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SPATIAL VARIABILITY OF PHYSICAL AND HYDRAULIC ATTRIBUTES OF A SANDY SOIL IN THE NORTHEAST BRAZIL[‡]

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ABSTRACT

The knowledge of field management zones based on soil attributes can be helpful for the implementation of site-specific management. This work had the objective of analyzing the spatial dependence of soil attributes of the 0-0.20 m and 0.20-0.40 m layers of an Entisols Quartzipsamments, in Petrolina, Northeast Brazil, which has been cultivated with micro sprinkler irrigated grapevines. In a rectangular grid with 168 points spaced by 4.0 x 3.5 m, soil samples were collected from each layer to determine soil bulk density, contents of clay, silt and sand, soil water contents at field capacity and wilting point. All data sets were submitted to classic statistical and geostatistical analyses. For the 0-0.20 m layer, the distributions of soil bulk density, clay content and soil water content at field capacity presented a spatial dependence structure, with ranges of 10.0 m, 8.3 m and 7.2 m, respectively. In the 0.20-0.40 m layer, spatial dependence was found for soil density, sand content (6.6 m for both attributes) and soil water content at field capacity (6.8 m range). Distributions of silt and sand contents and soil water content at wilting point presented no spatial dependence in the upper layer as well as the clay and silt contents and soil water content at wilting pointing in the deeper layer. By constructing the soil attribute contour maps, distinct management zones were defined as well as their extension. Practical uses for irrigation scheduling purposes were proposed.

VARIABILIDAD ESPACIAL DE ATRIBUTOS FÍSICOS E HIDRAULICOS DE UN SUELO ARENOSO EN EL NORESTE DE BRASIL

Keywords*:*

Soil attributes
Semivariogram
Contour maps
Spatial dependence
Kriging

Palabras claves:

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RESUMEN

El conocimiento de zona de manejo basadas en atributos del suelo Este trabajo tuvo como objetivo el análisis de la dependencia especial de atributos del suelo a diferentes profundidades 0-0.20 m y 0.20-0.40 m de un Entisol, Quartzipsamment, en Petrolina, Noreste de Brasil, el cual ha sido cultivado con uvas de vino irrigadas con micro-aspersores. Se espera que esta información sea útil en la implementación de manejo-por sitio-especifico. En una cuadrícula rectangular con 168 puntos espaciada a 4.0 x 3.5 m, muestras de suelos se colectaron de cada profundidad para determinar la densidad aparente del suelo, los contenidos de arcilla, limo y arena, los contenidos de agua en el suelo a capacidad de campo y punto de marchitez. Todos los datos fueron sometidos a análisis estadísticos clásicos y geoestadísticos. Para la profundidad de 0-0.20 m, las distribuciones de la densidad aparente, el contenido de arcilla y el contenidos de humedad a capacidad de campo presentaron una estructura de dependencia espacial, con rangos de 10.0, 8.3 y 7.2 m, respectivamente. En la profundidad de 0.20-0.40 m, la dependencia especial se detectó para la densidad aparente del suelo, el contenido de arcilla (6.6 m para ambos atributos) y el contenido de humedad a capacidad de campo (rango de 6.8 m). Las distribuciones de los contenidos de limo y arena y el contenido de humedad del suelo no presentaron dependencia espacial en la profundidad superior también como el contenido de arcilla y limo y el contenido de humedad al punto de marchitez en la profundidad inferior. Mediante la construcción de los mapas de contorno de los atributos del suelo, se definieron distintas zonas de manejo también como su extensión. Aplicaciones prácticas de estos resultados en la programación de irrigación fueron propuestas.

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INTRODUCTION

The grapevine cropping system in the São Francisco Valley, Northeast Brazil, is characterized by an intensive use of irrigation due to irregular and not sufficient rainfall distribution throughout the year. In relation to soil water management practices in the Brazilian semi arid region, the spatial variability of soil physical and hydraulic attributes has not yet been taken into account, and the fact that a considerable amount of orchards is established on sandy soils with variable soil profile depths, raises more relevance to this situation (Bassoi *et al.* 2007).

