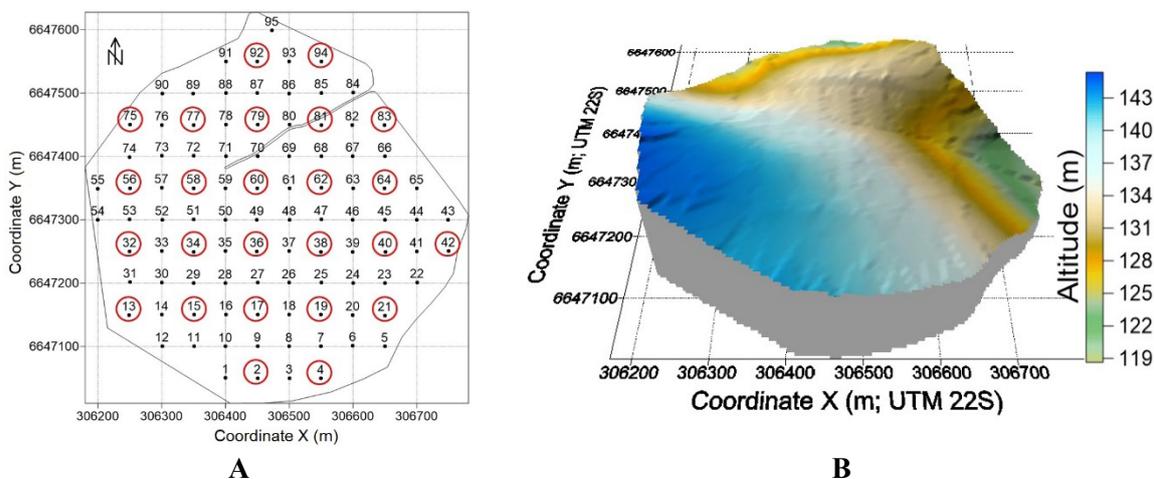**A**   **B**

Figure 1. Study area and points used as a basis for measuring soil penetration resistance (PR, MPa) and soil samples collection (A) and digital terrain elevation model (B)

Figure 2. A quadricycle plus penetrograph plus Terram set in the study area (A) and walking map detailing the reading points of the ECa on the soil (B)

First, CEa data were filtered and those considered different were removed. For their identification, it was used the method proposed by Libardi *et al.* (1996), with the critical threshold defined from the interquartile dispersion (DQ), in which the upper limit is defined by (Q3 + 1.5 x DQ) and the lower by (Q1 - 1.5 x DQ), where Q1 and Q3 are the first and third quartiles, respectively. The filtered CEa values and the PR readings (0-40 cm) composed the database used in the analysis. The spatial dependence of CEa and PR were evaluated using variogram adjustments, assuming the stationarity of the intrinsic hypothesis, defined by Equation 1.

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(xi) - Z(xi+h)]^2 \quad (1)$$

Where;

$\hat{\gamma}(h)$ = Semi-variance as a function of the separation distance (h) among the point pairs;
h = Separation distance among the pairs of points, m;
N (h) = Number of experimental observation pairs Z(xi) and Z (xi + h) separated by an *h* distance.

The Gaussian, spherical and exponential models were tested. The selected model was that with the smallest residual sum of squares (OLIVER; WEBSTER, 2014). The selected model was evaluated using the cross-validation technique, which consists of removing the value from the database and estimating it using the adjusted model. The measured and estimated values are plotted on a graph. The accuracy of the model is reflected by the following parameters: coefficient of determination (the closer to 1, the more accurate the estimates), standard error of prediction (the smaller the more accurate the estimates), and intercept (the closer to zero, more accurate are the estimates).

Once the spatial dependence was detected and the theoretical semi-variance model adjusted, spatial variability maps for CEa and PR were produced. Value interpolation was performed using ordinary kriging. This interpolation method was selected because it provides the best linear predictions without bias (BLUP), seeking the minimum variance (OLIVER; WEBSTER, 2014). For the estimates of values in non-sampled locations, 16 close neighbors and a search radius equal to 50% of the range value found in the variogram adjustment were used, in order to guarantee the interval of the spatial continuity.

After choosing the model, the following parameters were determined: nugget effect (C_0), plateau effect ($C_0 + C_1$), range effect (A), fit determination coefficient (r^2), and residual sum of squares (RSS). The geostatistical analysis was performed using the computer program GS+, version 7 (GAMMA DESIGN, 2006) and spatial variability maps made in the Surfer program, version 10 (GOLDEN SOFTWARE, 2011).

Using the data files estimated by kriging, originated in the geostatistical analysis, the management zones were delimited, based on the CEa measurements on the two sampling dates. The delimitation of management zones was carried out using the KrigMe computer program, developed

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by Valente (2010). The program uses the Fuzzy k-means classification algorithm in the analysis of data clustering and class generation. Maps of management zones with 2, 3, and 4 classes were generated for each of the CEa reading dates.

The ECa data measured for the two sampling dates and RP, obtained for the four soil layers, were submitted to descriptive statistical analysis. The mean, minimum and maximum values, standard deviation, and coefficient of variation were calculated. The PR sampling points map was overlapped on the management zone maps previously made. The PR sampling points belonging to each class of the MZ map were identified and their values made up the database used in the mean test. Sampling points close to the boundary between two zones were not considered in the statistical analysis in order to reduce errors associated with the characterization of each zone.

Next, the Shapiro-Wilk normality test (W; $p<0.05$) was performed, a basic premise for the execution of the t-means test. The management classes in which the PR values were normally distributed were then submitted to the t-test ($p<0.05$), to identify whether the management zones generated from the measurement of ECa were able to differentiate soil PR levels. Statistical

analyses were performed using Statistica software, version 7 (STATSOFT, 2004).

RESULTS AND DISCUSSION

The soil in the experiment area showed average values of 340 g kg^{-1} for clay, 460 g.kg^{-1} for sand, and 20 g.kg^{-1} for silt. It was classified as average texture (EMBRAPA, 2013). Table 1 shows the statistical summary for CEa readings in both soil moisture conditions in which they were carried out.

It was observed for the measured ECa that soil had higher moisture content (16.45%), higher mean (7.89 mS m^{-1}), and lower CV% (17.79) values. This fact can be explained because the electrical conductivity depends to a large extent on the electrolyte solution existing in the soil instead of its solid particles. Therefore, the level of the soil electrical conductivity is mainly due to its water content and the content of dissolved salts in it (FREELAND, 1989).

