

Adjustment of Sampling Grids for Soil Penetration Resistance, Bulk Density, and Soil Moisture Mapping

ABSTRACT

There is still a lack of information in the literature regarding the sampling grid size and its influence on the accuracy of soil attributes spatial variability mapping. Thus, the present study aimed to evaluate the influence of different sampling grid sizes in terms of accuracy for soil penetration resistance (SPR), soil bulk density (SBD) and soil moisture (SM) spatial variability characterization, as well as the correlation between these attributes. The study was conducted in a 5.7 ha Red Yellow Latosol area in Januária, Minas Gerais state, Brazil. Soil samples were taken at the 0.00–0.20 m layer, using a regular sampling grid of 20x20 m. (145 points). Other two grids (41 and 21 points) were derived by deleting lines or lines and points from the initial grid. SPR, SBD, and SM data were subjected to descriptive statistics and geostatistical analyses. Furthermore, the similarity of the thematic maps and correlation among these attributes were analyzed through the relative deviation coefficient (RDC), and Pearson's correlation matrix. The reduction of the grid density (number of points) increased the estimation error for SPR, SBD, and SM, especially when using only 21 points (grid C), whereas, denser grids (Grid A and B) showed maps with greater similarity (accuracy). The SPR levels are directly related to SBD levels, in other words, the highest SPR levels in the area occurred due to higher SBD levels, as well as the lowest values, whereas SM levels presented opposite correlation with SPR values since wetter areas presented lower SPR levels. In addition, denser areas are directly correlated with higher levels of SM in the study area. In essence, only the grid with 25 points per hectare (20x20 m) is recommended for mapping these attributes spatial variability.

Keywords: Precision agriculture; Spatial variability; Soil compaction; Penetrometer.

1. INTRODUCTION

Precision agriculture (PA) is referred as a technological advancement for management of the soil-plant-atmosphere system, which is based on principles of spatial variability and information management that encompasses factors of soil attributes and crop production [1]. Among the PA tools, georeferenced soil sampling by means of regular grids, to characterize the variability of soil attributes, is one of the most important and traditionally used in agriculture. However, georeferenced soil sampling, even when used on a large scale, still lacks methodological definitions, especially regarding the sampling grid size [2, 3].

The efficiency of a soil sampling plan is dependent on prior knowledge of the spatio-temporal variability structure that the investigated attributes present in the soil [4, 5]. Thus, the knowledge of soil attributes and crop property variability, in space and time, is considered a basic principle for the precise management of agricultural areas, independent of their scale [6, 7]. However, the spatio-temporal variability of soil attributes, resulting from soil formation and anthropogenic interventions, varies at different spatial and temporal scales [8].

Based on that, different scales of soil attributes levels make it complex to develop a sampling plan that uses a single-spaced sample grid when several soil attributes are involved [1, 9]. This justifies investigations that aim to define the ideal size of the sample grid for specific soil attributes, such as soil penetration resistance (SPR), soil bulk density (SBD) and soil moisture (SM). SPR is used to quantify the mechanical impedance of the soil for plant root growth [10]. In this sense, SPR has been considered one of the main parameters for diagnosis of soil compaction and determination of restrictive soil layers for plant development [11, 12].

Additionally, the SPR levels vary with temporally and spatially highly dynamic soil properties such as SBD and SM. Experiments conducted with various soils clearly revealed that SPR is directly correlated to SBD

and it exhibits an inverse relationship to SM [13]. As a consequence, high coefficients of variation (CV) were usually observed in different studies [14; 15]. Therefore, to correctly determine the spatial variability of the SPR, it is crucial to establish an adequate density of sampling points per area that best represents each sampling point.

The sampling density is an important factor in the management of soil attributes spatial variability. About 80–85 % of the total error in the application of agricultural inputs, as fertilizers and corrective materials, is attributed to poorly planned soil sampling [16]. Due to this issue, the optimization of sampling grids should consider the allocation of sampling points, which plays a key role in the economic feasibility of PA. Researchers have demonstrated that ideal sampling grids are approximately 50 × 50 m (*i.e.*, four samples per ha) [17] or 30 × 30 m (*i.e.*, more than 10 samples per ha) [18].

Thus, the primary purpose for performing this study is to show that a single size of a grid sampling cannot be used in all areas. Moreover, the sampling grid must meet two main requirements. First, the number and spatial distribution of the sampled points should ensure a minimum precision for estimating in unsampled locations. Secondly, the optimization technique must be numerically practicable [19].

In essence, the optimal sampling grid density is one that, with a minimal amount of points, is able to characterize the spatial variability of soil attributes, guaranteeing the reliability of an estimate. Among the difficulties in providing this kind of information, the level of detail required [20] and implementation costs [21; 22] must be considered. Thus, the objective of this study was to evaluate the influence of different sampling grid densities in terms of accuracy for SPR, SBD and SM spatial variability characterization, as well as to evaluate the correlation between these attributes.

