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SAMPLING DENSITY TO DETECT SPATIAL DEPENDENCE OF POTASSIUM, CALCIUM AND MAGNESIUM IN SANDY SOILS

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ABSTRACT

The sampling grid density for georeferenced soil collection must be large enough to allow the identification of the spatial dependence of attributes with representative accuracy of the cultivated area, but not large enough to make fertility mapping unfeasible. The objective of this study was to define, from the evaluation of geostatistical parameters obtained from a super dense soil sampling, an efficient grid for detecting the spatial dependence of potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) in a sandy soil. The experiment was conducted in a 3.2 hectare annatto crop (*Bixa orellana* L.), in 2017. The geostatistical grid consisted of 31 points per hectare, totaling 101 georeferenced points in an 18x18 m spacing. Soil was sampled at the depths of 0-0.20 m and 0.20-0.40 m. A strong spatial dependence was found for all soil attributes in both depths, while the semivariograms fitted to the spherical model with good coefficients of determination (R^2) indicating a spatial correlation between the attributes. The range of spatial dependence was close to 100 m for all attributes in both layers. In sandy soils, an efficient sampling grid to detect the spatial dependence of K^+, Ca^{2+} and Mg^{2+} must consider a semivariogram range of approximately 100 meters.

Palavras-chave:
Geoestatística
Semivariograma
Agricultura de precisão

DENSIDADE AMOSTRAL PARA DETECÇÃO DA DEPENDÊNCIA ESPACIAL DE POTÁSSIO, CÁLCIO E MAGNÉSIO EM SOLOS ARENOSOS

RESUMO

A densidade de um grid amostral para coleta georreferenciada de solo precisa ser suficiente para garantir a observância da dependência espacial dos atributos com acurácia representativa da área de cultivo, todavia, não deve ser demasiada a ponto de tornar inviável o mapeamento da fertilidade. O objetivo deste trabalho foi definir, a partir da avaliação de parâmetros geoestatísticos obtidos de uma amostragem de solo super densa, um *grid* eficiente para detecção da dependência espacial de potássio (K^+), cálcio (Ca^{2+}) e magnésio (Mg^{2+}) em um solo arenoso. A pesquisa foi realizada em 2017 em uma área de 3,2 hectares de cultivo de urucum (*Bixa orellana* L.). O *grid* geoestatístico foi de 31 pontos por hectare, totalizando 101 pontos georreferenciados com espaçamento de 18x18 m. As coletas de solo foram realizadas nas camadas 0-0,20 m e 0,20-0,40 m. Foi confirmada forte dependência espacial para todos os atributos do solo nas duas camadas avaliadas, ao passo que os semivariogramas foram ajustados, com bons coeficientes de determinação (R^2) ao modelo esférico, indicando correlação espacial entre os atributos. O alcance da dependência espacial esteve próximo a 100 m para todos os atributos nas duas camadas. Em solos arenosos, um *grid* amostral eficiente para detecção da dependência espacial de K^+, Ca^{2+} e Mg^{2+} deve considerar um alcance semivariográfico de aproximadamente 100 metros.

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INTRODUCTION

Efficient soil fertility mapping, which provides accurate representation of a cultivated area, allows the improvement of soil management using precision agriculture techniques. Precision agriculture involves the rational use of inputs and fertilizers by applying variable fertilizer rates, according to the needs of each crop site.

In the field of geostatistics applied to the study of spatial variability of soil attributes, there has been a long debate about the optimal number of points to be sampled per unit of area to provide accurate information consistent with the characteristics of a cropped area (SILVA *et al*., 2020). Thus, one of the main limitations to the use of the technique of applying inputs at variable rates is the number of samples needed for the optimal grid, which efficiently represents the spatial dynamics of soil attributes (SOUZA *et al*., 2014)

According to Molin *et al*. (2015), determining the sampling density of the geostatistical grid is crucial for the quality of the final map and its ability to properly represent the actual spatial variability of soil attributes. However, in the planning of the georeferenced sample grid usually lacks a methodology for defining the number of soil samples needed, in addition to the fact that the decision has been based on economic rather than technical indicators.