The statistical summary for soil PR values is shown in Table 2. The mean values ranged from 0.9 (0-10 cm) to 2.10 Mpa (30-40 cm). This variation shows an increasing trend of the PR according to the increment in the measured depth

The rise in the PR values of the soil as a function

Table 1. Descriptive statistical summary of the soil apparent electric conductivity (ECa, mS m^{-1}) measured in the experiment area in two soil moisture conditions

Soil attribute	Depth (cm)	Statistical parameters	Lower moisture	Higher moisture
ECa (mS m^{-1})	0 – 25	Average	5.72	7.89
		Minimum	3.44	4.79
		Maximum	10.70	12.29
		Standard deviation	1.22	1.40
		CV (%)	21.38	17.79

CV (%): Coefficient of variation

Table 2. Descriptive statistical summary of penetration resistance (PR, MPa).

Depth (cm)	Mean (MPa)	Minimum	Maximum	Standard deviation	CV (%)
0-10	0.90	0.30	1.67	0.29	32.20
10-20	1.67	1.05	2.30	0.23	13.72
20-30	1.74	1.08	2.43	0.24	13.75
30-40	2.10	1.39	3.49	0.32	15.17

CV (%): Coefficient of variation

of the measurement depth was expected, as the soil in the experimental area presents a textural horizon in the subsurface. Studies conducted by Cortez *et al.* (2014), in a yellow Argisol, indicated an increase in PR in depth up to the 0.25-0.30 m layer. According to the authors, this behavior is caused by a set of factors, such: 1) greater deposition of organic matter and biological activity in the superficial layers and 2) intense machine/implement traffic in an area without soil disturbance. Factor 1 reduces soil density. Factor 2, on the other hand, promotes the distribution of pressures resulting from the soil-rolled contact, contributing to the formation of compacted layers and the increase in PR in the subsurface layers. The results obtained in this study corroborate those observed by the authors and can be explained by the cultivation system adopted in the area, which was the no-tillage system with crop rotation.

Figure 3 shows the semi-variograms and cross-validation graphs, corresponding to the modeling of the spatial dependence of the ECa for readings with different soil moisture contents. ECa showed spatial dependence for the two soil moisture

conditions in which it was measured. According to Wagner *et al.* (2018), among other attributes, ECa is related to soil texture, cation exchange capacity, water storage, organic matter content, porosity, salinity, acidity attributes, and subsoil characteristics. Therefore, variations in these characteristics will also cause variations in ECa readings. The spherical model was the one that best fit the semi-variance of the experimental data.

It is shown in Figure 4 the semi-variograms and cross-validation graphs, corresponding to the modeling of the spatial dependence of the PR for the four soil layers. Spatial dependence was observed for PR in the 0-10, 20-30, and 30-40 cm layers, with the Gaussian Model adjusted for the first soil layer and the Spherical model for the others. In the 10-20 cm layer, there was no spatial variability of PR (Figure 4C), which can be explained by the non-existence, in fact, of the variability or even by the need for a denser grid to detect such variability, which is discarded, as the variability was detected for the other layers. In addition, this soil layer has a greater accumulation of organic matter, which influences its density and, consequently, its PR (CUSTÓDIO *et al.*, 2015).
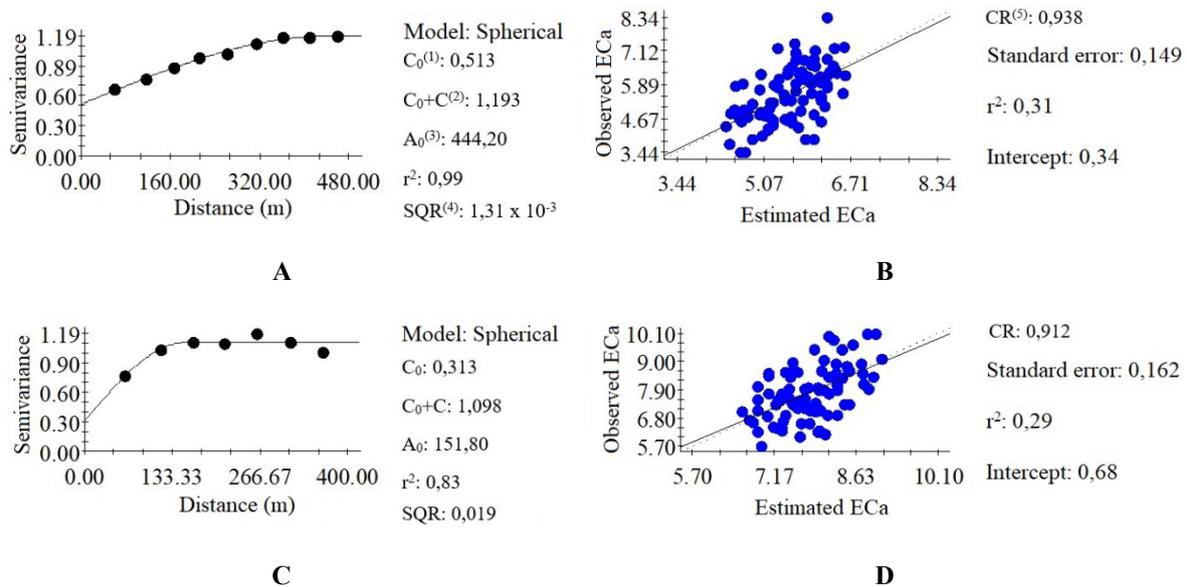