Several statistical tools have been applied to evaluate soil spatial variability for management zone identification; however, geostatistics allows the analysis of its structure for soil attributes and the construction of contour maps having in mind site-specific management (Nielsen & Wendroth 2003). Kriging, as a geostatistics interpolator, has a specific feature because it takes into account the spatial dependence of the variables, expressed by adjusted semivariogram models to estimate values at any position inside an area (Isaaks & Srivastava 1989, Vieira 2000). However, in many cases, soil attributes do not present any spatial dependence structure, and the use of other interpolators as inverse distance weighting is recommended for contour map construction (Mello *et al*. 2003). This method uses an intermediate value of a variable, the distance between the point to be estimated and the neighbors, i.e., it does not consider the spatial variability structure of a specific variable.

Several reports have presented the importance in taking into account the spatial variability structure in soil-water-atmosphere-plant systems (Warrick & Nielsen 1980, Vieira *et al*. 1983, Sousa *et al*. 1999, Webster & Oliver 2001, Tominaga *et al*. 2002, Timm *et al*. 2003, Timm *et al*. 2004, Mzuku *et al*. 2005, Grego *et al*. 2006, Timm *et al*. 2006, Silva *et al*. 2007, Parfitt *et al*. 2009). The knowledge and understanding of the spatial and temporal variability of soil and plant attributes, together with the possibility of variations in management over large fields, make the application of the zone management concept feasible (Coelho 2003).

Based on this, a table grape growing area of the semi-arid region of Northeast Brazil was chosen to carry out the following objectives: (i) to analyze the spatial dependence structure of physical and hydraulic soil attributes of an Entisol Quartzipsamment, cultivated with microsprinkle irrigated grapevines; (ii) in case of spatial variability characterization, to construct contour maps using an ordinary kriging interpolator; and (iii) in case of no characterization, to construct contour maps using the inverse distance weighting interpolator.

MATERIALS AND METHODS

The experiment was carried out in a commercial growing area of grapevine cv. Festival, grafted on the SO4 rootstock, planted in May 2002 in a grid spacing of 4 x 3.5 m, and irrigated by micro sprinklers, in Petrolina, PE, Brazil. In this region grapevines are cultivated intensively throughout the year due to high solar radiation availability and water application through irrigation. The soil was classified as a Neossolo Quartzarênico according to the Brazilian Soil Taxonomy (EMBRAPA 1999), which corresponds to a Quartzipsamment (USDA-NRCS 1999). A grid of 14 x 12 points was established in 2006, involving 168 sampling points from the 0-0.20 m and 0.20-0.40 m soil layers. Soil bulk density was determined by the volumetric ring method (EMBRAPA 1997), using 98.17 cm^3 rings. Soil particle size fractions (clay, silt, and sand) were determined by the gamma-ray attenuation method (Vaz *et al*. 1999), and based on these data, the soil water contents at field capacity θ_{FC} (-10 kPa) and wilting point θ_{WP} (-1500 kPa) were estimated by the model developed by Arya & Paris (1981), validated to a wide variety of soil types by Vaz *et al.* (2005), and using the Qualisolo software (Naime *et al.* 2004).

Classical statistics was applied for exploratory analysis of position (mean value, median), dispersion (coefficient of variation, minimum and maximum values), and distribution (skewness and kurtosis coefficients) of the data. The normality hypothesis was evaluated by the Kolmogorov-Smirnov (K-S) test (Landim 2003). For the data that presented significant skewness and kurtosis, indicating non-normal distribution, outliers were identified and judiciously eliminated, and the skewness and kurtosis coefficients were recalculated. After this semivariograms were obtained.

The structure of the spatial variability was analyzed by geostatistics using the GS+ software version 7.0 (GAMMA DESIGN SOFTWARE 2004), which provided semivariograms and their respective adjusted parameters (nugget C_0; sill C_0+C; and range A_0). The choice of the most appropriate mathematical model was based on the highest determination coefficient (r^2) and the lowest residual sum of squares (RSS). The dependence degree (DD) was calculated using the $C_0/(C_0+C)$ ratio, being considered strong when DD < 25%; moderate when 25% < DD < 75%; and weak when DD > 75%, as proposed by Cambardella *et al.* (1994).