Ferraz *et al*. (2017) stated that underestimated soil sampling grids may lead to maps that do not reflect the conditions in the field, resulting in erroneous technical recommendations for the farm.

In this sense, a georeferenced sampling grid for soil collection cannot be economically unfeasible for the farmer. However, it must be at least large enough to ensure the detection of spatial dependence of the attributes, which is in agreement with Cherubin *et al*. (2015), who stated that increasing the sampling density increases the efficiency in detecting and mapping the spatial variability of soil chemical attributes.

On the other hand, there is great difficulty in establishing an optimal grid, since different scales of variation considering the different attributes and even field variations such as soil type and management make it difficult to determine a sampling design using single spacing (NANNI *et al*., 2011; MONTANARI *et al*., 2012; STEPIEN *et al*., 2013; SOUZA *et al*., 2014; STAMPER *et al*., 2014). Therefore, due to the absence of well-established criteria, the sampling density of a georeferenced grid is still a topic of discussion among scientists, technicians, and farmers (FIGUEIREDO *et al*., 2018).

The objective of this study was to define, based on the evaluation of geostatistical parameters obtained from a super dense soil sampling, an efficient grid for detecting the spatial dependence of potassium, calcium and magnesium in a sandy soil.

MATERIAL AND METHODS

The experiment was conducted in a 3.2 hectare of a 48-month annatto crop (*Bixa orellana* L.), cultivar Piavê Vermelha, located in the municipality of Vilhena, Rondônia (Figure 1), between the coordinates 12°45’51.11 “S and 60°12’1.75”W, in 2017.

The climate of Rondônia according to the Köpen, is classified as tropical hot and humid type Am (monsoon). The average rainfall is around 1,400 to 2,600 mm year^{-1}, while the average annual air temperature ranges from 24 ºC to 26 ºC (ALVARES *et* al., 2013).

The soil in the study area is classified as Quartzarenic Neosol (SANTOS *et al*., 2018), containing 830 g kg^{-1} sand, 70 g kg^{-1} silt, and 100 g kg^{-1} clay. The relief is undulating and average 12% slope.

At planting, in 2013, 1.5 kg of dolomitic limestone and 300 g of composted cattle manure was applied to the holes. From planting to 2017, the soil was managed with NPK mineral fertilizer applied in single doses, in January or February of each year. The application rates were 40g of N, 40g of K_2O and 15g of P_2O_5 per plant. Liming was not applied after planting.

First, Google Earth was used to map the crop area and the sampling grid was designed for the data collection using the QGis software version 3.14.1. The regular geostatistical grid presented 101 sampling points spaced 18x18 m. The grid UTM coordinates were transferred to a Trimble

