



Article

Soil Density Characterization in Management Zones Based on Apparent Soil Electrical Conductivity in Two Field Systems: Rainfed and Center-Pivot Irrigation

Eduardo Leonel Bottega ^{1,*},†, Cristielle König Marin ¹, Zanandra Boff de Oliveira ^{1,†},
Christiano de Carvalho Lamb ² and Telmo Jorge Carneiro Amado ^{3,†}

¹ Federal University of Santa Maria (UFSM), Cachoeira do Sul 96503-205, RS, Brazil

² Nossa Senhora da Conceição State Technical School, Tres Vendas, Cachoeira do Sul 96511-000, RS, Brazil

³ Rural Sciences Center (CCR), Federal University of Santa Maria (UFSM), Santa Maria 97105-900, RS, Brazil

* Correspondence: eduardo.bottega@ufsm.br

† Graduate Program in Precision Agriculture (PPGAP), Polytechnic College of UFSM, Central Campus, Camobi District, Santa Maria, RS 97105-000, Brazil.

Abstract: Understanding the spatial variability of factors that influence crop yield is essential to apply site-specific management. The present study aimed to evaluate apparent soil electrical conductivity (ECa) in two fields (A = rainfed; B = central-pivot irrigation), based on delimited management zones (MZs). In each MZ, the soil density (Sd) was characterized at two soil depths, and whether the delimitation of MZs, based on the spatial variability of ECa, was able to identify regions of the field with different Sd was assessed. In general, MZs with the highest mean value of ECa also presented the highest mean values of Sd. The highest Sd values were observed in the 0.1–0.2 m layer, regardless of the studied area. Regardless of soil texture, the proposed ECa was able to detect in-field differences in Sd. The delimitation of MZs, based on the spatial variability of ECa mapping, was able to differentiate the mean values of Sd between MZ 1 (1.53 g cm⁻³) and MZ 2 (1.67 g cm⁻³) in field A, in the 0.1–0.2 m layer. A statistical difference was observed for the mean values of Sd, in MZ 1, at layer 0.1–0.2 m, when comparing the two fields: A (1.53 g cm⁻³) and B (1.64 g cm⁻³). We suggest that further studies should be carried out to confirm the efficiency of ECa in detecting the soil bulk density at different soil depths.

Keywords: no-till; soil compaction; precision agriculture; soil physics



Citation: Bottega, E.L.; Marin, C.K.; Oliveira, Z.B.d.; Lamb, C.d.C.; Amado, T.J.C. Soil Density Characterization in Management Zones Based on Apparent Soil Electrical Conductivity in Two Field Systems: Rainfed and Center-Pivot Irrigation. *AgriEngineering* **2023**, *5*, 460–472. <https://doi.org/10.3390/agriengineering5010030>

Academic Editors: Santosh Pandey and Tiago Paim

Received: 5 December 2022

Revised: 8 February 2023

Accepted: 13 February 2023

Published: 23 February 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Brazil and USA are currently the world's largest producers of soybean. In the 2020/21 season, Brazil reached the record mark of 135.4 M T, produced in a cropped area of 38.5 M ha, with average productivity estimated at 3517 kg ha⁻¹ [1]. Brazilian farmers have been using technologies in order to conciliate the increase in productivity and cropped area and, thus, improve profitability [2].

In this context, we highlight the successful adoption, on a large scale, of the no-tillage system (NTS). According to Salomão and colleagues [3], the adoption of NTS represents an alternative for economic and sustainable production, which makes it possible to solve environmental problems such as soil erosion, and the loss of nutrients by lixiviation and transport of agrochemical inputs, soluble nutrients, and organic matter into water courses and natural ecosystems.

Associated with the NTS, the use of precision agriculture techniques and digital tools, such as those aimed at mapping the spatial variability of soil attributes, has been consolidated as an efficient agronomic practice, especially in the management of soil fertility through georeferenced soil sampling [4]. The mapping of the spatial variability of soil

and plant attributes provides tools to scout the fields with layers of information, allowing site-specific interventions [5], in particular, in soil attributes that are crop yield limiting.

The choice of the soil sampling method will affect the characterization quality of the spatial variability of soil attributes. Soil sampling based on a grid of georeferenced points is the most used in Brazilian precision agriculture [6]. However, the representativeness of the spatial variability of soil attributes is dependent on the number of points that compose the grid [7]. Some soil attributes such as phosphorus content and soil resistance penetration demand a large amount of sampling. In this context, grids composed of many sampling points can make the characterization of spatial variability economically unfeasible [8].

In the literature, there are numerous studies on the mapping of the spatial variability of soil chemical properties for the purpose of site-specific management, using precision agriculture tools. Among the reasons that justify this large number of studies, in addition to the relevance of improving soil fertility in dystrophic tropical soils, is the availability of equipment to mechanically operationalize the sampling. Studies related to the spatial variability of soil physical attributes, such as bulk density, are less frequent. Soil density can be used as an indicator of changes in soil structure [9]. According to Stone and Silveira [10], soil density is a factor that affects soil water storage, plant nutrient uptake, root growth, and crop yield. Although, its relevance to crop performance is that the high labor demand for soil density evaluation limits the spatial variability characterization.

The search for technical approaches that aim to apply smart sampling for the purpose of characterizing soil density in homogeneous zones with low cost is in high demand. In this scenario, the apparent soil electrical conductivity can help to guide the sampling for the purpose of characterizing the spatial variability of the bulk density. Therefore, allowing site-specific chiseling or cover crops that can mitigate soil compaction.

The present study, firstly, maps the spatial variability of apparent soil electrical conductivity (ECa) in two fields, one a rainfed and the second irrigated with a center-pivot system. Secondly, management zones (MZs) were delimited based on the spatial variability of the ECa in each field. Finally, the soil density was evaluated at two depths, according to the MZ. The hypothesis of the study was that the delimitation of MZs, based on the ECa, was able to capture regions with different soil densities in both fields.

2. Materials and Methods

This study was carried out in two farm fields, located in the municipality of Cachoeira do Sul, Rio Grande do Sul State, Southern Brazil. These fields are managed under a no-tillage system and oriented to grain crop production. The soil is classified as Red Acrisol, according to Soil Taxonomy 1975 [11].

Field A has 26.7 ha, cropped in a dryland system. The management adopted in this area includes NT of soybeans in the summer season, and harrowing and sowing of oats (for cover crop/pasture) in the winter season. Field B has 24.1 ha, cropped with irrigation of a center-pivot irrigation system. In the summer season, part of the pivot is cropped with soybean and part with corn, for silage production. In the winter, the whole field is sown with oat for animal pasture.