2. MATERIAL AND METHODS

The study was conducted in the Federal Institute of Northern Minas Gerais – Campus Januária, located between the geographical coordinates of 15° 28' 55" S and 44° 22' 41" W. The average altitude is 474 m. The relief of the area is classified as smoothly undulating, and the soil is classified as Red Yellow Latosol according to the Brazilian System of Soil Classification [23]. The experimental site has a total area of 5.7 ha, where sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays*) were cultivated in crop rotation using conventional tillage system for at least 20 years.

In order to map the soil attributes, the agricultural area was georeferenced and divided into a regular sampling grid of 20 x 20 m density consisting of 145 points. All soil samples and analyses were performed in the 0 – 0.20 m layer depth. The SPR was determined using a portable digital penetrometer (PenetroLOG). The SM at the moment of SPR evaluation was determined through the gravimetric method using a Dutch type soil auger for soil sampling. The SBD was determined through the volumetric ring method using a soil auger for undisturbed samples [24]. Four subsamples were collected within a radius of 5 m from the georeferenced point. Then, all subsamples were identified and sent to the lab for the proposed analyses.

In order to evaluate the effects of using different sampling grids densities for mapping the spatial variability of SPR, SBD, and SM, other two grids were created from the sampling grid density of 145 points (A). The grids were composed of 41 (B) and 21 sampling points (C). The sampling grid (B) was originated by eliminating one interspersed line from grid A. On the other hand, the sampling grid (C) emerged eliminating one interspersed line from (B) (Fig. 1).

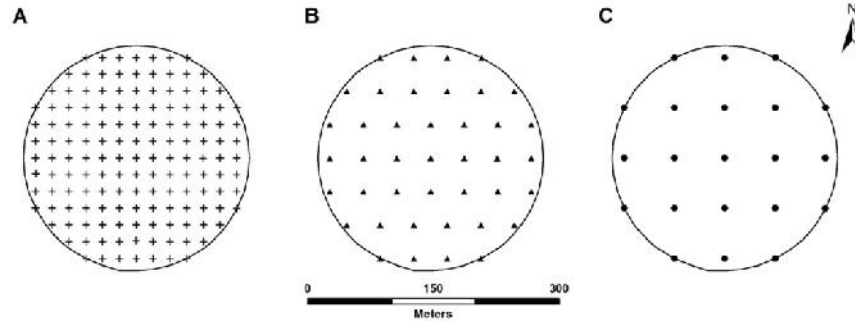


Fig 1. Sampling grids evaluated: (a) 145 points, (B) 41 points, and (C) 21 points.

The datasets from each soil attribute were organized into a spreadsheet and subjected to outlier analysis. Any values outside the range of two standard deviations from the mean were considered outliers. The SPR, SBD, and SM data considering all sampling grids were subjected to a descriptive statistical analysis to obtain the positional means (mean, median, minimum and maximum) and dispersion (coefficients of variation – CV, and standard deviation - SD) skewness and kurtosis. The CV values were used to classify the data variability into low (CV < 12%), medium (12 % < CV < 62 %) and high (CV > 62 %) as proposed in the literature [25].

The spatial dependence of the soil attributes using the three sampling grids densities was evaluated by adjusting semivario-grams, assuming the hypothesis of intrinsic stationarity, defined by Equation 1.

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

Where:

$\gamma(h)$: semivariance as a function of separation distance (h) between pairs of points

h: separation distance between pairs of points, m

N (h): number of experimental pairs of points separated by a distance h

The model that best represented the relationship between experimental semivariance and distance h was adjusted based on the highest coefficient of determination (R^2), the smallest residual sum of squares (RSS), and was confirmed by the cross validation technique. After that, parameters, such as nugget effect (C_0), sill ($C_0 + C_1$) and range (A) were determined. The spatial dependence index (SDI) was determined and classified according to [26], by using the relation $C_1 / (C_0 + C_1)$ and assuming the following intervals: low spatial dependence for SDI < 25%, moderate for 25% < SDI < 75% and strong for SDI > 75%.

Maps interpolation was performed using ordinary kriging and inverse distance weighting (IDW), in case of absence of spatial dependence. Regardless of the sampling grid density used, the maps were generated with the same spatial resolution (pixel size). Thus, it was guaranteed that all maps possess the same number and location of points.

In order to evaluate the effect of different grid densities on the accuracy of thematic maps and the correlation between SPR, SBD, and SM, two parameters were used: The relative deviation coefficient (RDC) and Pearson's linear correlation coefficient ($p < 0.05$). The RDC index expresses the mean difference as an absolute value, which shows the dissimilarity between two maps as demonstrated by the differences between the interpolated points of each map [27]. The lower the percentage found, the greater is the similarity between maps.