For data with spatial dependence contour maps were constructed using an ordinary kriging interpolator (Nielsen & Wendroth 2003):

$$z^*(x_0) = \sum_{i=1}^{N} \lambda_i z(x_i) \qquad (1)$$

where $z^*(x_0)$ is the estimated variable, λ_i are the associated weights to the neighbor points, and $z(x_i)$ is the value of the variable at the neighbor point. When there was no spatial structure, the contour maps were constructed using the inverse distance weighting interpolator (Mello *et al.* 2003):

$$X_p = \frac{\sum_{i=1}^{n}\left(\frac{1}{d_i^2}\times X_i\right)}{\sum_{i=1}^{n}\left(\frac{1}{d_i^2}\right)} \qquad (2)$$

where X_p is the estimated value of the variable, d_i is the distance between the i^{th} neighbor point and the estimated point, , X_i is the value of the variable at the i^{th} neighbor point, and n is the number of points used to estimate X_p.

RESULTS AND DISCUSSION

The mean values of soil bulk density were 1.450 Mg m^{-3} and 1.446 Mg m^{-3} for the 0-0.20 m and 0.20-0.40 m soil layers, respectively and they did not differ using the Tukey statistical test at the 5% probability level (Table 1). These soils presented higher bulk density than that reported by Kiehl (1979) for sandy soils (1.25 to 1.40 Mg m^{-3}), because soil particle packing caused by clay eluviation makes clay particles to occupy the pore spaces between coarse particles (Dantas *et al*. 1998). For Ultisols from Petrolina, Silva (2000) found soil bulk densities ranging from 1.46 to 1.50 Mg m^{-3} for the A horizon (0.15-0.18 m layer) and B horizon (0.17-0.30 m layer), for loamy sand and sandy loam soil textures, and Fante Junior *et al*. (2002) reported soil bulk densities from 1.54 to 1.65 Mg m^{-3} for the 0-0.45 m layer (A horizon, loamy sand texture, under native vegetation).

Using Wilding & Drees (1983) criteria, the coefficients of variation (CV) of soil bulk density and sand content data sets are of low variability ($CV \leq 15\%$) for both soil layers. Data sets of clay and silt contents exhibit moderate variability ($15\% < CV \leq 35\%$) and high variability ($CV > 35\%$), respectively, also for both soil layers. Similar results were reported by Warrick & Nielsen (1980), Grossman & Reinsch (2002), Mzuku *et al*. (2005), and Timm *et al*. (2006).

The mean values of θ_{FC} and θ_{WP} data sets were 0.127 m^3 m^{-3} and 0.024 $m^3 m^{-3}$, respectively, for the 0-0.20 m soil layer, and 0.126 $m^3.m^{-3}$ and 0.027 $m^3.m^{-3}$, respectively, for the 0.20-0.40 m soil layer (Table 1). CV values of θ_{FC} (7.7%) and θ_{WP} (35.1%) were relatively higher in the lower layer when compared to the CVs of these variables in the upper layer (7.4% for θ_{FC} and 31.1 % for θ_{WP}). For both soil layers θ_{FC} data sets were classified as of low variability; θ_{WP} data sets as moderate and high variability in the 0-0.20 m and 0.20-0.40 m layers, respectively (Wilding & Drees 1983). Similar results were found by Warrick & Nielsen (1980) and Timm *et al*. (2006), i.e., CV values were decreasing at increasing soil water contents and vice-versa.

According to Hausenbuiller (1978), typical values of θ_{FC} are of the order of 3-10% for sandy soils; 10-25% for loamy soils; and 25-50% for clayey soils. Typical values of θ_{WP} are of the order of 1-5% for sandy soils; 5-15% for loamy soils; and 15-20% for clayey soils. The θ_{FC} and θ_{WP} concepts have been continuously discussed (Reichardt 1988, Kutílek & Nielsen 1994), but are still successfully used to estimate the available soil water capacity (AWC) (Kutílek & Nielsen 1994, Reichardt & Timm 2008).