Soil sampling scheme was a grid with points regularly spaced at 50×50 m (Figure 1). These points served as a basis for measuring the ECa (mS m^{-1}). A Garmin GPS receiver, model GPSMAP 62sc, was used to locate the sample points in the study areas.

Soil moisture was estimated by the gravimetric method with the aid of a Dutch auger, and representative soil samples from the 0 to 0.2 m soil layer were collected at random points in both fields. The soil samples were stored in aluminum recipients, and identified and taken to the laboratory for drying in an oven for 24 h at 105°C .

To determine the ECa, the electrical resistivity method was used. The electrical resistivity was obtained by introducing four equally spaced electrodes into the soil. An electric current was applied to the external electrodes and the potential difference was measured at the internal electrodes. The electrode assembly configuration used was the Wenner Matrix [12,13].

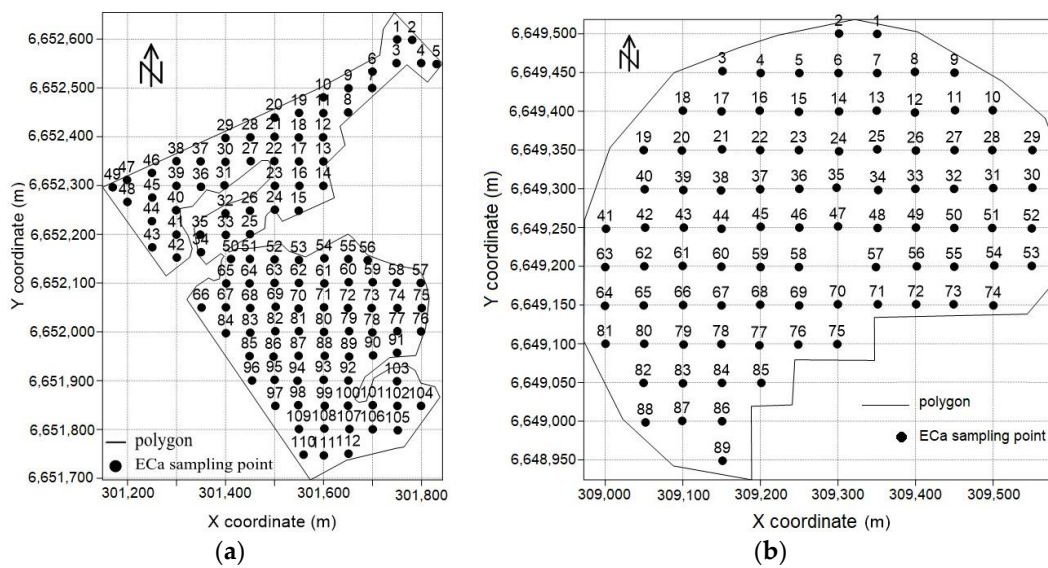


Figure 1. Soil sampling grid used to evaluate apparent soil electrical conductivity (ECa) in field A under rainfeed, of 26.7 hectares (a), and in field B under center-pivot irrigation, of 24.1 hectares (b). Cachoeira do Sul, RS.

The resistivity obtained using the Wenner Matrix was calculated by Equation (1).

$$\rho = \frac{2 \cdot \pi \cdot a \cdot \Delta V}{i} \tag{1}$$

where

- ρ = Resistivity, Ohm m⁻¹;
- a = Spacing between electrodes, m;
- ΔV = Measured potential difference, V;
- i = Applied electric current, A.

The apparent soil electrical conductivity represents the inverse of the resistivity, calculated by Equation (2).

$$ECa = \frac{1}{\rho} \tag{2}$$

where

ECa = Apparent soil electrical conductivity, S m⁻¹.

To obtain the ECa, a portable electrical conductivity meter, assembled by Landviser[®], model LandMapper[®] ERM-02, was used. A Wenner matrix was constructed with four electrodes arranged in order to obtain measurements at 0.20 m soil depth. The electrode support structure was developed using metalon tubes, steel screws, and flexible wires in different colors for current electrodes (red wire) and electrodes used to determine the potential difference (black wire). The contact between the steel screws and the metalon was isolated by covering the screws with a PVC hose. Figure 2 shows the portable meter and the electrode array.

ECa data were submitted to the Shapiro–Wilk normality test. The spatial dependence of the ECa was evaluated by variogram adjustments, assuming the stationarity of the intrinsic hypothesis, defined by Equation (3).

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \tag{3}$$

where

$\hat{\gamma}(h)$ = Semivariance as a function of the separation distance (h) between pairs of points;

h = Separation distance between pairs of points, m ;
 $N(h)$ = Number of experimental pairs of observations $Z(x_i)$ and $Z(x_i + h)$ separated by a distance, h .

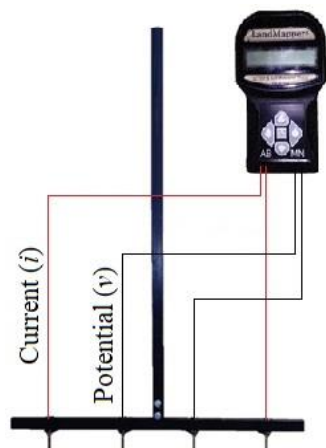


Figure 2. Wenner matrix and portable electrical conductivity meter, assembled by Landviser[®], model LandMapper[®] ERM-02 (image without scale).

Gaussian, spherical, and exponential models were tested in the semivariograms. The model that presented the smallest residual sum of squares was adjusted [14]. The selected model was evaluated using the cross-validation technique, which consists of plotting the observed values in the field versus those estimated by the selected model on a graph. The model accuracy is reflected by the parameters obtained in the cross-validation analysis, which are the coefficient of determination (the closer to the value 1, the more accurate the estimates), standard error of prediction (the smaller, the more accurate the estimates), and intercept (the closer to zero, the more accurate the estimates).

Once the spatial dependence was determined and the theoretical semivariance model adjusted, the map of spatial variability of ECa was made. The interpolation of values was performed using ordinary kriging. This interpolation method was selected because it provides the best linear unbiased predictions (BLUP), seeking the minimum variance [14]. For the estimation of values in unsampled locations, 16 close neighbors and a search radius of 50% of the range value found in the variogram adjustment were used, in order to guarantee the spatial continuity interval.

The analysis of spatial variability was performed using the computer program GS+, version 7. The ECa values resulting from the kriging interpolation were organized into 2 MZs. These zones were generated through the KrigMe computer program, developed by Valente [15], using the Fuzzy k-means classification algorithm in the data cluster analysis and management zone generation.