In this study, the sampling grid A (145 points) was considered as a reference (standard) for comparison with the other two sampling grids (41 and 21 points). The RDC was determined using Equation 2, which was adapted from [27].

$$RDC = \sum \left| \frac{T_{ij} - T_{iref}}{T_{iref}} \right| \times \frac{100}{n} \quad (2)$$

Where:

T_{iref} : is the soil attribute value at point i (reference value) using the sampling grid A;

T_{ij} : is the soil attribute value at point i determined using the sampling grids B and C;

n : is the number of sampling points (145).

3. RESULTS AND DISCUSSION

A descriptive statistical summary for all the studied attributes is presented in Table 1. A low variability on the mean and median values of all attributes can be observed among the different sampling grids. Moreover, as the size of the sampling grid increased, there was a reduction in amplitude among the minimum and maximum values obtained, tending towards an approximation to the mean values.

Thus, the increase in the number of samples (n) provided by denser sampling grids, made it possible to identify sites on the field where levels of SPR, are higher and if not taken into consideration can induce the occurrence of restriction zones to root development of crops. Similar behavior was found by other authors [28] when analyzing the spatial variability of phosphorus (P) and potassium (K). Also, [27] found similar results after evaluating the soybean yield spatial variability through different sampling grids.

Additionally, the CV values for these attributes were classified as low ($CV < 12\%$) for SBD in all sampling grids and medium ($12\% < CV < 62\%$) for SPR and SM grids. This higher variation in SPR values may be related to the system and management practices adopted in the area. As the area is managed under conventional planting system, the major structural modification occur in this layer (0 to 20 cm), which could happen due to mechanical action from plant roots, edaphic fauna, and machinery/equipment traffic.

According to [29], the observation of higher CV values is an indication of higher spatial variability of these attributes (SPR and SM) in the area. These results reinforce the use of sampling grids with a larger number of samples to precisely reproduce the spatial variability of SPR, SBD and SM values. Even though we did not investigate the effect of using a different number of subsamples per sampling point in this study, the results obtained by [12] indicated that using a higher number of subsamples per sampling point could be an SPR mapping alternative to use less dense sampling grids.

Table 1. Descriptive statistics of soil penetration resistance (SPR, MPa), soil bulk density (SBD, g/cm³) and soil moisture (SM, %) using different sampling grids in Januária, Northern Minas Gerais

Soil Attributes	Statistical Parameters							
	Mean	Median	Min	Max	SD	CV	Cs	Sk
20 x 20 meters								
SPR	2.06	1.93	0.90	3.66	0.61	29.71	-0.54	0.30
SBD	1.69	1.73	1.41	1.90	0.11	6.78	-1.07	-0.20
SM	5.14	5.21	3.23	7.18	0.98	19.11	-0.85	0.09
40 x 40 meters								
SPR	2.23	2.28	1.24	3.66	0.66	29.50	-0.89	0.00
SBD	1.67	1.65	1.41	1.85	0.11	6.81	-1.07	-0.23
SM	5.25	5.29	3.36	7.18	1.06	20.27	-0.87	-0.06
60 x 60 meters								
SPR	1.96	1.93	1.24	2.97	0.54	27.73	-1.21	0.15
SBD	1.70	1.74	1.51	1.87	0.11	6.48	-1.21	-0.36
SM	4.74	4.46	3.38	6.75	0.97	20.52	-0.66	0.61

MIN: Minimum; MAX: Maximum; SD: Standard deviation; CV: Coefficient of variation; Cs: Skewness; Ck: Kurtosis; SPR: Soil penetration resistance; SBD: Soil bulk density; and SM: Soil Moisture.

Results of the geostatistical analysis (Table 2) showed that all variables presented spatial dependence, except to SBD at the 60x60 m grid density, which showed a random behavior expressed as a pure

SM	Spherical	129.9	0.989	0.072	94.91	0.014	0.722
----	-----------	-------	-------	-------	-------	-------	-------

SDI: Spatial dependence index; RSS: Residual sum of squares; R²: Coefficient of determination;

The maps of attributes which presented spatial dependence were interpolated through ordinary kriging, whereas the inverse distance weighting (IDW: power = 2) method was used for mapping the SBD at the 60x60 m grid that presented pure nugget effect. Moreover, the similarity between grids A, B and C was evaluated through de RDC index. On the other hand, Pearson's linear correlation coefficient ($p \leq 0.05$) was used to verify the correlation between all attributes using 145 points extracted from all maps. The spatial distribution maps of SPR, SBD, and SM levels are shown below (Fig. 2, 3 and 4).