According to Webster & Oliver (2001), skewness is a measure of the degree of asymmetry of a distribution and the kurtosis a measure of whether the data are peaked or flat relative to a normal distribution. Table 1 shows that there was a trend of increasing of the skewness coefficients of soil bulk density, contents of clay and silt, and θ_{WP} as soil depth increased, while skewness coefficients of sand content and θ_{FC} presented a decreasing and signal change as soil depth increased (0-0.20 m to 0.20-0.40 m). A trend on CV increasing with the soil depth was also observed indicating that the variable values showed smaller dispersion around the mean value in the 0-0.20 m layer, which should be explained by the manure application to soil surface, a regular practice for this crop in the São Francisco Valley (Bassoi *et al*. 2003), which can lead to a greater homogeneity of this upper layer, reducing the spatial variability of soil attributes. The spatial variability of physical and hydraulic attributes depends on soil use and management, as well as on the origin material (Grego & Vieira 2005).

In relation to the flat tail of the data distributions, with exception to silt content (both soil layers) and clay content (0-0.20 m) values, all data sets presented kurtosis coefficients greater than zero, which characterizes the distributions as leptokurtic (Landim 2003). The behavior of skewness and kurtosis coefficients of θ_{WP} in both soil layers was different when compared with other attributes (skewness of +0.14 and +1.71, and kurtosis of +0.01 and +5.56, in

Table 1. Descriptive statistics of soil bulk density, contents of clay, silt and sand, and soil water contents at field capacity (θ_{FC}) and wilting point (θ_{WP}), at 0-0.20 m and 0.20-0.40 m soil layers of an Entisol Quartzipsamment, Northeast Brazil.

Soil attributes	Sample number	Mean	Median	CV (%)	Mininum value	Maximum value	Skewness	Curtosis	K-S test
0 – 0.20 m soil layer									
Soil bulk density ($Mg.m^{-3}$)	168	1.450^a	1.470	5.6	1.160	1.620	-0.90	0.79	0.139
Clay content ($g.kg^{-1}$)	168	79^b	79	24.8	23	128	-0.02	0.13	0.058*
Silt content ($g.kg^{-1}$)	168	37^c	34	38.7	12	75	0.56	-0.34	0.100*
Sand content ($g.kg^{-1}$)	168	884^d	883	2.3	840	954	0.57	0.49	0.099*
θ_{FC} ($m^3.m^{-3}$)	168	0.127^e	0.128	7.4	0.098	0.147	-0.47	0.06	0.076*
θ_{WP} ($m^3.m^{-3}$)	168	0.024^f	0.024	31.1	0.005	0.049	0.14	0.01	0.051*
0.20 – 0.40 m soil layer									
Soil bulk density ($Mg.m^{-3}$)	168	1.446^a	1.481	7.1	1.121	1.596	-1.12	0.79	0.180
Clay content ($g.kg^{-1}$)	168	79^b	80	24.6	32	130	-0.08	-0.43	0.082*
Silt content ($g.kg^{-1}$)	168	36^c	30	43.8	9	85	0.6	-0.26	0.098*
Sand content ($g.kg^{-1}$)	168	885^d	887	2.3	820	925	-0.37	0.22	0.061*
θ_{FC} ($m^3.m^{-3}$)	168	0.126^e	0.126	7.7	0.104	0.162	0.12	0.49	0.044*
θ_{WP} ($m^3.m^{-3}$)	168	0.027^g	0.026	35.1	0.011	0.077	1.71	5.56	0.136
θ_{WP} ($m^3.m^{-3}$) without outliers	156	0.025	0.025	23.7	0.011	0.038	0.08	-0.35	0.048**

For each soil attribute, results followed by the same letters do not differ using the Tukey statistical test at the 5% probability level

Results from the Kolmogorov-Smirnov test at 5% of confidence level (K-S critical = 0.104).

* Results from Kolmogorov-Smirnov test were lower than 5% of confidence level (K-S critical).