After defining the MZ, soil texture (0–0.2 m) and soil bulk density (0–0.1; 0.1–0.2 m) evaluations were carried out in each of these zones. Data collections were carried out at three sampling points within each MZ. Soil sampling for soil texture was performed using a cutting shovel, removing representative soil from the 0 to 0.2 m layer. The soil samples were packed in plastic bags, identified, and sent for laboratory analysis.

Soil bulk density was determined by the soil volumetric ring method, which is considered a standard for bulk density assessment. To collect the undisturbed soil sample, steel cylinders with beveled edges (4 cm diameter, 3 cm height, and 37.7 cm³ volume) were used. The cylinders were introduced in the soil profile, in the 0–0.1 and 0.1–0.2 m depths, with the aid of a sledgehammer and an auger; later, with the aid of a cutting shovel, the rings were collected. Excess soil beyond the dimensions of the rings was removed with a knife, until the ring's surface was cleaned.

The rings with the soil were then packed in aluminum recipients capsules and taken to the laboratory. The samples were placed to dry in an oven at 105 °C for a 24 h period. After

that, they were weighed on a precision scale; the weight of the aluminum capsule + ring (tare) was deducted from the weight obtained, in order to obtain the dry soil mass. Soil bulk density was determined based on Equation (4).

$$Sd = \frac{m_s}{V} \quad (4)$$

where

Sd = Soil bulk density, g cm^{-3} ;

m_s = Dry soil mass, g;

V = Ring volume, cm^3 .

Figure 3 illustrates the collection of undisturbed soil samples at depths of 0–0.1 m (a; b) and 0.1–0.2 m (c), and the sample that was prepared to be sent to the laboratory for soil bulk density determination (d).

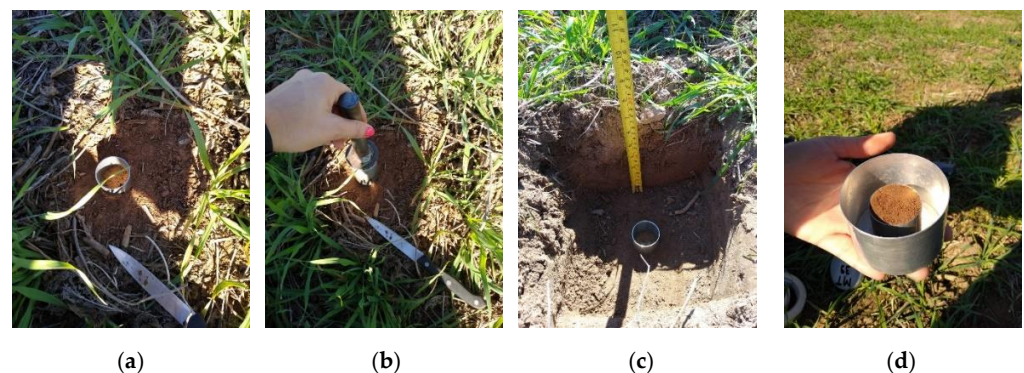


Figure 3. Collection of undisturbed soil samples at depths of 0–0.1 m (a,b), at a depth of 0.1–0.2 m (c), and field soil sample preparation procedure to be taken to the laboratory (d). Cachoeira do Sul, RS.

The ECa, bulk density, and soil texture data were submitted to descriptive statistical analysis, calculating the values of minimum, average, maximum, standard deviation, and coefficient of variation. The average values of soil density, between the MZ for the same field and between the MZ of the different fields, were compared by the t-test of means. Statistical analyses were performed using the statistical program Statistica, version 7.

3. Results

The average of soil moisture, representative of the 0–20 cm layer, at the time of soil ECa evaluation was 0.130 g g^{-1} for field A and 0.127 g g^{-1} for field B. ECa data for field A showed a normal distribution, which was not observed for field B. According to Cressie [16], geostatistics does not require data normality to be applied, it is only convenient that the distribution does not present very elongated tails. The spatial variability of ECa was determined for the two fields. The theoretical model that best explained the empirical semivariance of ECa was the spherical model, with a coefficient of determination (r^2) of 0.78 for field A and 0.93 for field B. The greatest range was observed in field B (497 m) and the smallest in field A (161.8 m). These values were higher than the distance between the soil sampling collect points (50 m). Figure 4 shows the semivariograms with adjustment parameters, cross-validation graphs with adjustment parameters, and the maps of spatial variability of ECa for the two fields.

Figure 5 shows the maps of MZs, divided into two classes, and delimited based on the spatial variability of the ECa (Figure 4). In both fields, class MZ 1 represents low ECa sites and class MZ 2 represents high ECa areas. Due to the small areas, the MZ map was divided only into two classes, as, according to Tisseyre and McBratney [17], the increase in the number of classes leads to irregularity in the field, creating small MZs that are difficult to manage.