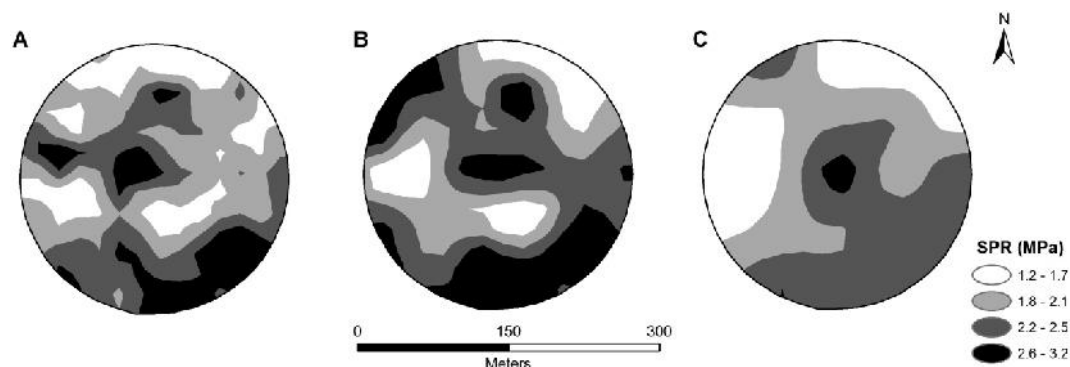


Fig 2. Thematic maps of soil penetration resistance (SPR) obtained by different sampling grids in Januária, Northern Minas Gerais. (A) 145 points, (B) 41 points, and (C) 21 points

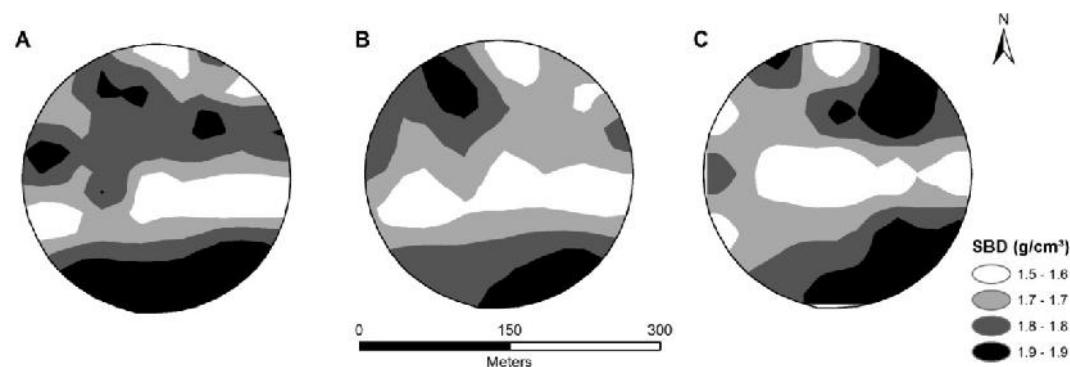


Fig 3. Thematic maps of soil bulk density (SBD) obtained by different sampling grids in Januária, Northern Minas Gerais. (A) 145 points, (B) 41 points, and (C) 21 points

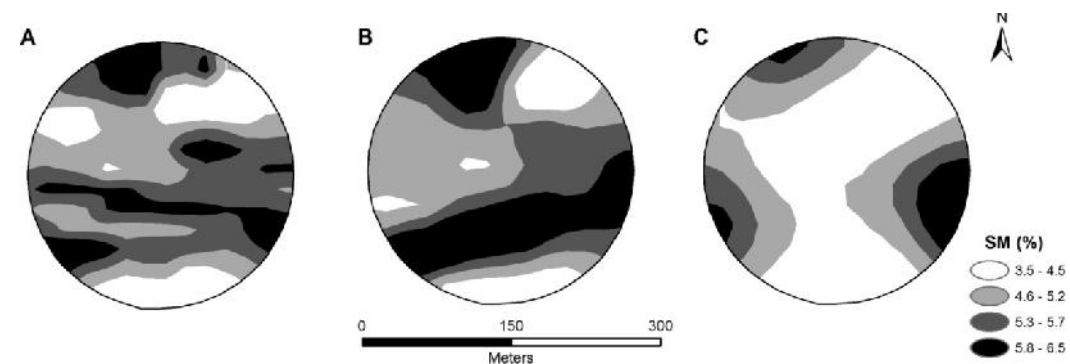


Fig 4. Thematic maps of soil moisture (SM) obtained by different sampling grids in Januária, Northern Minas Gerais. (A) 145 points, (B) 41 points, and (C) 21 points

Looking at the thematic maps it is possible to observe that the SPR levels are directly related to SBD levels, in other words, the highest SPR levels in the area correlated to higher SBD levels, and possibly to the same soil management practices for many years and uncontrolled machinery traffic. Regarding SM levels, the relation was the opposite, since wetter areas presented lower SPR levels. In addition, denser areas presented the highest levels of SM in the study area. Similar spatial distribution SPR, SBD, and SM levels were observed by several authors [13, 36].