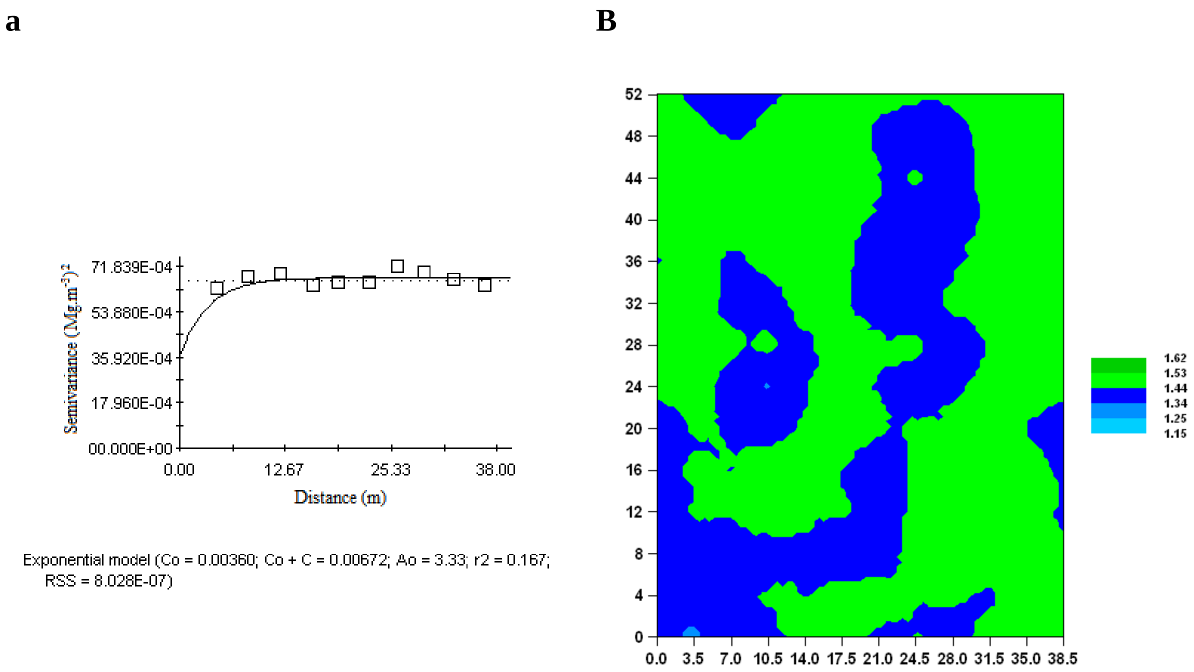
** Result from Kolmogorov-Smirnov test was lower than 5% of confidence level (K-S critical = 0.108).

0-0.20 m and 0.20-0.40 m, respectively), indicating that there was a greater distance to the normal distribution in the 0.20-0.40 m layer for the θ_{WP} data. When they are greater than zero, the frequency distribution tends to be distant from the normal, and this was the case of θ_{WP} in the 0.20-0.40 m soil layer (Table 1), characterizing a localized distribution inside the experimental plot (Grego *et al*. 2006). By constructing a box plot graph of θ_{WP} values for the 0.20-0.40 m layer, 12 outliers were identified and eliminated from the distribution. From this, it was verified that the θ_{WP} data tended to follow normal distribution through the K-S test at 5% confidence level. Although the K-S values calculated for soil bulk density for both soil layers were higher than the 5% critical level of confidence, there was no outlier removal based on the fact that the skewness coefficients indicated a smooth asymmetry (-0.90 for 0-0.20 m and –1.12 for 0.20-0.40 m). For the other attributes the trend to normal distribution was observed by the K-S test application (Table 1).