Figure 3. Theoretical semi-variance models, parameters of the mathematical models of the adjusted semi-variograms, and cross-validation graphs of the spatial dependence modeling of the soil apparent electrical conductivity (ECa, mS m^{-1}) measured in lower soil moisture (A and B) and higher soil moisture (C and D). [1]Nugget effect. [2]Threshold. [3]Range (m). [4]Sum of Squares of the Residue. [5]Regression coefficient
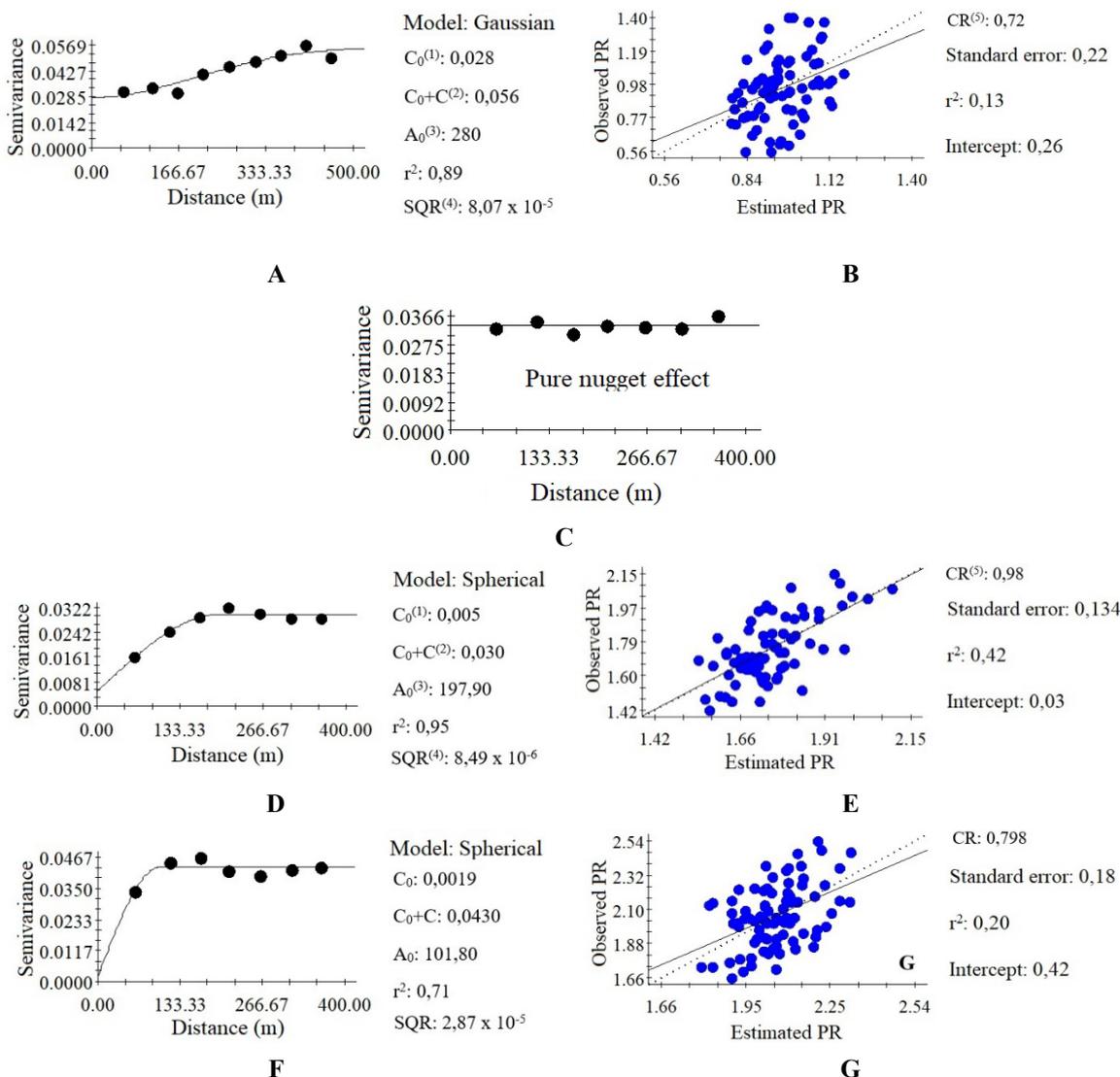
Figure 4. Theoretical semi variance models, parameters of the mathematical models of the fitted semi-variograms, and cross-validation graphs of modeling the spatial dependence of penetration resistance (PR, MPa) at the depths of 0-10 cm (A and B); 10-20 cm (C); 20-30 cm (D and E) and 30-40 cm (F and G). [1]Nugget effect. [2] Threshold. [3]Range (m). [4]Residual sum of squares. [5] Regression coefficient

The greatest ranges were observed for electrical conductivity measured in soil with low moisture content and PR in the 0-10 cm layer. Range values can influence the quality of estimates as it determines the number of values used in the interpolation. Thus, estimates made with interpolation through ordinary kriging using values with larger ranges tend to be more reliable, presenting maps that better represent the reality (CORÁ *et al.*, 2004).

The representative thematic maps of the spatial variability of the CEa and the PR are shown in Figure 5.

The variations observed in ECa maps can be explained by the variations in the soil attributes. ECa is influenced by texture, soil moisture, organic matter content, acidity, fertility level, and compaction level (CORASSA *et al.*, 2016) and these factors are related to each other. An experiment conducted by Wagner *et al.* (2018) demonstrated a significant relationship between ECa and soil PR, where this relationship was greater in the superficial layers, up to 25 cm. Also, according to the authors,
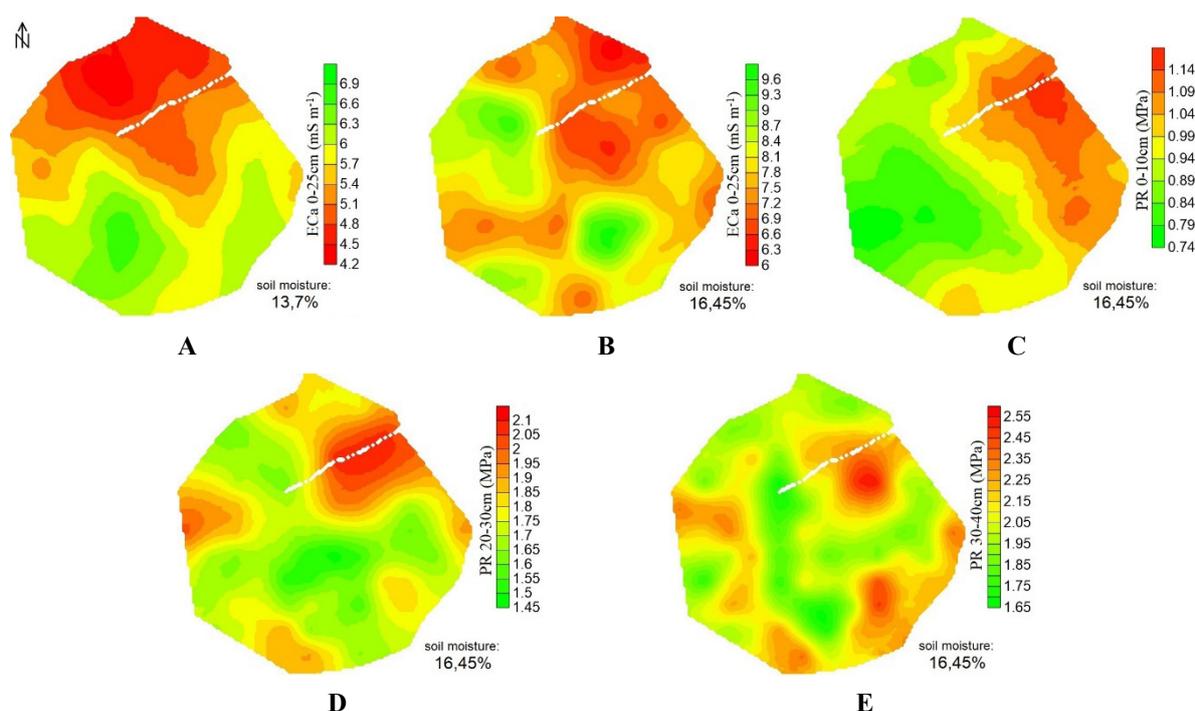
Figure 5. Thematic maps representative of the spatial variability of the apparent electrical conductivity of the soil (ECa; mS m^{-1}) measured in lower (A) and higher soil moisture (B) and of the penetration resistance (PR, MPa) in the layers of 0-10 cm (L), 20-30 cm (D) and 30-40 cm (E)