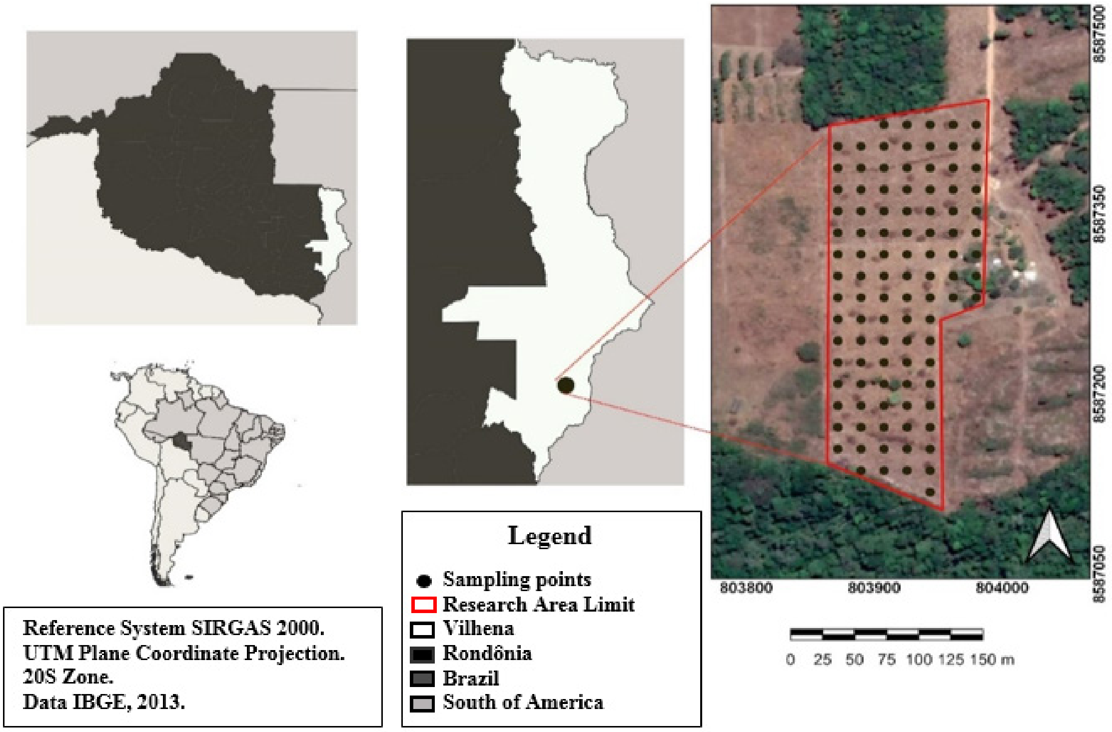


Figure 1. Location map of study area in Vilhena – RO and representation of the geostatistical grid with 101 georeferenced sampling points [SIRGAS Coordinate Reference System 2000, EPSG: 31980]

Juno 3B GNSS receiver, enabling navigation to the data collection points.

Soil chemical attributes were analyzed at the 0-0.20 m and 0.20-0.40 m depths, totaling 202 soil samples collected with a Dutch auger from the center of each grid square.

The following soil chemical attributes were determined: available K^+, and exchangeable Ca^{2+} and $Mg^{2+,}$ using ion exchange resin. All laboratory analyses followed the methodology described by Raij *et al*. (2001).

Classic descriptive analysis was performed for each attribute evaluated, using the SAS statistical software (SCHLOTZHAVER & LITTELL, 1997) to calculate the mean, median, minimum and maximum values, standard deviation, Coefficient of Variation (CV), kurtosis, skewness and Frequency Distribution (FD).

Afterwards, the outliers were identified, replacing their values by the average value of the attribute. The hypothesis of normality or lognormality was tested by the Shapiro and Wilk (1965) statistic at 1%. Subsequently, a geostatistical analysis was carried out with the Gamma Design Software package (GS+, 2004) to study the spatial dependence through the simple semivariogram and to characterize the spatial variability with the Ordinary Kriging technique. This allowed the creation of thematic maps for the attributes of this study, which were generated from the directional grid (Figure 2) of orientation within the study area. The simple semivariograms for the attributes analyzed in this study fitted to the spherical model with the following equation 1:

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

where,

y(h) is the estimated semivariance and N(h) the number of pairs of measured values, Z(xi) and Z(xi+h) and separated by distance h.

The spatial dependence evaluator (SDE) followed the criteria of Cambardella *et al*. (1994): a) SDE < 50% = weak spatial dependence; b) 50% ≤ SDE ≤ 75% = moderate spatial dependence; and c) SDE > 75% = strong spatial dependence.