After analyzing the RDC results, it was verified that, as the sampling grid size increased, and consequently, the distance between the sampling points, there was an increase in the dissimilarity (accuracy) among maps when compared to the reference map (grid A). The SPR maps showed the highest dissimilarity among each other, with RDC ranging from 22.85 % to 24.71 %, whereas for SBD and SM maps the RDC values ranged from 3.86 % to 4.54 % and from 12.44 % to 13.32 %, respectively. Thus, it is possible to observe that the kriging method was more influenced by the use of less sampled points due to its robustness and complexity for unsampled point's estimation. On the other hand, the IDW method which was used for the SBD data interpolation in grid C was less influenced by this scenario.

As the RDC value was calculated from the mean difference in modulus of the interpolated values in relation to the reference map, there is no RDC value considered as optimum, and the choice of an acceptable RDC percentage value depends on the degree of accuracy desired by the user. Based on that, an RDC of 15% was considered a suitable value for guiding the interpretation of the results. Thus, the values obtained for SPR using grids B and C would not be recommended to represent the spatial variability of this attribute. Therefore, the utilization of an insufficient number of subsamples results in an erroneous representation of its variability and can indicate a necessity for denser sampling grids, which increases the sampling and lab analysis cost. However, the use of grids with less sampled points would still be useful for cokriging analysis if attributes present correlation among each other, which would reduce the sampling costs.

These results indicate that the CDR was an efficient parameter to evaluate the similarity among maps from different grid densities (A, B, and C), which confirms its potential for use in precision agriculture studies. Similar results were previously reported by several authors when analyzing spatial variability of SPR [12], K and P [28], and grain yield [27, 37, 38].

In order to perform the linear correlation between the SPR, SBD and SM maps, 145 points were extracted from all raster's using grid A as a reference. Thus, it was found that significant correlation between SPR, SBD, and SM ranged from -0.17 to 0.48 as shown in Table 3. These results show that SM levels are inversely proportional to SPR values as mentioned before. However, the SBD values presented the highest correlation coefficient with SPR (0.48), which confirms the results of [39] that high SBD values and machinery traffic could speed up SPR and consequently reduce crop's yield.

Table 3. Correlation between soil penetration resistance (SPR), soil bulk density (SBD) and soil moisture (SM) using 145 sampled points in Januária, Northern Minas Gerais

	Grid Sampling								
	SPR (A)	SPR (B)	SPR (C)	SBD (A)	SBD (B)	SBD (C)	SM (A)	SM (B)	SM (C)
SPR (A)									
SPR (B)	-								
SPR (C)	-	-							
SBD (A)	0.36*	0.27*	0.11 ^{ns}						
SBD (B)	0.26*	0.48*	0.21*	-					
SBD (C)	0.13 ^{ns}	0.04 ^{ns}	0.09 ^{ns}	-	-				
SM (A)	-0.17*	-0.19*	0.05 ^{ns}	-0.08 ^{ns}	-0.18*	-0.25*			
SM (B)	-0.10 ^{ns}	-0.05 ^{ns}	0.27*	-0.02 ^{ns}	0.06 ^{ns}	-0.18*	-		

SM (C)	-0.12 ^{ns}	0.07 ^{ns}	0.09 ^{ns}	-0.29*	-0.22*	-0.21*	-	-	-
--------	---------------------	--------------------	--------------------	--------	--------	--------	---	---	---

* and ns: significant and non-significant Pearson's correlation coefficients ($p < 0.05$), respectively. A: 20x20 m; B: 40x40 m; and C: 60x60 m.

Regarding the spatial distribution of SPR, SBD and SM levels on the soil, it was possible to detect zones with uniform patterns, which would allow the adoption of more adequate management practices for each level of these attributes in the area, which would be impossible from an analysis by descriptive methods. In relation to SPR levels, average values ranged from 1.96 MPa to 2.23 MPa (Grids A, B, and C) which are between the interval (2 MPa to 2.5 MPa) considered as the critical limit for root development as suggested by [40]. However, divergent opinions exist regarding the SPR value that should be considered as the critical limit for plant development. Other studies have shown that higher SPR values are tolerable (up to 3 MPa) in areas with no-tillage systems [11, 41, 42], which area probably due to better soil structure [12, 43].

Independent of the critical limit considered for SPR, the maps showed that the study area presented restrictive values for root growth using all three grids. However, grids with 6.25 and 2.78 samples per hectare (B and C) are not recommended for representation of SPR, SBD and SM spatial variability mapping since the RDC values were above the maximum value proposed (15%). Thus, only the grid with 25 points per hectare (grid A) is recommended for mapping these attributes. Furthermore, one way to reduce the number of necessary samples is to divide the field in specific management zones and then use a stratified sampling or a less dense sampling grid with at least 4 samples per hectare (50x50 m) as recommended by [17]. In sum, this study could be used as an assistant tool for decision making, when regarding the sampling grid density that should be used for these attributes evaluation.