this relationship is negative in the superficial layers and positive in the subsurface layers. The negative relationship in the surface layer may be associated with higher organic matter content, fertilization, root development, and biological activity in this layer.

Another fact that can be seen in the maps is that the PR in the study area is not uniform. According to Richart *et al*. (2005), compaction depends on external factors such as the type, intensity, and frequency of the applied load, as well as internal soil factors, especially moisture, texture, structure, carbon content, initial density, and records of stress throughout the crops. These factors influence not only the PR spatial variability but also its magnitude as a function of the different soil layers studied.

According to Lima *et al*. (2012), the PR value normally used as a threshold is 2.0 MPa. Some studies have pointed to the possibility of increasing the limiting values of resistance to soil penetration to 3.5 MPa (BETIOLI JÚNIOR *et al*., 2012). It is observed, based on the PR values, that in the area under study there would be no need to carry out any mechanical intervention for soil decompaction. As a measure of containment and reduction of PR values, for this situation, the adoption of the crop rotation system is recommended. In this system,

different plant species are cultivated in an alternate and orderly manner in a given period, in the same area, and the same season of the year, using plants with different root systems in order to explore different layers of soil.

Another alternative to be highlighted is the use of the furrower shank in the precision seeder-fertilizer at sowing. This type of furrower can help reduce PR, providing greater depth to the roots of the crops, by breaking the more compacted surface layer (RINALDI *et al*., 2019). The combination of these methods, crop rotation, and mechanics, can significantly improve soil physical conditions and consequently crop yield.

The representative thematic maps MZ delimited on the basis of ECa performed in lower soil moisture (13.7%) organized in classes are shown in Figure 6.

Table 3 shows the outcome of the Normality test. It was observed a non-normal distribution for the following situations: 20-30 PR for Class 2 for the map divided into two classes and for Class 3 for the map divided into four classes. The 30-40 cm for Class 1 for the map is divided into two, three, and four classes. Therefore, the average PR for these classes at these soil layers was not compared with the others.
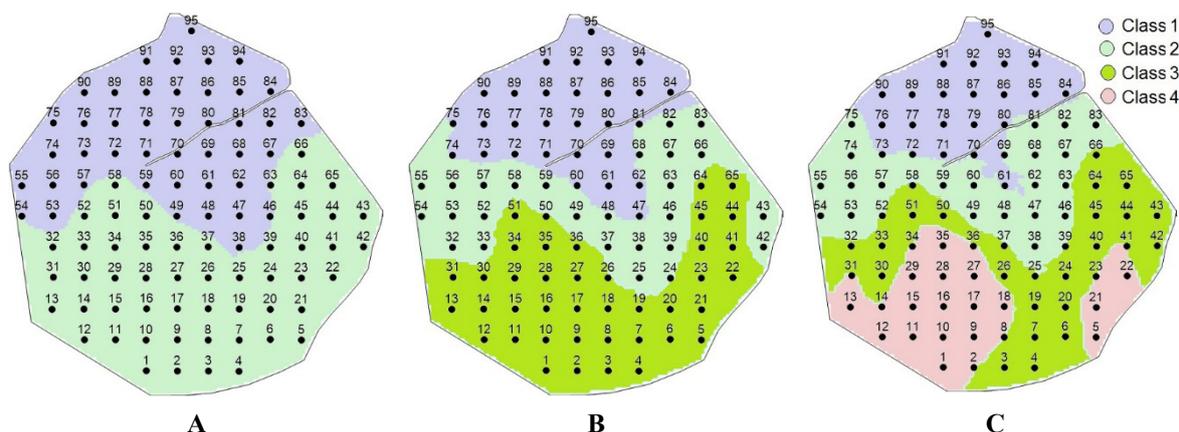
Figure 6. Management zone maps (MZ) delimited on the basis of apparent electrical conductivity measurement (ECa) performed in lower soil moisture (13.7%), organized in 2 classes (A), 3 classes (B), and 4 classes (C)

Table 3. Normality test for the values of penetration resistance (PR; MPa), in the different assessed layers for each class of management zone maps (MZ) generated on the basis of the measurement of soil apparent electrical conductivity (ECa, mS m^{-1}) performed in lower soil moisture (13.7%)