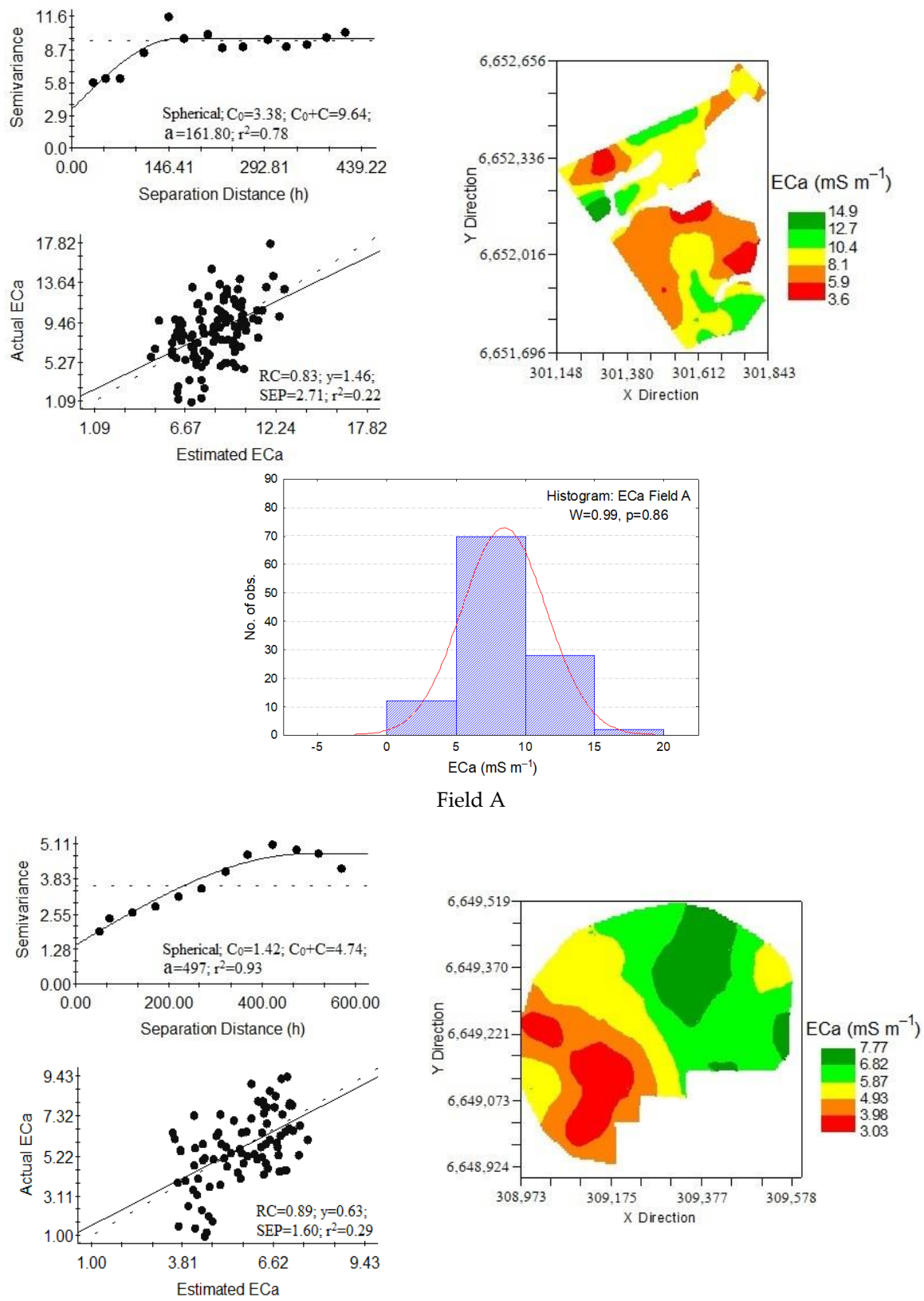


Figure 4. Cont.

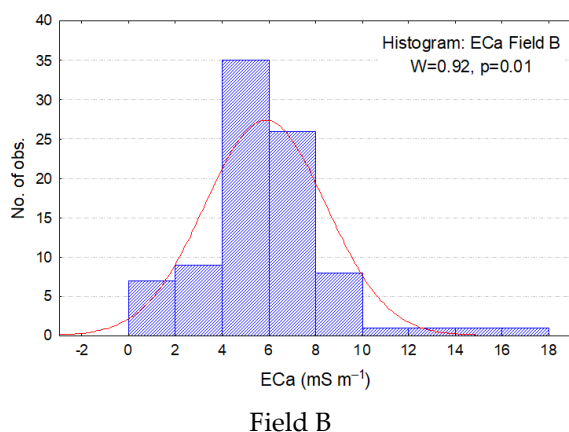


Figure 4. Semivariograms, cross-validation plots, and maps of spatial variability of ECa for the two fields selected. Adjustment parameters of the semivariograms: C_0 : Nugget effect; C_0+C : Level; a : Range (m); r^2 : coefficient of determination. Cross-validation parameters: RC: regression coefficient; y : intercept; SEP: standard error of prediction; r^2 : coefficient of determination. Cachoeira do Sul, RS.

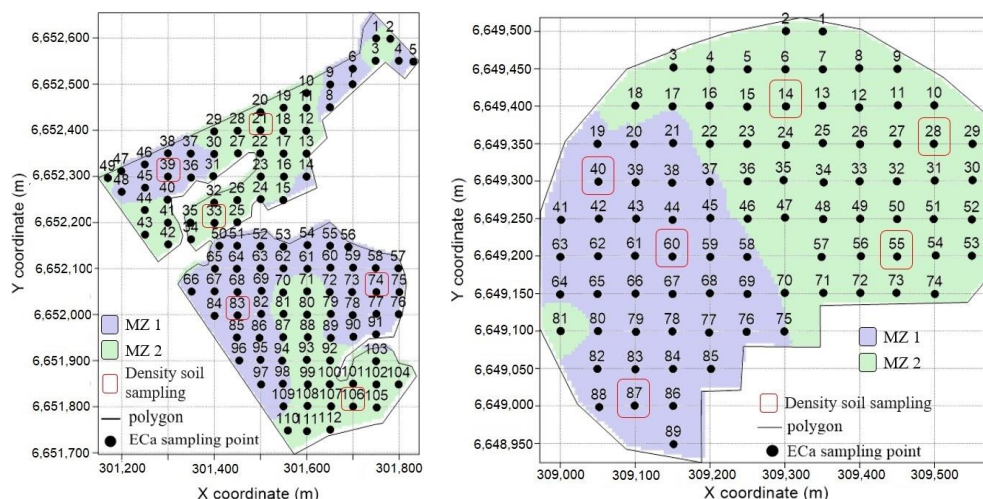


Figure 5. Maps of management zones delimited based on the spatial variability of the apparent soil electrical conductivity in fields A (rainfed) and B (irrigated by central pivot). Cachoeira do Sul, RS.

Table 1 shows the descriptive statistical parameters of soil attributes: apparent soil electrical conductivity (ECa; mS m^{-1}), soil bulk density (Sd; g cm^{-3}), gravimetric soil moisture (Sm, g g^{-1}), sand, silt, and clay contents, for the management zones delimited in field A (rainfed). Cachoeira do Sul, RS.

ECa ranged from 3.62 to 14.94 mS m^{-1} , with the highest mean value observed for MZ 2 (10.05 mS m^{-1}). In MZ 2, the zone with the highest ECa had higher values of Sd for both depths evaluated, when compared to Sd values obtained in MZ 1.

Considering the 0–0.1 m soil layer, the mean Sd in MZ 1 was 1.34 g cm^{-3} , while in MZ 2 it was 1.46 g cm^{-3} . For the 0.1–0.2 m layer, in MZ 1, the Sd was 1.53 g cm^{-3} and in MZ 2, it was 1.67 g cm^{-3} , confirming the efficiency of the ECa as a delimiting factor for MZs.

The CV for the Sd estimates, regardless of the soil layer and the MZ investigated, was below 6%, and classified as low variability ($\text{CV} < 12\%$) as proposed by Warrick and Nielsen [18]. In relation to the soil texture, the MZs presented very similar values for the attributes sand, silt, and clay, suggesting that the differences in the Sd reported were not associated with soil texture.

Table 2 shows the descriptive statistical parameters of soil attributes: apparent soil electrical conductivity (ECa; mS m^{-1}), soil density (Sd; g cm^{-3}), soil moisture (Sm, g g^{-1}), sand, silt, and clay, for the management zones delimited in field B.