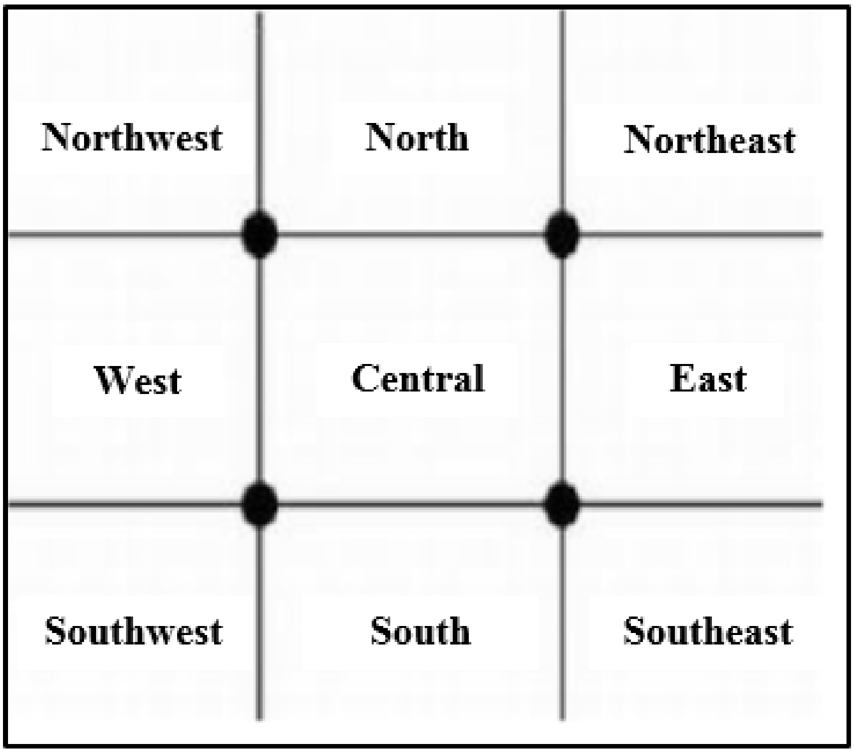


Figure 2. Directional grid of kriging maps

RESULTS AND DISCUSSION

The mean values of the descriptive data analysis (Table 1) showed a low level of soil fertility in the two layers evaluated. The availability of K^+ (0.47 and 0.38 mmolc dm^{-3}), the concentration of Ca^{2+} (3.08 and 2.63 mmolc dm^{-3}) and Mg^{2+} (1.41 and 1.30 mmolc dm^{-3}) were far below the lowest fertility classes proposed by Sousa and Lobato (2004) for Cerrado soils. Santos *et al*. (2018) highlighted that the physicochemical attributes of Quartzarenic Neosols, with emphasis on the low concentration of clay, imply low natural fertility. Table 1 presents the complete descriptive analysis of the attributes evaluated in this study.

All soil attributes in both layers showed very high CV (PIMENTEL-GOMES, 2009), and indeterminate DF (Shapiro & Wilk, 1965). CV is a parameter that provides indication of the regularity of samples (ANDRIOTTI, 2003), demonstrating the degree of heterogeneity of data. In relation to DF, a sample with normal behavior, although desirable, is not a fundamental presupposition for geostatistical formality (ISAAKS & SRIVASTAVA, 1989).

Several studies on spatial variability mapping of soil chemical attributes with emphasis on potassium, calcium, and magnesium carried out with different types of soils, crops, and sampling densities presented CV values ranging from moderate to very high, corroborating the results of this study (CARVALHO *et al*., 2018; FIGUEIREDO *et al*., 2018; LIMA *et al*., 2018; NOETZOLD *et al*., 2018; MATIAS *et al*., 2019; LEANDRO JUNIOR *et al*., 2020; GELAIN *et al*., 2020; GELAIN *et al*., 2021; SANTOS *et al*., 2021, SANTOS JUNIOR *et al*., 2021; CORRÊA *et al*., 2022).

The spatial variability of soil attributes occurs naturally due to the morphological characteristics of the relief and the complex physical-chemical-biological interactions in its interior that result from the process of formation, in addition, this variation or heterogeneity increases through management practices of livestock activities (ARTUR *et al*., 2014; DIAS *et al*., 2015; SANTOS *et al*., 2015).