	Classes	N[1]	Mean	SD[2]	W[3]	p-value		Classes	N	Mean	SD	W	p-value
RP 0-10 cm	1	41	0.93	0.31	0.98	0.68	**PR 10-20 cm**	1	41	1.73	0.24	0.98	0.62
	2	47	0.88	0.28	0.98	0.75		2	47	1.62	0.22	0.96	0.14
	1	25	0.93	0.35	0.98	0.95		1	25	1.69	0.23	0.95	0.31
	2	22	0.96	0.22	0.95	0.37		2	22	1.80	0.21	0.92	0.07
	3	39	0.85	0.29	0.97	0.50		3	39	1.59	0.22	0.97	0.44
	1	17	0.90	0.37	0.96	0.71		1	17	1.66	0.20	0.94	0.27
	2	21	0.90	0.25	0.96	0.47		2	21	1.78	0.22	0.92	0.07
	3	24	0.90	0.24	0.99	0.99		3	24	1.59	0.24	0.93	0.11
	4	18	0.86	0.30	0.96	0.69		4	18	1.65	0.21	0.91	0.10
	Classes	N	Mean	SD	W	p-value		Classes	N	Mean	SD	W	p-value
PR 20-30 cm	1	41	1.78	0.30	0.99	0.91	**PR 30-40 cm**	**1**	**41**	**2.17**	**0.39**	**0.91**	**0.00**
	2	**47**	**1.70**	**0.18**	**0.90**	**0.00**		2	47	2.04	0.22	0.98	0.72
	1	25	1.76	0.31	0.97	0.68		**1**	**25**	**2.19**	**0.41**	**0.81**	**0.00**
	2	22	1.82	0.29	0.97	0.69		2	22	2.11	0.36	0.99	0.99
	3	39	1.68	0.13	0.97	0.50		3	39	2.03	0.22	0.98	0.78
	1	17	1.82	0.32	0.95	0.54		**1**	**17**	**2.28**	**0.47**	**0.84**	**0.01**
	2	21	1.80	0.28	0.98	0.90		2	21	2.11	0.37	0.99	1.00
	3	**24**	**1.72**	**0.20**	**0.84**	**0.00**		3	24	2.07	0.18	0.94	0.19
	4	18	1.68	0.14	0.96	0.52		4	18	2.03	0.22	0.94	0.31

[1]Number of sample points that make up the class. [2] standard deviation. [3]Value of the Shapiro-Wilk normality test

Figure 7 shows the mean values of penetration resistance (PR; MPa) that presented a statistically significant difference by the t-test ($p < 0.05$) as a function of the number of classes (C) in the management zone map (MZ) delimited on the basis of the apparent electrical conductivity readings taken in lower soil moisture (13.7%). The highest PR value for the 10-20 cm layer was 1.8 MPa, obtained when the CEa map was divided into three classes. For the 20-30 cm layer, the highest value observed was 1.82 MPa, obtained when the ECa map was also divided into three classes. The division of the ECa map into three classes was sensitive for detecting the highest PR values. This fact is an indication that for a PR sampling, directed from maps of management zones generated on the basis of the ECa spatial variability, the division into a smaller number of classes may not be sensitive to detect differences in the soil PR, although the values showed a statistical difference.
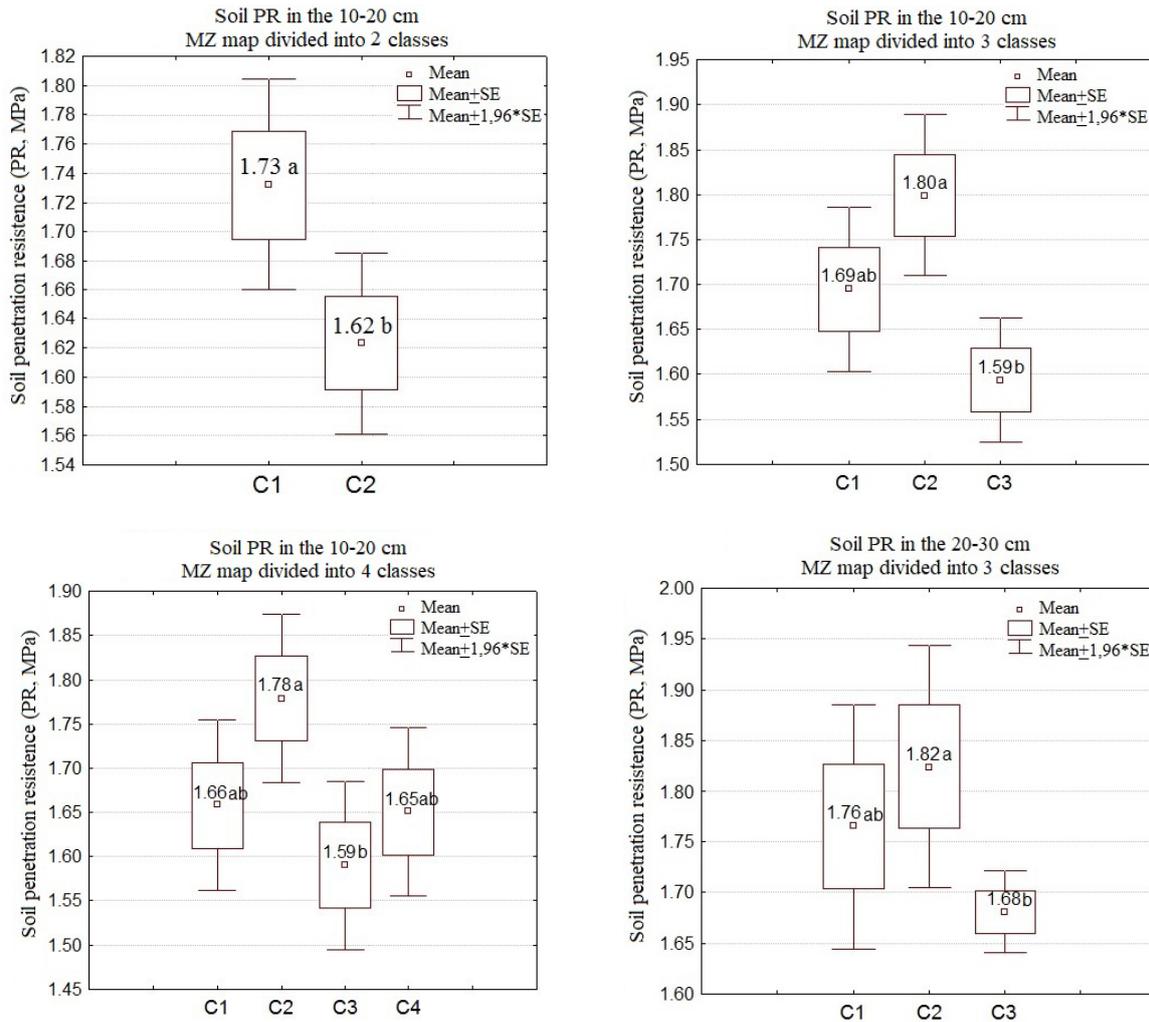
Figure 7. Box-Plot graphs for values of penetration resistance (PR; MPa) that presented a statistically significant difference by the t-test (p<0.05) as a function of the number of classes (C) in the management zone map (MZ) delimited on the basis of the apparent electrical conductivity readings taken at lower soil moisture (13.7%)

The management zone maps generated from measurements of ECa in higher soil moisture present differences in relation to maps of management zones generated from measurements of ECa in lower soil moisture. This fact possibly occurred due to greater participation of the liquid phase of the soil, since this phase promotes the conduction of electric current through the soil.