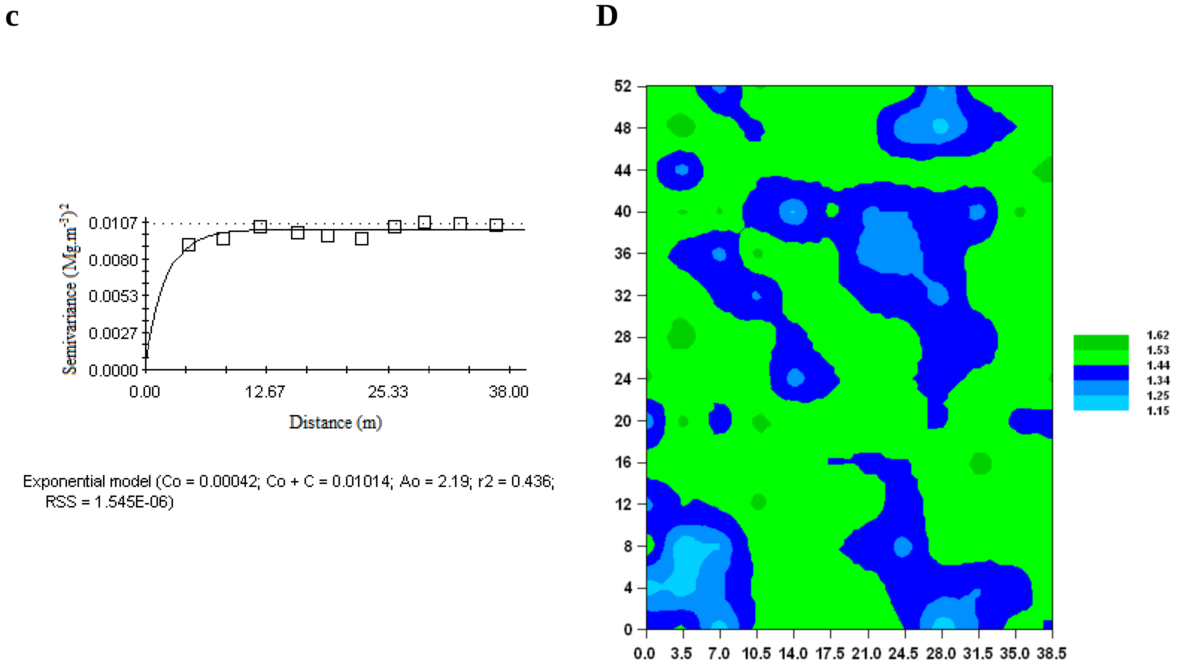
Figures 1a and 1c present the semivariogram models that described the soil bulk density spatial variability in the experimental area. In both cases, the exponential model was adjusted with ranges of 10.0 m (Figure 1a) and 6.6 m (Figure 1c), respectively, which indicates that an observation of soil bulk density taken at distances lower than 10.0 m (0-0.20 m) and 6.6 m (0.20-0.40 m) were auto correlated in space and that the spatial variance structure available in the semivariogram can be used to estimate an unmeasured value calculated from weighted values measured in these ranges (Nielsen & Wendroth 2003). The adjustment of the experimental data to theoretical semivariogram models was performed with the first values of the semivariances and a refinement of the experimental grid could lead to a better confidence in this adjustment. However, the adjusted models indicate the importance of considering the variability of the attributes for irrigation management.

The DD was 54 % and 3.96 % for the 0-0.20 m and 0.20-0.40 m soil layers, respectively, and according to Cambardella *et al*. (1994), this classifies the spatial dependence of soil bulk density as moderate and strong in the upper and lower soil layers, respectively. Based on the fact that semivariograms depend on distance, soil bulk densities were interpolated, without trend and with minimum variance, using ordinary kriging to construct the contour maps (Figures 1b and 1c).

Experimental and theoretical isotropic semivariograms with its adjusted parameters, and the contour maps of clay, silt and sand contents, respectively, for the 0-0.20 m and 0.20-0.40 m soil layers (Figures 2, 3 and 4), show that the distributions of clay content at 0.20-0.40 m (Figure 2c), silt content for both layers (Figure 3a and 3c), and the sand content for 0.20-0.40 m (Figure 4a) presented nugget effects, showing that the data from these variables had a randomized spatial distribution for the chosen sampling scale, therefore, the inverse distance weighting interpolator was employed to construct the contour maps (Figures 2d, 3b, 3d and 4b).