4. CONCLUSION

Reduction of the grid density (number of points) increased the estimation error for SPR, SBD, and SM, especially when using only 21 points (grid C), whereas, denser grids (Grid A and B) showed maps with greater similarity (accuracy).

Regarding the spatial distribution of these attributes, the SPR levels are directly related to SBD levels, in other words, the highest SPR levels in the area occurred due to higher SBD levels and vice versa, whereas SM levels presented opposite correlation with SPR values since wetter areas presented lower SPR levels. Furthermore, denser areas are directly correlated with higher levels of SM in the study area.

Grids with 6.25 and 2.78 samples per hectare (B and C) are not recommended for representation of SPR, SBD and SM spatial variability mapping, since the RDC values were above the maximum value proposed (15%). Thus, only the grid with 25 points per hectare (grid A) is recommended for mapping these attributes.

REFERENCES

1. Montanari R, Souza GSA, Pereira GT, Marques J, Siqueira DS, et al. The use of scaled semivariograms to plan soil sampling in sugarcane fields. *Precision Agriculture*. 2012; 13(5):542-552. DOI: <http://sci-hub.tw/10.1007/s11119-012-9265-6>.
2. Nanni MR, Povh FP, Demattê JAM, Oliveira RBD, Chicati ML, et al. Optimum size in grid soil sampling for variable rate application in site-specific management. *Scientia Agricola*. 2011; 68(3):386-392. DOI: <http://sci-hub.tw/10.1590/S0103-90162011000300017>.
3. Souza ZM de, Souza GS de, Marques Júnior J, Pereira GT. Número de amostras na análise geostatística e na krigagem de mapas de atributos do solo. *Ciência Rural*. 2014; 44(2): 261-268. DOI: 10.1590/S0103-84782014000200011. Portuguese.

4. Mallarino AP, Wittry D. Efficacy of grid and zone soil sampling approaches for site-specific assessment of phosphorus, potassium, pH, and organic matter. *Precision Agriculture*. 2004; 5(1): 131-144. <https://doi.org/10.1023/B:PRAG.0000022358.24102.1b>
5. Montanari R, Lima RC, Bonini AS, Marques L S, Minguini R, Carvalho MP, Costa NR. Variabilidade dos atributos de um latossolo vermelho sob plantio direto no cerrado brasileiro e produtividade da soja. *Cadernos do Laboratório Xeoloxico de Laxe*. 2011; 36(1) 219-237. Portuguese.
6. Corá JE, Araújo AV, Pereira GT, Beraldo JMG. 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*. 2004; 28(6); 1013-1021. DOI: <http://sci-hub.tw/10.1590/S0100-06832004000600010>. Portuguese.
7. Grego, R. G.; Vieira, S. R. Variabilidade espacial de propriedades físicas do solo em uma parcela experimental. *Revista Brasileira de Ciência do Solo*. 2005; 29 (2): 169-177. DOI: <http://dx.doi.org/10.1590/S0100-06832005000200002>. Portuguese.
8. Cambardella CA, Moorman TB, Novak JM, Parkin TB, Karlen DL, Turco RF, et al. Field-scale variability of soil properties in central Iowa soils. *Soil Science Society of America Journal*. 1994; 58: 1501–1511. DOI: <http://sci-hub.tw/10.2136/sssaj1994.03615995005800050033x>.
9. Stepien M, Gozdowski D, Samborski S. A case study on the estimation accuracy of soil properties and fertilizer rates for different soil sampling grids. *Journal of Plant Nutrition and Soil Science*. 2013; 176(1): 57-68. DOI: 10.1002/jpln.201100422.
10. Bengough AE, McKenzie BM, Hallet PD, Valentine TA. Root elongation, water stress, and mechanical impedance: A review of limiting stress and beneficial root tip trails. *Journal of Experimental Botany*. 2011; 62(1): 59-68. DOI: <https://doi.org/10.1093/jxb/erq350>.
11. Girardello VC, Amado TJC, Santi AL, Cherubin MR, Kunz J, Teixeira TG. Resistência à penetração, eficiência de escarificadores mecânicos e produtividade da soja em Latossolo argiloso manejado sob plantio direto de longa duração. *Revista Brasileira de Ciência do Solo*. 2014; 38 (4): 1234-1244. DOI: <http://sci-hub.tw/10.1590/S0100-06832014000400020>. Portuguese
12. Pias OHDC, Cherubin MR, Basso CJ, Santi AL, Molin JP, Bayer C. Soil penetration resistance mapping quality: effect of the number of subsamples. *Acta Scientiarum. Agronomy*. 2018; 40:1-11. DOI: <http://dx.doi.org/10.4025/actasciagron.v40i1.34989>
13. Vaz, CM, Manieri, JM, De Maria, IC. Tuller, M. Modeling and correction of soil penetration resistance for varying soil water content. *Geoderma*. 2011. 166(1), 92-101. DOI: <https://doi.org/10.1016/j.geoderma.2011.07.016>
14. Beutler NA, Cehturion JF, Centurion MAPC, Leonel CL, São João ACE, Freddi OS. Intervalo hídrico ótimo no monitoramento da compactação e da qualidade física de um Latossolo Vermelho cultivado com soja. *Revista Brasileira de Ciência do Solo*. 2007; 31 (6):1223-1232. DOI: <http://sci-hub.tw/10.1590/S0100-06832007000600001>. Portuguese.
15. Storck L, Kobata SGK, Brum B, Soares AB, Modolo AJ, Assmann TS. Sampling plan for using a motorized penetrometer in soil compaction evaluation. *Revista Brasileira de Engenharia Agrícola e Ambiental*. 2016; 20(3):250-255. DOI: <http://sci-hub.tw/10.1590/1807-1929/agriambi.v20n3p250-255>
16. Siqueira DS, Marques Jr J, Pereira GT, Barbosa RS, Teixeira DB, Peluco RG. Sampling density and proportion for the characterization of the variability of Oxisol attributes on different materials. *Geoderma*. 2014; 232:172-182. DOI: <https://doi.org/10.1016/j.geoderma.2014.04.037>.