Figure 8 shows the maps of management zones delimited based on the measurement of apparent electrical conductivity of the soil (ECa) performed at higher soil moisture, organized into 2 classes (A), 3 classes (B), and 4 classes (C). It should be observed that the area was not divided into a greater number of management classes, as it would make operational management difficult, given the technological level of the farmers in the experimental region.

Table 4 shows the outcome of the Normality test. Non-normal distribution was observed for the following situations: 30-40 PR for class 1 when the map was divided into two classes, for classes 1 and 2 when the map was divided into 3 classes, and for class 1 when the map was divided into 4 classes. Due to the non-normality, the average PR of these classes, in these soil layers, was not tested in comparison with the others.

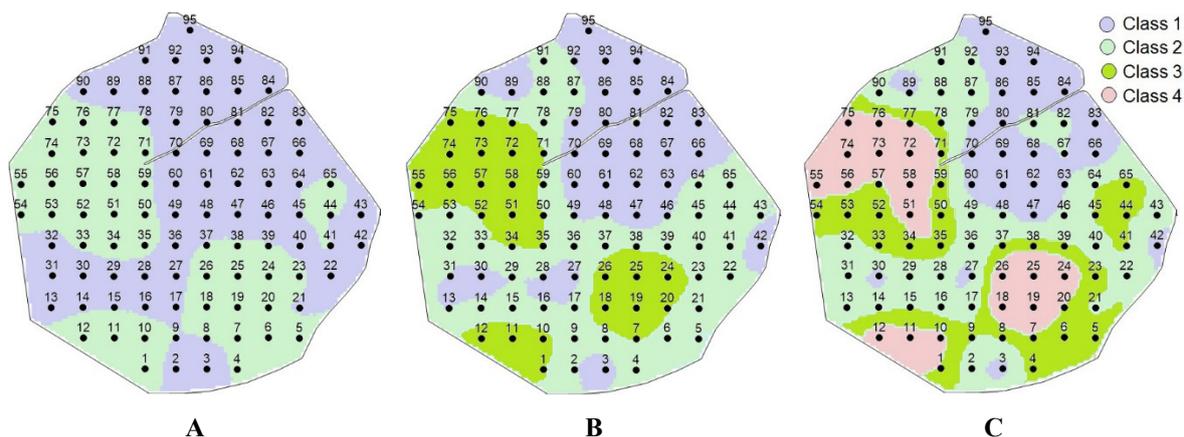Figure 9 shows the mean PR values for the

Figure 8. Maps of management zones (MZ) delimited on the basis of the soil apparent electrical conductivity (ECa) performed at higher soil moisture (16.45%), organized into 2 classes (A), 3 classes (B), and 4 classes (C)

Table 4: Normality test for the values of penetration resistance (PR; MPa) at the different assessed layers for each class of the management zone map (MZ) generated on the basis of the measurement of soil apparent electrical conductivity (ECa, mS m^{-1}) performed at the highest soil moisture (16.45%)

	Classes	N[1]	Mean	SD[2]	W[3]	p-value		Classes	N	Mean	SD	W	p-value
PR 0-10 cm	1	48	0.91	0.29	0.98	0.71	PR 10-20 cm	1	48	1.69	0.26	0.98	0.71
	2	36	0.90	0.29	0.98	0.65		2	36	1.66	0.20	0.95	0.10
	1	25	0.96	0.30	0.98	0.87		1	25	1.73	0.29	0.99	0.98
	2	27	0.85	0.29	0.96	0.30		2	27	1.62	0.21	0.94	0.11
	3	21	0.88	0.31	0.96	0.47		3	21	1.65	0.23	0.94	0.20
	1	16	1.01	0.32	0.99	1.00		1	16	1.78	0.27	0.96	0.75
	2	18	0.92	0.24	0.95	0.49		2	18	1.75	0.22	0.96	0.62
	3	17	0.89	0.30	0.93	0.20		3	17	1.66	0.18	0.95	0.50
	4	16	0.88	0.35	0.95	0.45		4	16	1.64	0.26	0.92	0.20

	Classes	N	Mean	SD	W	p-value		Classes	N	Mean	SD	W	p-value
PR 20-30 cm	1	48	1.79	0.26	0.98	0.55	PR 30-40 cm	**1**	**48**	**2.16**	**0.38**	**0.92**	**0.00**
	2	36	1.72	0.19	0.98	0.87		2	36	2.07	0.23	0.97	0.43
	1	25	1.83	0.31	0.99	0.99		**1**	**25**	**2.23**	**0.44**	**0.91**	**0.04**
	2	27	1.69	0.21	0.93	0.09		**2**	**27**	**2.05**	**0.28**	**0.91**	**0.02**
	3	21	1.72	0.20	0.97	0.81		3	21	2.10	0.21	0.96	0.52
	1	16	1.92	0.34	0.97	0.77		**1**	**16**	**2.32**	**0.46**	**0.85**	**0.01**
	2	18	1.75	0.19	0.93	0.19		2	18	2.06	0.31	0.96	0.63
	3	17	1.66	0.23	0.94	0.36		3	17	2.01	0.23	0.93	0.23
	4	16	1.69	0.19	0.92	0.17		4	16	2.06	0.18	0.92	0.17

[1]Number of sampling points that make up the class. [2]standard deviation. [3]Value of the Shapiro-Wilk normality test

study area for each of the four classes. A significant difference was observed between the PR of class 1 (1.92 MPa) and mean values of PR of classes 3 and 4 (1.66 and 1.69 MPa, respectively).

When the ECa was measured in the soil with higher moisture content, the need to divide the area into a greater number of management zones was clear, so that it is possible to differentiate the PR values. In the present study, a significant difference

was observed for the mean PR values in the 20-30 cm layer when the area was divided into four classes. This may be the result of the high moisture content present in the soil at the readings.