The results about the geostatistical parameters

Table 1. Descriptive analysis of soil chemical attributes at 0-0.20 m and 0.20-0.40 m depths in a Quartzarenic Neosol in the municipality of Vilhena, Rondônia, 2017

Attribute [(a)]	Descriptive statistical measures								
	Mean	Value		Standard deviation	Coefficient		Test probability [(b)]		
		Minimum	Maximum		Variation (%)	Kurtosis	Asymmetry	SY<w	DF
Soil chemical attributes (layer 0-0.20 m)									
K^+ (mmol$_c$ dm^{-3})	0.47	0.00	1.00	0.27	57.18	-1.19	0.54	<0.0001	IN
Ca^{2+} (mmol$_c$ dm^{-3})	3.08	1.00	11.0	2.52	81.94	1.18	1.24	<0.0001	IN
Mg^{2+} (mmol$_c$ dm^{-3})	1.41	1.00	3.00	0.57	40.74	0.48	1.15	<0.0001	IN
Soil chemical attributes (layer 0,20-0,40 m)									
K^+ (mmol$_c$ dm^{-3})	0.38	0.00	1.00	0.28	73.01	-1.22	0.64	<0.0001	IN
Ca^{2+} (mmol$_c$ dm^{-3})	2.63	1.00	9.00	2.13	81.11	-0.09	1.01	<0.0001	IN
Mg^{2+} (mmol$_c$ dm^{-3})	1.30	1.00	2.00	0.45	34.66	-1.18	0.89	<0.0001	IN

Note: [(a)] SY PR = seed yield; K^+ = available potassium in the soil; Ca^{2+} = calcium content in the soil; Mg^{2+} = magnesium content in the soil. (b) IN = indeterminate frequency distribution.

Source: From authors

Table 2. Parameters of the simple semivariograms adjusted for some chemical attributes of the soil in the layers 0-0.20 m and 0.20-0.40 m of a Quartzarenic Neosol in the municipality of Vilhena, Rondônia, 2017

Attribute [(a)]	Geostatistical parameters							
	Model [(b)]	Nugget effect (C_0)	Sill (C_0+C)	Range (A_0) (m)	r^2	SQR[(c)]	Spatial Dependency Evaluator SDE[(d)]	Class
γ(h) simple of the soil attributes in the layer 0-0,20 m								
K^+	sph	7.90x10^{-3}	8.78x10^{-2}	103.00	6.81x10^{-1}	1.80x10^{-3}	91.0%	strong
Ca^{2+}	sph	3.50x10^{-1}	0.56x10^{-1}	112.30	6.24x10^{-1}	1.22x10^{1}	93.7%	strong
Mg^{2+}	sph	8.28x10^{-2}	3.84x10^{-1}	101.90	6.58x10^{-1}	3.04x10^{-2}	78.4%	strong
γ(h) simple of the soil attributes in the layer 0,20-0,40 m								
K^+	sph	1.00x10^{-4}	9.92x10^{-2}	103.60	7.73x10^{-1}	1.78x10^{-3}	99.9%	strong
Ca^{2+}	sph	7.40x10^{-1}	0.57 x10^{-1}	113.90	8.38x10^{-1}	0.35x10^{1}	87.0%	strong
Mg^{2+}	sph	1.00x10^{-4}	2.57x10^{-1}	104.20	7.00x10^{-1}	2.02x10^{-2}	100.0%	strong

[a)] K^+ = potassium; Ca^{2+} = calcium; Mg^{2+} = magnesium. [(b)] sph = spherical. [(c)] SQR = sum of squared residuals. (d) SDE = spatial dependence evaluator

were similar for all the attributes in the two layers examined, which allowed us to infer that there is a significant spatial correlation between them. Table 2 presents the complete geostatistical analysis of the data.

All attributes evaluated, in both layers, presented semivariogram fitted to the spherical model and semivariographic range of approximately 100 meters. Cambardella *et al*. (1994), Oliveira *et al.* (2013), Leite *et al*. (2015), Matias *et al*. (2015), Ribeiro *et al*. (2016), Freitas *et al*. (2017), Noetzold *et al*. (2018) and Matias *et al*. (2019) indicated the spherical model as predominant in geostatistical research on soil attributes, corroborating the results of this research.