17. Cherubin MR, Santi AL, Basso CJ, Eitelwein MT, Vian AL. Variabilidade da resistência do solo à penetração em função da dimensão da malha amostral. *Revista Plantio Direto*. 2011; 125 (5); 4-9. Portuguese.
18. Debiassi H, Franchini JC, Oliveira FA, Machado TM. Ajuste de grades amostrais para o mapeamento da resistência à penetração de um Latossolo Bruno. In: Inamasu BY, Naime JM, Resende AV, Bassoi LH. *Agricultura de Precisão: Um novo olhar*. Embrapa CNPSo. 2012; 138-42. Portuguese.
19. Bottega EL, Queiroz DMD, Pinto FA, Oliveira Neto AMD, Vilar, CC, Souza C. Sampling grid density and lime recommendation in an Oxisol. *Revista Brasileira de Engenharia Agrícola e Ambiental*. 2014; 18(11):1142-1148. DOI: <http://sci-hub.tw/10.1590/1807-1929/agriambi.v18n11p1142-1148>.
20. Delden H, Van Vliet J, Van Rutledge DT, Kirkby MJ. Comparison of scale and scaling issues in integrated land-use models for policy support. *Agriculture, Ecosystems & Environment*. 2011; 142(2):18–28. DOI: <https://doi.org/10.1016/j.agee.2011.03.005>.
21. Demattê JAM, Galdos MV, Guimarães R, Genú AM, Nanni MR, Zullo Jr. J. Quantification of tropical soil attributes from ETM+/Landsat-7 data. *International Journal of Remote Sensing*. 2007; 28(17). 813-829. DOI: <https://doi.org/10.1080/01431160601121469>.
22. McBratney A, Mynasny B, Cattle Stephen R, Willem Vervoort R. From pedotransfer functions to soil inference systems. *Geoderma*. 2002; 109; 41–73. DOI: [https://doi.org/10.1016/S0016-7061\(02\)00139-8](https://doi.org/10.1016/S0016-7061(02)00139-8).
23. Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA). *Sistema Brasileiro de Classificação de Solos*. 3rd ed.. Brasília: Embrapa, 2013. Portuguese.
24. Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA). *Manual de métodos de análise de solo*. 2nd ed. Rio de Janeiro, Embrapa. 1997. Portuguese.
25. Warrick, AW, Nielsen, DR. Spatial variability of soil physical properties in the field. In Hillel, D. Editors. *Applications of soil physics* (p. 319-44). New York: Academic Press. 1980.
26. Zimback, CRL. *Análise espacial de atributos químicos de solos para fins de mapeamento da fertilidade do solo*. PhD Research Thesis. Botucatu: UNESP, 2001. Portuguese.
27. Coelho EC, Souza EG, Uribe-Opazo MA, Pinheiro Neto R. Influência da densidade amostral e do tipo de interpolador na elaboração de mapas temáticos. *Acta Scientiarum Agronomy*. 2009; 31(1): 165-174. DOI: <http://sci-hub.tw/10.4025/actasciagron.v31i1.6645>. Portuguese.
28. Cherubin MR, Santi AL, Eitelwein MT, Amado TJC, Simon DH, Damian JM. Dimensão da malha amostral para caracterização da variabilidade espacial de fósforo e potássio em Latossolo Vermelho. *Pesquisa Agropecuária Brasileira*. 2015; 50 (2): 168-177. DOI: <http://sci-hub.tw/10.1590/S0100-204X2015000200009>. Portuguese.
29. Oliveira IA, Junior JM, Campos MCC, Aquino RE, Freitas L, Siqueira DS, Cunha JM. Variabilidade espacial e densidade amostral da suscetibilidade magnética e dos atributos de Argissolos da Região de Manicoré, AM. *Revista Brasileira de Ciência do Solo*. 2015; 39(3): 668-681. DOI: <http://sci-hub.tw/10.1590/01000683rbc20140496>. Portuguese.
30. Webster R, Oliver MA. *Geostatistics for environmental scientists*. 2nd ed. Chichester: J. Wiley, 2007.
31. Webster R, Lark M. *Field sampling for environmental science and management*. 1st ed. London: Routledge, 2012.