Table 1. Descriptive statistics of soil attributes: Apparent soil electrical conductivity (ECa; mS m⁻¹), soil bulk density (Sd; g cm⁻³), soil moisture (Sm, g g⁻¹), sand, silt, and clay contents, for the delimited management zones (MZs) in field A. Cachoeira do Sul, RS, BR.

Field	MZ	Attribute	Minimum	Mean	Maximum	Standard Deviation	CV (%)
A	1	ECa (mS m ⁻¹)	3.62	6.91	8.48	0.98	14.18
		Sd (0–0.1 m)	1.31	1.34	1.38	0.04	3.05
		Sm (0–0.1 m)	0.110	0.128	0.145	0.018	13.84
		Sd (0.1–0.2 m)	1.50	1.53	1.56	0.03	1.94
		Sm (0.1–0.2 m)	0.103	0.124	0.138	0.018	14.85
		Sand	-	63	-	-	-
		Silt	-	19	-	-	-
	Clay	-	18	-	-	-	
	2	ECa (mS m ⁻¹)	8.49	10.05	14.94	1.12	11.14
		Sd (0–0.1 m)	1.40	1.46	1.54	0.08	5.21
		Sm(0–0.1 m)	0.093	0.127	0.169	0.038	30.40
		Sd (0.1–0.2 m)	1.61	1.67	1.73	0.06	3.75
		Sm (0.1–0.2 m)	0.104	0.123	0.146	0.021	17.41
		Sand	-	62	-	-	-
Silt		-	20	-	-	-	
Clay	-	18	-	-	-		

d.f.: degrees of freedom.

Table 2. Descriptive statistics of soil attributes: Apparent soil electrical conductivity (ECa; mS m⁻¹), soil bulk density (Sd; g cm⁻³), gravimetric soil moisture (Sm, g g⁻¹), sand, silt, and clay content (%), for the management zones (MZs) delimited in Field B (irrigated by central pivot). Cachoeira do Sul, RS, BR.

Fields	MZ	Attributes	Minimum	Mean	Maximum	Standard Deviation	CV (%)
B	1	ECa (mS m ⁻¹)	3.03	4.46	5.43	0.62	14.00
		Sd (0–0.1 m)	1.25	1.35	1.54	0.16	12.12
		Sm (0–0.1 m)	0.136	0.158	0.186	0.026	16.19
		Sd (0.1–0.2 m)	1.61	1.64	1.66	0.03	1.67
		Sm (0.1–0.2 m)	0.138	0.146	0.154	0.008	5.31
		Sand	-	59	-	-	-
		Silt	-	17	-	-	-
	Clay	-	24	-	-	-	
	2	ECa (mS m ⁻¹)	5.44	6.43	7.77	0.58	8.97
		Sd (0–0.1 m)	1.26	1.46	1.62	0.18	12.29
		Sm(0–0.1 m)	0.132	0.140	0.148	0.008	5.40
		Sd (0.1–0.2 m)	1.65	1.74	1.81	0.08	4.87
		Sm (0.1–0.2 m)	0.119	0.126	0.137	0.010	7.82
		Sand	-	54	-	-	-
Silt		-	22	-	-	-	
Clay	-	24	-	-	-		

d.f.: degrees of freedom.

Field B had the lowest range of ECa values, which ranged from 3.03 to 7.77 mS m⁻¹. The average soil Sd, regardless of the MZ, was lower for the 0–0.1 m layer than the 0.1–0.2 m layer.

Table 3 presents the results of the test of means for Sd, in each field investigated, according to the MZ delineated. A significant statistical difference was observed only for the comparison between the averages of Sd in the 0.1–0.2 m layer, between MZ 1 and 2, for field A.

Regardless of the field investigated, the highest Sd values were observed for the MZ 2; that is, the one with the highest ECa reported. Furthermore, the highest Sd values were obtained for the 0.1–0.2 m layer, regardless of the field or the MZ investigated.

Table 3. Test of means for bulk soil density (Sd; g cm⁻³) in each field investigated, according to the management zones (MZ 1 and MZ 2) delineated based on apparent soil electrical conductivity. Cachoeira do Sul, RS, BR.

Field	Soil Depth (m)	Soil Density (g cm ⁻³)		t-Value	d.f.	p-Value
		MZ 1	MZ 2			
A	0–0.1	1.34	1.46	–2.42	4.00	0.07
	0.1–0.2	1.53	1.67	–3.39	4.00	0.03
B	0–0.1	1.35	1.46	–0.73	4.00	0.51
	0.1–0.2	1.64	1.74	–1.84	4.00	0.14

d.f.: degrees of freedom; t-value = student test; p-value = significance.

The test of means did not detect significant differences among soil attributes (except for the Sd as previously reported); this fact, considering the values of Sd reported, suggests a certain level of soil compaction. Therefore, the spatial variability of ECa shows potential to be a guiding factor for smart Sd sampling able to identify areas in the field with distinct Sd values. This spatial variability delineation is agronomic relevant because Sd is an indicator of the soil’s physical quality, an attribute that directly influences crop performance [19,20].

Table 4 presents a test of means for Sd in both fields investigated according to the MZ delineated. A statistically significant difference was observed for the mean values of Sd between fields A and B for the soil layer of 0.1–0.2 m, with values of 1.53 and 1.64 g dm⁻³, respectively.

Table 4. Test of means for bulk soil density (Sd; g cm⁻³), in two management zones (MZ 1 and MZ 2) delineated based on apparent soil electrical conductivity, according to the fields. Cachoeira do Sul, RS, BR.

MZ	Soil Depth (m)	Soil Density (g cm ⁻³)		t-Value	d.f.	p-Value
		Field A	Field B			
1	0–0.1	1.34	1.35	–0.18	4.00	0.86
	0.1–0.2	1.53	1.64	–4.80	4.00	0.01
2	0–0.1	1.46	1.46	0.01	4.00	1.00
	0.1–0.2	1.67	1.74	–1.17	4.00	0.31

d.f.: degrees of freedom; t-value = student test; p-value = significance.

Table 5 presents the Sd, in each field, as a function of the different depths investigated in each MZ. The Sd values of the 0.1–0.2 m were higher in the 0–0.1 m in field A, for both MZs investigated. In field B, although the same trend of higher values of Sd in the deeper layer compared to the shallow was observed in both MZs, a significant statistical difference was only observed for MZ 1.

Table 5. Soil bulk density (Sd; g cm⁻³), in two fields (A and B), and two depths (0–0.10 m and 0.10–0.20 m) in management zones delineated based on apparent electrical conductivity. Cachoeira do Sul, RS, BR.