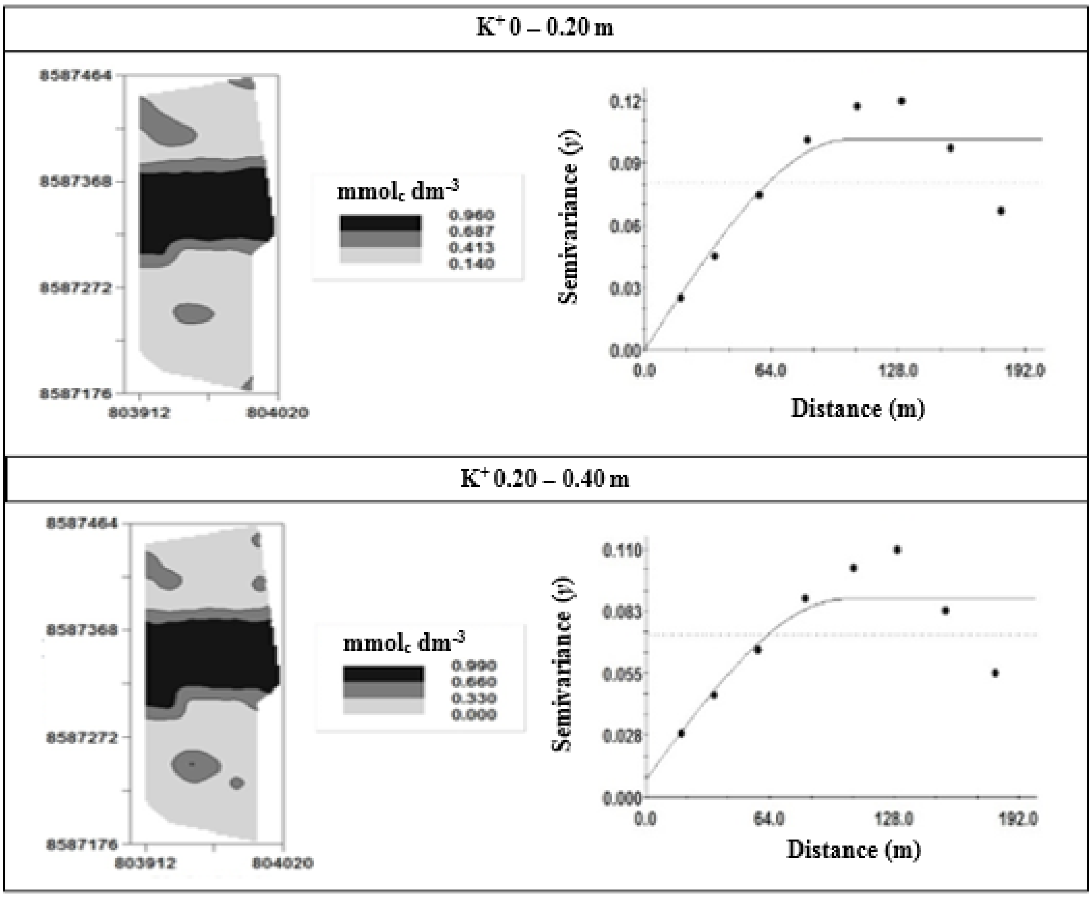
The coefficients of determination (R^2), the main parameter considered for deciding on the mathematical model, were above 60% for all attributes in the two layers, while the threshold and nugget effects were close to zero, confirming strong spatial dependence up to the range observed.

The range of semivariogram reflects the degree of homogenization of a variable, that is, the smaller the range, the greater the variability of the attribute at short distances and the smaller the sample density. Molin *et al*. (2015) highlighted that this geostatistical parameter produces fundamental practical information for the design of georeferenced soil sampling, proposing that an efficient sampling grid should be planned from half the value of the range of semivariogram obtained in previous studies carried out in the cultivation area.