32. Campos MCC, Marques Júnior J, Pereira GT, Montanari R, Siqueira DS. Variabilidade espacial da textura de solos de diferentes materiais de origem em Pereira Barreto, SP. *Revista Ciência Agronômica*. 2007; 38: 149-157. Portuguese.
33. Machado LO, Lana AMQ, Lana RMQ, Guimarães, EC Ferreira CV. Variabilidade espacial de atributos químicos do solo em áreas sob sistema plantio convencional. *Revista Brasileira de Ciência do Solo*. 2007; 31(3): 591-599. DOI: <http://sci-hub.tw/10.1590/S0100-06832007000300019>. Portuguese.
34. Silva AA, Nanni MR, da Silva Junior CA, Romagnoli F, Chicati ML, de Carvalho Gasparotto A. Diferentes grades de amostragem para avaliação de atributos químicos do solo na distribuição espacial em áreas de cana-de-açúcar. *Agrarian Academy*. 2014; 1(1): 159-171. Portuguese.
35. Landim PMB. Sobre geoestatística e mapas. *Terræ Didática*. 2006; 2 (1):19-33. Portuguese.
36. Kılıç K, Özgöz E, Akbaş F. Assessment of spatial variability in penetration resistance as related to some soil physical properties of two fluvents in Turkey. *Soil and Tillage Research*. 2004; 76(1):1-11. DOI: <https://doi.org/10.1016/j.still.2003.08.009>.
37. Bazzi CL, Souza EG, Uribe Opazo MA, Nóbrega LHP, Neto RP. Influência da distância entre passadas de colhedora equipada com monitor de colheita na precisão dos mapas de produtividade na cultura do milho. *Engenharia Agrícola*. 2008; 28(2): 355-363. DOI: <http://dx.doi.org/10.1590/S0100-69162008000200016>. Portuguese.
38. Spezia GR, Souza EGD, Nóbrega LH, Uribe-Opazo MA, Milan M, Bazzi CL. Model to estimate the sampling density for establishment of yield mapping. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 2012; 16(4): 449-457. DOI: <http://sci-hub.tw/10.1590/S1415-43662012000400016>.
39. Carvalho LA, Valdemar Neto VJ, Silva LF, Pereira JG, Nunes Waga, Chaves CHC. Resistência mecânica do solo à penetração (RMP) sob cultivo de cana-de-açúcar, no município de Rio Brillhante-MS. *Agrarian*. 2008;1:7-22. Portuguese.
40. Silveira DC, Melo Filho JF, Sacramento Jaas, Silveira ECP. Relação umidade versus resistência do solo à penetração para um Argissolo Amarelo distrocoeso no Recôncavo da Bahia. *Revista Brasileira Ciência do Solo*. 2010; 34(3): 659-667. DOI: <http://sci-hub.tw/10.1590/S0100-06832010000300007>. Portuguese.
41. Coelho DS, Cortez JW, Olszewski N. Variabilidade espacial da resistência mecânica à penetração em Vertissolo cultivado com manga no perímetro irrigado de Mandacaru, Juazeiro, Bahia, Brasil. *Revista Brasileira de Ciência do Solo*. 2012;36:755-764. DOI: <http://sci-hub.tw/10.1590/S0100-06832012000300007>. Portuguese.
42. Secco D, Reinrt DJ, Reichert JM, Silva VR. Atributos físicos e rendimento de grãos de trigo, soja e milho em dois Latossolos compactados e escarificados. *Ciência Rural*. 2009; 39: 58-64. DOI: <http://dx.doi.org/10.1590/S0103-84782009000100010>. Portuguese.
43. Moraes MT, Debiasi H, Carlesso R, Franchini JC, Silva VR. Critical limits of soil penetrations resistance in a Rhodic Eutrudox. *Revista Brasileira Ciência do Solo*. 2014; 38: 288-298. DOI: <http://sci-hub.tw/10.1590/S0100-06832014000100029>.