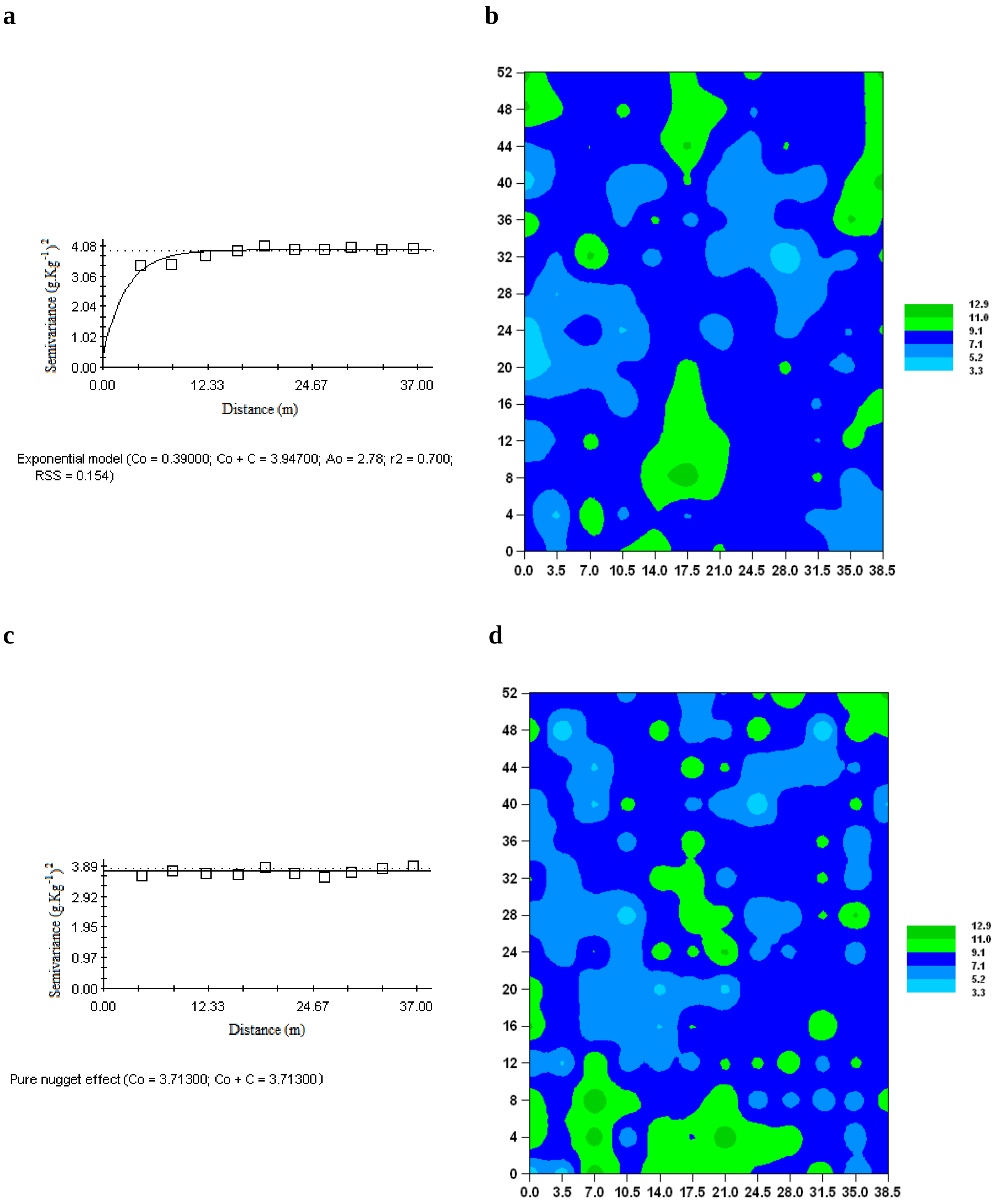


Exponential model (Co = 0.00360; Co + C = 0.00672; Ao = 3.33; r2 = 0.167; RSS = 8.028E-07)



Exponential model (Co = 0.00042; Co + C = 0.01014; Ao = 2.19; r2 = 0.436; RSS = 1.545E-06)