In moist soil, ECa is favored by the liquid route, as demonstrated in works conducted by Nadler and Frenkel (1980). In addition to this fact, works conducted by Silva *et al*. (2002) and Vaz *et al*. (2011) clearly and objectively show that changes
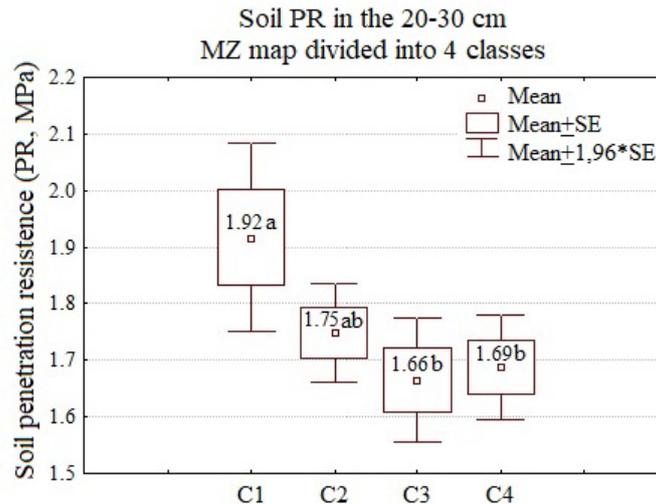
Figure 9. Box-Plot graph for values of penetration resistance (PR; MPa) that presented a statistically significant difference by the t-test ($p<0.05$) as a function of the number of classes (C) in the management zone map (MZ) delimited on the basis of the soil apparent electrical conductivity readings taken at higher soil moisture (16.45%)

in soil moisture also change its PR, as the increase in soil water content tends to reduce values of PR. Although a significant difference was observed, the highest PR value (class 1) is not restrictive to root development (LIMA *et al.*, 2012; BETIOLI JÚNIOR *et al.*, 2012), thus indicating that in this situation mechanical intervention, such as subsoiling is not needed.

CONCLUSION

- It was possible to differentiate the mean values of penetration resistance (PR), which range between 0.9 and 2.10 Mpa, supported by the characterization of management classes generated on the basis of spatial variability of the soil apparent electrical conductivity (ECa).

- The greatest stratification of PR values was obtained as a function of sampling directed at management zones made from the ECa spatial variability measured when the soil had low moisture content (13.7%).

- The highest mean PR values were obtained for the division of the ECa map into at least three classes.

- Based on the methodology used, it was identified that for the study area there is no need to carry out any mechanical decompaction operation in any of the delimited management zones.

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.

REFERENCES

BETIOLI JÚNIOR, E.; MOREIRA, W.H.; TORMENA, C.A.; FERREIRA, C.J.B.; SILVA, A.P. da; GIAROLA, N.F.B. Intervalo hídrico ótimo e grau de compactação de um Latossolo Vermelho após 30 anos sob plantio direto. **Revista Brasileira de Ciência do Solo**, Viçosa, v.36, n. 3, p. 971-982, 2012.

BOTTEGA, E.L.; QUEIROZ, D.M.; PINTO, F.A.C.; VALENTE, D.S.M.; SOUZA, C.M.A. Precision agriculture applied to soybean crop: Part II – Temporal stability of management zones. **Australian Journal of Crop Science**, v. 11, n. 06, p. 676-682, 2017.

COMPAGNON, A.M.; GUILHERME, I.H.; PEREIRA FILHO, W.J.; RODOVALHO, R.S.; ARRIEL, F.H. Variabilidade espacial da resistência mecânica do solo à penetração na colheita mecanizada de milho para silagem. **Científic@ Multidisciplinary Journal**, v. 8, n. 2, p. 1-12, 2020.

CORÁ, J.E.; ARAUJO, A.V.; PEREIRA, G.T.; BERALDO, J.M.G. Variabilidade espacial de atributos do solo para adoção do sistema de agricultura de precisão na cultura de cana-de-açúcar. **Revista Brasileira de Ciência do Solo**, v. 28, n. 06, p. 1013-1021, 2004.

CORASSA, G.M.; AMADO, T.J.C.; TABALDI, F.M.; SCHWALBERT, R.A.; REIMCHE, G.B.; DALLA NORA, D.; ALBA, P.J.; HORBE, T. de A.N. Espacialização em alta resolução de atributos da acidez de Latossolo por meio de sensoriamento em tempo real. **Pesquisa Agropecuaria Brasileira**, v. 51, n. 9, p. 1306-1316, 2016.

CORTEZ, J.W.; OLSZEVSKI, N.; PIMENTA, W.A.; PATROCÍNIO FILHO, A.P.; SOUZA, E.B. de.; NAGAHAMA, H. de J. Avaliação da intensidade de tráfego de tratores em alguns atributos físicos de um Argissolo Amarelo. **Revista Brasileira de Ciência do Solo**, v.38, n.3, p. 1000-1010, 2014.

CORWIN, D.L.; LESCH, S.M. Application of Soil Electrical Conductivity to Precision Agriculture: Theory, Principles, and Guidelines. **Agronomy Journal**, v.95, n. 3, p. 471-471, 2003.

CUSTÓDIO, G.D.; RIBON, A.A.; FERNANDES, K.L.; HERMÓGENES, V.T.L.; BARROS, L.R. Densidade do solo e densidade relativa-indicadores da qualidade física de um latossolo amarelo sob diferentes manejos de pastagens e mata nativa. **Campo Digit@l: Revista Ciências Exatas e da Terra e Ciências Agrárias,** v.10, n.1, p. 50-62, 2015.

DALCHIAVON, F.C.; CARVALHO, M.P.; ANDREOTTI, M.; MONTANARI, R. Variabilidade espacial de atributos da fertilidade de um Latossolo Vermelho Distroférrico sob Sistema Plantio Direto. **Revista Ciência Agronômica**, v. 43, n. 3, p. 453-461, 2012.

EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. Sistema Brasileiro de Classificação de Solos. 3. ed. Brasília: Embrapa Informação Tecnológica, 2013.

FREELAND, R.S. Review of soil moisture sensing using soil electrical conductivity. **Transaction of the ASAE**, v. 32, n.6, p. 2190-2194, 1989.

GAMMA DESIGN SOFTWARE, LLC. GS+ Geoestatistics for the Environmental Sciences, version 7, 2006.

GELAIN, E.; BOTTEGA, E.L.; MOTOMIYA, A.V. de A.; MARIN, C.K.; OLIVEIRA, Z.B. de. Dependência e correlação espacial dos atributos de solo em função do arranjo amostral. **TECNO-LÓGICA**, Santa Cruz do Sul, v. 25, n. 1, p. 145-172, 2021.