Santos (2018) argued that the range of semivariogram explains the extent to which there is spatial dependence between samples, and thereafter, the pairs no longer show spatial dependence, thus belonging to the random field, and their spatial variability can no longer be explained based on geostatistics.

The ranges of spatial dependence for Ca^{2+} and Mg^{2+} were higher than those found by Matias et al. (2019) in Yellow Argisol cultivated with *Brachiaria brizantha* and by Santos *et al*. (2015) in Yellow Red Latosol under Conilon Coffee (*Coffea canefora* Pierre), both with super dense sampling grids, but were much below the values presented by Dalchiavon *et al*. (2017) in Red Latosol with no-till planted soybean (*Glycine max* L.) in super dense sampling grid. The range of K^+ was similar to values reported by these authors and similar to those reported by Ferraz *et al*. (2017), who evaluated different sampling densities in a Red Yellow Latosol cultivated with coffee (*Coffea arabica* L.).

Figure 2 shows the kriging maps and the respective semivariograms for each attribute in both layers examined. In this study, the kriged maps, which characterized the spatial variability, were essential for the understanding of the spatial dynamics of the attributes evaluated and resulted in the improvement of soil management from assertive decision-making for input use efficiency, i.e., in variable rates and site-specific application.



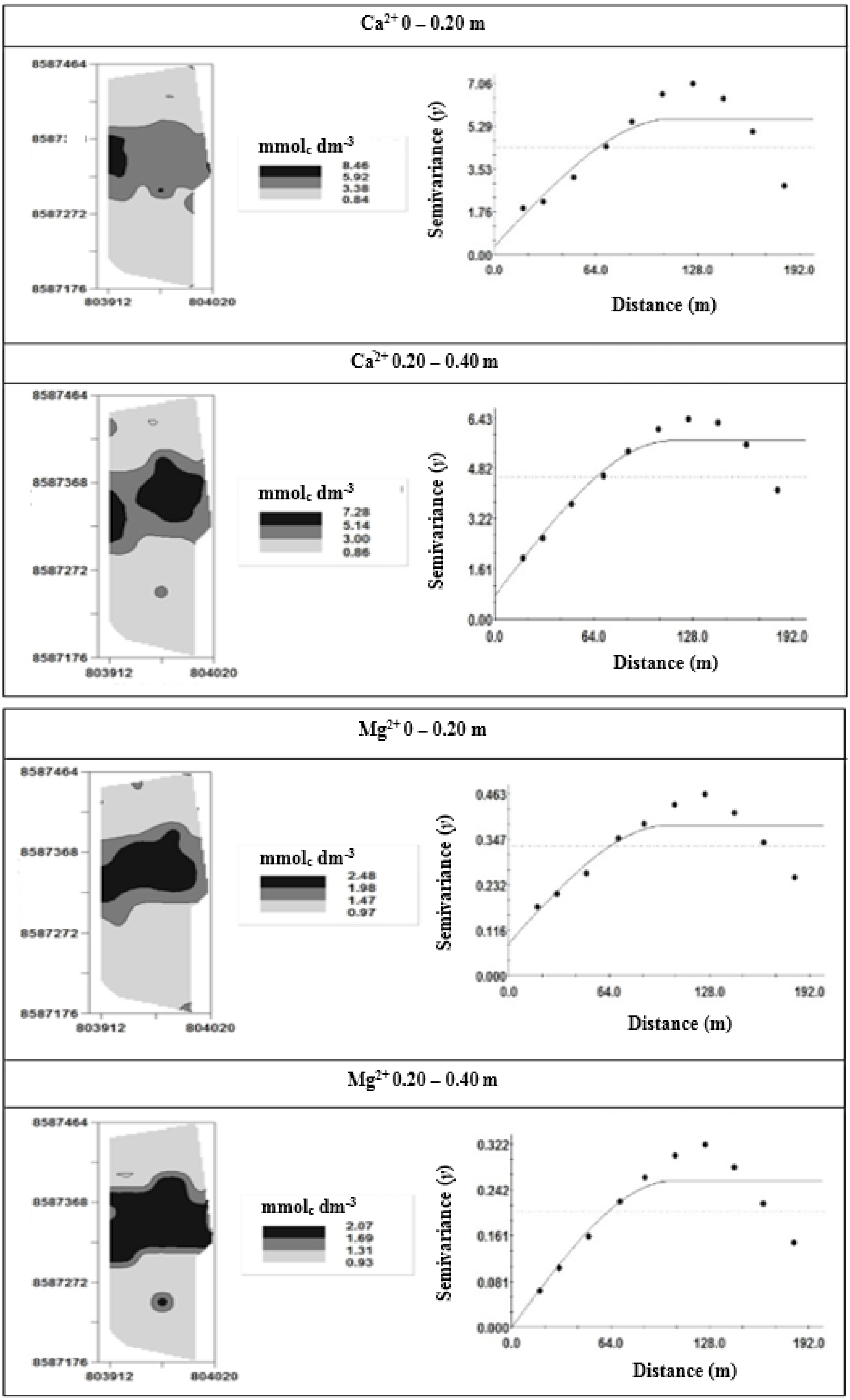


Figure 3. Kriging maps and simple semivariograms of soil chemical attributes at 0-0.20 m and 0.20-0.40 m depths in a Quartzarenic Neosol, in the municipality of Vilhena, Rondônia, 2017

The kriging maps enabled us to identify that, despite the typical low fertility of Quartzarenic Neosols, the West, Central and East bands of the crop, of approximately 1 hectare, were seen as a homogeneous region or unit with greater productive potential, since they presented the best class of K^+ availability (0.41 - 0.96 mmolc dm^{-3} in the first layer and 0.33 - 0.99 mmolc dm^{-3} in the second layer) and the best classes of contents of Ca^{2+} (3.38 - 8.46 mmolc dm^{-3} in the first layer and 3 - 7.28 mmolc d^{-3} in the second layer) and Mg^{2+} (1.47 - 2.48 mmolc dm^{-3} in the first layer and 1 .31 - 2.07 mmolc dm^{-3} in the second layer).