Fields	MZ	Sd by Depths		t-Value	d.f.	p-Value
		(0–0.1 m)	(0.1–0.2 m)			
A	1	1.34	1.53	–6.71	4.00	0.00
	2	1.46	1.67	–3.71	4.00	0.02
B	1	1.35	1.64	–3.02	4.00	0.04
	2	1.46	1.74	–2.47	4.00	0.07

d.f.: degrees of freedom; t-value = student test; p-value = significance.

4. Discussion

In the semivariograms of ECa, the range values used can influence the quality of estimates, since it determines the number of values used in the interpolation process;

thus, estimates made with interpolation by ordinary kriging using values of larger ranges tend to be more reliable, presenting spatial maps that more accurately represent the field variability [21]. The cross-validation regression coefficients showed values above 0.8 for both fields, indicating a satisfactory fit of the semivariance model. Cross-validation was an efficient tool to represent spatial ECa variability based on the agreement of estimated values and real field variability [22].

The ECa values represent the spatial changes in soil attributes. Previous studies have already reported that ECa values are affected by chemical and physical soil attributes. Peralta and colleagues [23] studied the correlation between soil attributes and ECa and identified that cation-exchange capacity and soil organic matter (SOM) contents were positively related to ECa. However, SOM had a significant correlation with the soil moisture, and this supports a higher electric current capacity and, therefore, drives the ECa spatial variability.

Medeiros [24] evaluated the correlation of ECa in two fields with different soil textures, one being a sandy and the other a clayey soil. The authors reported that in the sandy soil field, a positive correlation was found for the available soil phosphorus, and there was no correlation between ECa and SOM with either clay or sand contents. In the clayey soil field, ECa had a positive correlation with clay content and a negative correlation with sand content. Alves [25], who defined an MZ based on the spatial variability of ECA and SOM in corn and soybean fields, reported that they were efficient indicators of soil attribute spatial variability.

Research carried out by Bottega and colleagues [26] investigated the delimitation of MZs based on ECa, and concluded that the MZs obtained were able to capture the spatial variability of soil attributes such as the contents of clay, potassium, calcium, sum of bases, effective cation exchange capacity, and cation exchange capacity at pH 7.

In field A, the delimited management zones did not present spatial continuity, as observed in field B, in which the two MZs were better delimited. This fact can be explained by the management adopted by the farmers in each field. In MZ 1 of field B, the central pivot was used to grow corn for silage. In this MZ 1, there was intensive non-controlled traffic of heavy machines that are associated with a more intensive cropping system, resulting in soil compaction. In fields with high above-ground biomass exportation, low levels of SOM and nutrient depletion are generally reported [27], which can accelerate the soil compaction process, especially under traffic machinery with high soil moisture. Michelon and colleagues [28], investigating center-pivot fields in five Brazilian States, reported that in Sao Paulo State, 34% of fields had soil compaction. The authors evaluated soil density and macroporosity as key indicators of soil compaction suggesting that for the soil texture range of 200–300 g kg⁻¹ of clay, the bulk density > 1.55 and macroporosity < 10% were critical to crop performance and soil water storage. The change in soil hydro-physical attributes may affect ECa.

Regardless of the MZ, in our study, field B had Sd lower in the 0–0.1 m layer (MZ1 = 1.54; MZ2 = 1.46 g cm⁻³) than in the 0.1–0.2 m layer (MZ1: 1.66; MZ2: 1.74 g cm⁻³). Assuming the critical values of Sd as proposed by Michelon and colleagues [28], in our study, field B in the 0–0.1 m layer was not critical, but the 0.10–0.20 m had Sd values over this limit, affecting crop performance, water storage, and ECa. These results corroborate those obtained by Silveira [29], who observed a similar trend of lower Sd at depths of 0–0.1 m than 0.1–0.2 m. In addition, the study carried out by Assis [30] found that the Sd in layers 0–0.1 m had a lower change in Sd in a degraded pasture field. Custodio [19] attributed the higher accumulation of SOM in the shallow layer as a key factor to maintain soil biological activity and plant root growth, which can alleviate soil compaction.

The soil compaction reported in field B was possibly associated with random aleatory traffic of heavy machinery under high soil moisture and a greater number of livestock in the winter season (crop–livestock system). Machine traffic and overgrazing are among the main world causes of soil compaction, increasing soil bulk density and affecting plant root growth [20]. The increase in soil bulk density is associated with a linear decrease

in macroporosity that causes a slow infiltration rate, which, in turn, compromises soil water storage [31]. Bono; Macedo; Tormena [32] evaluated the soil physical attributes of *U. brizantha* pasture and found that the high bulk densities in the shallow layers were due to the livestock grazing effect. Similarly, Bell [33] reported that the major constraint on the adoption of integrated crop–livestock farming systems in Australia is the adverse impacts of soil compaction caused by grazing livestock, expressly by a decrease in soil porosity and infiltration rate, and an increase in soil bulk density and soil penetration resistance in the soil surface (top 5–10 cm). In field B of our study, there were three factors, associated random machinery traffic, livestock grazing, and silage production, which severely affected the soil physics attributes that were represented by the Sd captured by ECa.

The increase in Sd with depth in our study can be associated with a decline in SOM, lower soil aggregation, higher penetration resistance, and a decrease in soil porosity [34]. Mazurana [35] observed that machine traffic in an uncultivated system (fallow) affected soil macroporosity up to a 0.10 m depth, also changing Sd.

Soil density values tend to increase under continuous no-till due to a lack of soil disturbance and crop rotation. The soil macroporosity, microporosity, and total porosity also increase when the principles of NTS are fully integrated (permanent soil cover, minimum soil disturbance, and crop rotation) [29]. Moreover, according to Kunz [36], depending on the soil physics conditions at the beginning of NTS adoption reported mainly in clay soil, they were expressed by an increase in Sd and a decrease in macroporosity.

A continuous and rotational grazing system alters the physical properties of the soil, such as soil porosity, leading to soil compaction [37]. Collares [38], who aimed to evaluate the impacts of machine traffic and cattle hooves on soil physics attributes, reported that immediate compaction was observed in soils under machinery traffic, while in soils with livestock grazing, an increase in soil compaction was observed only in shallow layers, altering the soil macroporosity. Chyba and colleagues [39], comparing soil compaction by machinery traffic and cattle hooves, reported that the effect could be similar where saturated hydraulic conductivity values are reduced by 80% compared to non-compacted treatment, confirming the negative effect on the infiltration rate. In our study, the high Sd in field 2 had both sources of soil compaction machinery traffic and cattle hooves justifying the high ECa.