GOLDEN SOFTWARE, Inc. Surface Mapping System – Surfer, version 10.1.561, 2011.

LIBARDI, P.L.; MANFRON, P.A.; MORAES, S.O. TUON, R.L. Variabilidade da umidade gravimétrica de um solo hidromórfico. **Revista Brasileira de Ciência do Solo**. v. 20, n.1, p. 1-12, 1996.

LIMA, C.L.R.; MIOLA, E.C.C.; TIMM, L.C.; PAULETTO, E.A.; SILVA, A.P. da. Soil compressibility and least limiting water range of a constructed soil under cover crops after coal mining in Southern Brazil. **Soil & Tillage Research**, v.124, p.190-195, 2012.

LOPES, K.A. do L.; PINTO JUNIOR, F.F.; AGUIAR, F.I. dos S.; SOUSA, A.E. da S.; OLIVEIRA, I.R. de.; DANTAS, J.S. diferentes densidades amostrais na caracterização da variabilidade espacial de atributos granulométricos de um argissolo amarelo distrocoeso típico. **Cultura Agronômica**, v.29, n.1, p. 50-60, 2020.

MAZURANA, M.; FINK, J.R.; SILVEIRA, V.H. da; LEVIEN, R.; ZULPO, L.; BREZOLIN, D. Propriedades físicas do solo e crescimento de raízes de milho em um argissolo vermelho sob tráfego controlado de máquinas. **Revista Brasileira de Ciência do Solo**, v.37, n.5, p.1185-1195, 2013.

MORAL, F.J.; TERRÓN, J.M.; REBOLLO, F.J. Site-specific management zones based on the Rasch model and geostatistical techniques. Computers and Electronics in Agriculture, v. 75, p. 223–230, 2011.

MORAL, F.J.; TERRÓN, J.M.; SILVA, J.R.M. Delineation of management zones using mobile measurements of soil apparent electrical conductivity and multivariate geostatistical techniques. **Soil & Tillage Research**, v. 106, p. 335–343, 2010.

NADLER, A; FRENKEL, H. Determination of soil solution electrical conductivity from bulk soil electrical conductivity measurments by the four electrode method. **Soil Science Society of America Journal**, v.44, n.5, p. 1216-1221, 1980.

OLIVER, M.A.; WEBSTER, R. A tutorial guide to geostatistics: Computing and modelling variograms and kriging. **Catena,** v.113, p.56-69, 2014.

RICHART, A.; TAVARES FILHO, J.; BRITO, O.R.; LLANILLO, R.F.; FERREIRA, R. Compactação do solo: causas e efeitos. **Semina: Ciências Agrárias**, v.26, n.3, p.321-344, 2005.

RINALDI, P.C.N.; ALVARENGA, C.B. de;1, ZAMPIROLI, R.; RIBEIRO, W. de S.; FERNANDES, H.C. Estabelecimento inicial da cultura do milho em função da velocidade de trabalho e dos mecanismos sulcadores da semeadora. **Acta Iguazu**, Cascavel, v.8, n.1, p. 23-31, 2019.

RODRIGUES JUNIOR, F.A.; VIEIRA, L.B.; QUEIROZ, D.M.; SANTOS, N.T. Geração de zonas de manejo para cafeicultura empregando-se sensor SPAD e análise foliar. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 15, n. 8, p. 778-787, 2011.

RODRÍGUEZ-PÉREZ, J.R.; PLANT, R.E.; LAMBERT, J.J.; SMART, D.R. Using apparent soil electrical conductivity (ECa) to characterize vineyard soils of high clay content. **Precision Agriculture**, v. 12, p. 775-794, 2011.

SANTOS, M.L dos; COMPAGNON, A.M.; PIMENTA NETO, A.M.; ARRIEL, F.H.; CINTRA, P.H.M. Variabilidade espacial das propriedades físicas do solo em primeiro ano de colheita de cana-de-açúcar. **Brazilian Journal of Development**, Curitiba, v. 6, n. 5, p. 27667-27682, 2020.

SILVA, V.R.; REINERT, D.J.; REICHERT, J.M. Fatores controladores da compressibilidade de um Argissolo Vermelho-Amarelo Distrófico arênico e de um Latossolo Vermelho distrófico típico. II – Grau de saturação em água. **Revista Brasileira de Ciência do Solo**, v.26, p.9-15, 2002.

SOUZA, M. da C.; OLIVEIRA, F.P. de.; SILVA, J.R.; MARTINS, A.F.; SILVA, P.L.F. DA. Spatial variability of resistance to penetration in soil under sugarcane crops with different harvest methods. **Revista Caatinga**, Mossoró, v. 33, n. 2, p. 480-489, 2020.

SPLIETHOFF, J.; RAMPIM, L.; POTT, C.A.; LUSTOSA, S.B.C. Implicação de grades amostrais na determinação da resistência do solo à penetração e indicação de manejo. **Research, Society and Development**, v. 9, n. 9, e790997871, 2020.

STATSOFT, Inc. STATISTICA (data analysis software system), version 7, 2004.

TAVARES FILHO, J.; FELTRAN, C.T. M.; OLIVEIRA, J.F.; ALMEIDA, E. Modelling of Soil Penetration Resistance for an Oxisol under No-Tillage. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 36, p. 89-95, 2012.

VALENTE, D.S.M. **Desenvolvimento de um sistema de apoio à decisão para definir zonas de manejo em cafeicultura de precisão**. 2010. 122 f. Tese (Doutorado em Engenharia Agrícola) Viçosa: Universidade Federal de Viçosa, 2010.

VAZ, C.M.P.; MANIERI, J.M.; DE MARIA, I.C.; TULLER, M. Modeling and correction of soil penetration resistance for varying soil water content. **Geoderma**, v. 166, n. 1, p. 92-101, 2011.

WAGNER, W.; Amado, T.J.C.; Pott, L.P.; Teixeira, T. de G.; Kerber, L. Condutividade elétrica e sua relação com a resistência a penetração do solo visando orientar a escarificação mecânica de sítio-específico em lavoura de soja. **Revista Plantio Direto & Tecnologia Agrícola**, ed. 161, p. 14-26, 2018.

XIAOHU, Z.; LI, J.; XIAOLEI, Q.; JIANXIU, Q.; JUAN, W.; YAN, Z. An improved method of delineating rectangular management zones using a semivariogram-based technique. **Computers and Electronics in Agriculture**, v. 121, p. 74-83, 2016.