Defining regions or homogeneous units in the crop leads to improvement of agricultural practices (BARBOSA *et al*., 2019) through soil fertility management with site-specific techniques (SILVA *et al*., 2018). This significantly increases efficiency (CARNEIRO *et al*., 2016), resulting in increased yield (LIMA *et al*., 2015), input saving and environmental preservation (DALCHIAVON *et al*., 2017), as it greatly assists in decision making regarding variable rate application and site-specific fertilizer rates (SILVA *et al*., 2020).

The high density of the sampling grid allowed semivariograms to be constructed with robust and efficient geostatistical parameters for the detection and mapping of the spatial variability of soil attributes, determining the efficiency of the methodology used. These results agree with Cherubin *et al*. (2015) and with Ferraz *et al*. (2017), who highlighted the importance of using dense grids for efficient characterization of the spatial dynamics of soil attributes. The authors underlined that choosing a sampling grid based on technical-scientific criteria is pivotal for a good performance in the application of precision agriculture techniques, as a condition for the success of soil management improvement by applying inputs at variable rates.

CONCLUSION

- The sampling grid used in the study produced reliable geostatistical parameters, allowing the conclusion that for sandy soils, a grid that takes into account the distance of 100 m of semivariogram range will be efficient for detecting the spatial dependence of K^+, Ca^{2+} and Mg^{2+}, aiming for the construction of maps consistent with the actual condition of the cultivation area.

AUTHORSHIP CONTRIBUTION STATEMENT

BATISTA, J.A.: Formal Analysis, Methodology, Software, Writing – original draft, Writing – review & editing; **OLIVEIRA, F.A.S.:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing; **FOLADOR, M.E.S.:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing; **RUIZ JUNIOR, J.Z.:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing; **BATISTA, G.B.M.:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing; **SILVA, T.C.:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing; **MONTANARI, R.:** Formal Analysis, Methodology, Software, Writing – original draft, Writing – review & editing.

DECLARATION OF INTERESTS

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

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