The present study aimed to investigate whether the delimitation of MZ, based on the mapping of the spatial variability of ECa, is efficient in differentiating Sd values in two fields with different management systems but with a similar soil texture. The results demonstrate the great potential for ECa to be a tool to guide smart Sd sampling, supporting site-specific management to mitigate soil compaction in grain crops. The techniques and tools used in this study can be adopted in any rural property, regardless of its size or technological level. The delimitation of the MZ can contribute to the reduction in the time and costs involved in the quantification of Sd since each MZ can be considered homogeneous. Further studies should be carried out so that this technique can be consolidated as an effective tool in the site-specific management of soil compaction.

5. Conclusions

Spatial variability of apparent soil electrical conductivity was investigated and was detected in both fields that presented similar soil textures. Management zones with the highest value of apparent soil electrical conductivity had the highest values of soil density, in both soil layers analyzed. The highest soil bulk density was observed for the 0.1–0.2 m layer, regardless of the studied field. Although the fields had a different level of soil compaction based on soil bulk density and crop management adopted. The field under center-pivot irrigation had the highest soil bulk density associated with intensive random machinery traffic, livestock grazing effect, and crop residue remotion compared to the field under rainfeed management. As a consequence, a statistical difference for soil bulk density, in MZ 1, layer 0.1–0.2 m, was reported with a 7.2% higher bulk density in the field under center pivot than the rainfeed field, reaching values that affected soil water

storage and crop performance. In addition, the delimitation of management zones, based on the spatial variability of apparent electrical conductivity mapping, was an efficient and cheaper tool to guide smart soil sampling to explore the presence of soil compaction. Our study confirms that central-pivot irrigated fields need special attention regarding the risk of soil compaction, especially when submitted to intensive cropping systems, crop residue removal to silage, and livestock grazing.

Author Contributions: Conceptualization, E.L.B., C.K.M. and Z.B.d.O.; methodology, E.L.B. and Z.B.d.O.; software, E.L.B. and C.K.M.; formal analysis, E.L.B. and C.K.M.; data curation, E.L.B. and Z.B.d.O.; writing—original draft preparation, E.L.B. and C.K.M.; writing—review and editing, T.J.C.A. and C.d.C.L.; supervision, E.L.B. All authors have read and agreed to the published version of the manuscript.

Funding: We thank Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for granting an undergraduate research scholarship through Public Notice No. 009/2019—Institutional Scientific Initiation Scholarship Program (PIBIC and PIBIC Affirmative Actions) CNPq/UFMS. We thank CNPq for the research scholarship awarded to the last author.

Data Availability Statement: The databases used in this study are not publicly available, however, they can be obtained upon request to the corresponding author, provided that your request is justified.

Acknowledgments: We also thank Maurício Tisato and Paulo Ebbesen, for the availability of the study areas.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. CONAB—Companhia Nacional De Abastecimento. *Acompanhamento da Safra Brasileira de Grãos, v.8—Safra 2020/21, n° 8—Oitavo Levantamento*; CONAB: Brasília, Brasil, 2021; 115p.
2. Londero, R.; de Oliveira, R.B.; do Nascimento, J.M.; Arcoverde, S.N.S.; Secretti, M.L. Dependência espacial da fertilidade do solo sob plantio direto e suas relações com a produtividade da soja. *Cad. Cien. Agrárias* **2020**, *12*, 1–8. [[CrossRef](#)]
3. Salomão, P.E.A.; Kriebel, W.; dos Santos, A.A.; Martins, A.C.E. A importância do sistema de plantio direto na palha para reestruturação do solo e restauração da matéria orgânica. *Res. Soc. Dev.* **2020**, *9*, e154911870. [[CrossRef](#)]
4. Gelain, E.; Bottega, E.L.; de Araujo Motomiya, A.V.; Marin, C.K.; de Oliveira, Z.B. Dependência e correlação espacial dos atributos de solo em função do arranjo amostral. *Tecno-Lógica* **2021**, *25*, 145–172. [[CrossRef](#)]
5. Cintra, P.H.M.; Compagnon, A.M.; Arriel, F.H.; Ventura, G.S.; dos Santos, M.L.; Pimenta Neto, A.M. Variabilidade espacial e qualidade na semeadura de soja. *Braz. Appl. Sci. Rev.* **2020**, *4*, 1206–1221. [[CrossRef](#)]
6. Cherubin, M.R.; Santi, A.L.; Eitelwein, M.T.; Amado, T.J.C.; Simon, D.H.; Damian, J.M. Dimensão da malha amostral para caracterização da variabilidade espacial de fósforo e potássio em Latossolo Vermelho. *Pesqui. Agropecu. Bras.* **2015**, *50*, 168–177. [[CrossRef](#)]
7. Grego, C.R.; de Oliveira, R.P.; Vieira, S.R. Geostatística aplicada à agricultura de precisão. In *Agricultura de Precisão: Resultados de Um Novo Olhar*; Bernardi, A.C.D.C., Naime, J.D.M., de Resende, A.V., Bassoi, L.H., Inamasu, R.Y., Eds.; Embrapa: Brasília, Brasil, 2014; pp. 74–83.
8. Lopes, K.A.D.L.; Aguiar, F.I.D.S.; de Oliveira, I.R.; Dantas, J.S. Variabilidade espacial de atributos químicos de um argissolo amarelo distrocoeso em diferentes densidades de amostragem. *Rev. Cien. Rural* **2020**, *22*, 29–42. [[CrossRef](#)]
9. Campos, B.H. Estudo de Caso de Atributos Físicos de Solo No Bioma Cerrado, Em Diferentes Sistemas de Uso e Manejo. Bachelor's Thesis, Universidade Federal de Uberlândia, Uberlândia, MG, Brasil, 2021; 35p.
10. Stone, L.F.; da Silveira, P.M. Efeitos do sistema de preparo e da rotação de culturas na porosidade e densidade do solo. *Rev. Bras. Cienc. Solo* **2001**, *25*, 395–401. [[CrossRef](#)]
11. United States Department of Agriculture [USDA]. *Soil Taxonomy: Agriculture*; Handbook; USDA: Washington, DC, USA, 1975; 436p.
12. Corwin, D.L.; Hendrickx, J.M.H. *Electrical Resistivity: Wenner Array*. In *Methods of Soil Analysis Part 4 Physical Methods*; Silva, J.S., Ed.; SSSA Book Series: Madison, WI, USA, 2002; pp. 1282–1287.
13. Corwin, D.L.; Lesch, S.M. Application of soil electrical conductivity to precision agriculture: Theory, Principles, and Guidelines. *Agron. J.* **2003**, *95*, 455–471. [[CrossRef](#)]
14. Oliver, M.A.; Webster, R. A tutorial guide to geostatistics: Computing and modelling variograms and kriging. *Catena* **2014**, *113*, 56–69. [[CrossRef](#)]
15. Valente, D.S.M. Desenvolvimento de um Sistema de Apoio à Decisão Para Definir Zonas de Manejo em Cafeicultura de Precisão. Ph.D. Thesis, Universidade Federal de Viçosa, Viçosa, MG, Brasil, 2010; 122p.
16. Cressie, N.A. *Statistics for Spatial Data*; John Wiley & Sons: New York, NY, USA, 1993; 900p.

17. Tisseyre, B.; Mcbratney, A.B. A technical opportunity index based on mathematical morphology for site-specific management: An application to viticulture. *Precis. Agric.* **2008**, *9*, 101–113. [[CrossRef](#)]
18. Warrick, A.W.; Nielsen, D.R. Spatial variability of soil physical properties in the field. In *Applications of Soil Physics*, Hillel, D.; Academic Press: New York, NY, USA, 1980; pp. 319–344.
19. 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.* **2015**, *10*, 50–62.
20. dos Santos, F.F.; Savioli, J.S.; dos Santos, L.G.; Leite, F.; Castaldo, J.H. Uso de bioestimulante na cultura da soja sobre tráfego controlado. *Res. Soc. Dev.* **2020**, *9*, e238997096. [[CrossRef](#)]
21. 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 cana-de-açúcar. *Rev. Bras. Cienc. Solo* **2004**, *28*, 1013–1021. [[CrossRef](#)]
22. Landim, P.M.B. Sobre geoestatística e mapas. *Terrae Didat.* **2006**, *2*, 19–33. [[CrossRef](#)]
23. Peralta, N.R.; Costa, J.L.; Balzarini, M.; Angelini, H. Delineation of management zones with measurements of soil apparent electrical conductivity in the southeastern pampas. *Can. J. Soil Sci.* **2013**, *93*, 205–218. [[CrossRef](#)]
24. Medeiros, W.N.; Valente, D.S.M.; de Queiroz, D.M.; Pinto, F.d.A.d.C.; de Assis, I.R. Condutividade elétrica aparente do solo em dois tipos de solo. *Rev. Cien. Agron.* **2018**, *49*, 43–52. [[CrossRef](#)]
25. Alves, S.M.D.F.; Alcântara, G.R.; dos Reis, E.F.; de Queiroz, D.M.; Valente, D.S.M. Definição de zonas de manejo a partir de mapas de condutividade. *Biosci. J.* **2013**, *29*, 104–114.
26. Bottega, E.L.; Dias, R.F.; Sari, E.L.; Dorneles, A.B.; Marin, C.K.; de Oliveira, Z.B. Zonas de manejo: A teoria na prática. *Rev. Plantio Direto* **2019**, *171*, 11–14.
27. Molin, J.P.; Castro, C.N. Establishing management zones using soil electrical conductivity and other soil properties by the fuzzy clustering technique. *Sci. Agric.* **2008**, *65*, 567–573. [[CrossRef](#)]
28. Michelon, C.J.; Carlesso, R.; Petry, M.T.; Melo, G.L.; Spohr, R.B.; de Andrade, J.G. Qualidade física dos solos irrigados de algumas regiões do Brasil Central. *Rev. Bras. Eng. Agric. Ambient.* **2009**, *13*, 39–45. [[CrossRef](#)]
29. da Silveira, P.M.; Stone, L.F.; Alves Júnior, J.; da Silva, J.G. Efeitos do manejo do solo sob plantio direto e de culturas na densidade e porosidade de um Latossolo. *Biosci. J.* **2008**, *24*, 53–59.
30. Assis, P.C.R.; Stone, L.F.; Medeiros, J.C.; Madari, B.E.; Oliveira, J.D.M.; Wruck, F.J. Atributos físicos do solo em sistemas de integração lavoura-pecuária-floresta. *Rev. Bras. Eng. Agric. Ambient.* **2015**, *19*, 309–316. [[CrossRef](#)]
31. Nicoloso, R.D.S.; Amado, T.J.C.; Schneider, S.; Lanzanova, M.E.; Girardello, V.C.; Bragagnolo, J. Eficiência da escarificação mecânica e biológica na melhoria dos atributos físicos de um latossolo muito argiloso e no incremento do rendimento de soja. *R. Bras. Ci. Solo* **2008**, *32*, 1723–1734. [[CrossRef](#)]
32. Bono, J.A.M.; Macedo, M.C.M.; Tormena, C.A. Qualidade física do solo em um latossolo vermelho da região sudoeste dos cerrados sob diferentes sistemas de uso e manejo. *Rev. Bras. Cienc. Solo* **2013**, *37*, 743–753. [[CrossRef](#)]
33. Bell, L.W. Impacts of soil compaction by livestock on crop productivity—A modelling analysis. In *Proceedings of the 19th World Congress of Soil Science: Soil Solutions for a Changing World*, Brisbane, Australia, 1–6 August 2010.
34. Bicalho, I.M. Um estudo da densidade do solo em diferentes sistemas de uso e manejo. *Enciclopédia Biosf.* **2011**, *7*, 1–9.
35. Mazurana, M.; Fink, J.R.; da Silveira, V.H.; 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. *Rev. Bras. Cienc. Solo* **2013**, *37*, 1185–1195. [[CrossRef](#)]
36. Kunz, M. *Relações Físico-Hídricas De Um Latossolo Sob Plantio Direto*. Master's Thesis, Universidade Federal de Santa Maria, Santa Maria, RS, Brasil, 2010; 48p.
37. Cervelati, K.F.; de Sousa Neto, E.L.; Eguchi, E.S.; Silva, M.R.; Pierangeli, M.A.P. Efeito de diferentes sistemas de pastejo em atributos físicos do solo. *PUBVET Publicações Em Med. Veterinária E Zootec.* **2011**, *5*, 1142. [[CrossRef](#)]
38. Collares, G.L. *Compactação em Latossolos e Argissolo e Relação com Parâmetros de Solo e de Plantas*. Ph.D. Thesis, Universidade Federal de Santa Maria, Santa Maria, RS, Brasil, 2005; 107p.
39. Chyba, J.; Kroulík, M.; Křištof, K.; Misiewicz, P.A.; Chaney, K. Influence of soil compaction by farm machinery and livestock on water infiltration rate on grassland. *Agron. Res* **2014**, *12*, 59–64.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.