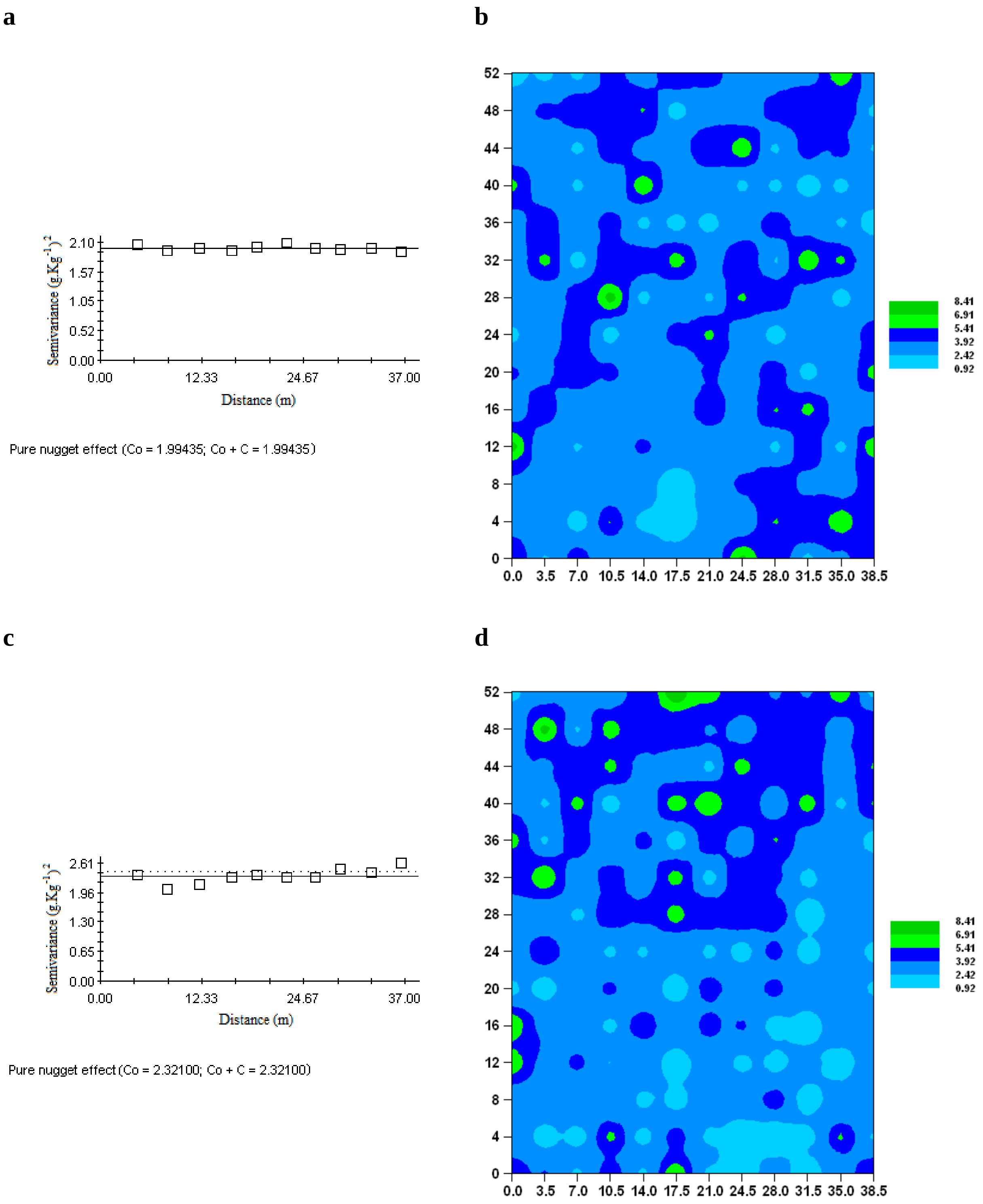
Figure 1. Experimental and theoretical isotropic semivariograms and contour maps of soil bulk density at 0-0.20 m (a, b) and 0.20-0.40 m (c,d) soil layers.



Exponential model (Co = 0.39000; Co + C = 3.94700; Ao = 2.78; r2 = 0.700; RSS = 0.154)

Pure nugget effect (Co = 3.71300; Co + C = 3.71300)

Figure 2. Experimental and theoretical isotropic semivariograms and contour maps of clay content at 0-0.20 m (a, b) and 0.20-0.40 m (c,d) soil layers.



Pure nugget effect (Co = 1.99435; Co + C = 1.99435)

Pure nugget effect (Co = 2.32100; Co + C = 2.32100)

Figure 3. Experimental and theoretical isotropic semivariograms and contour maps of silt content at 0-0.20 m (a, b) and 0.20-0.40 m (c,d) soil layers.

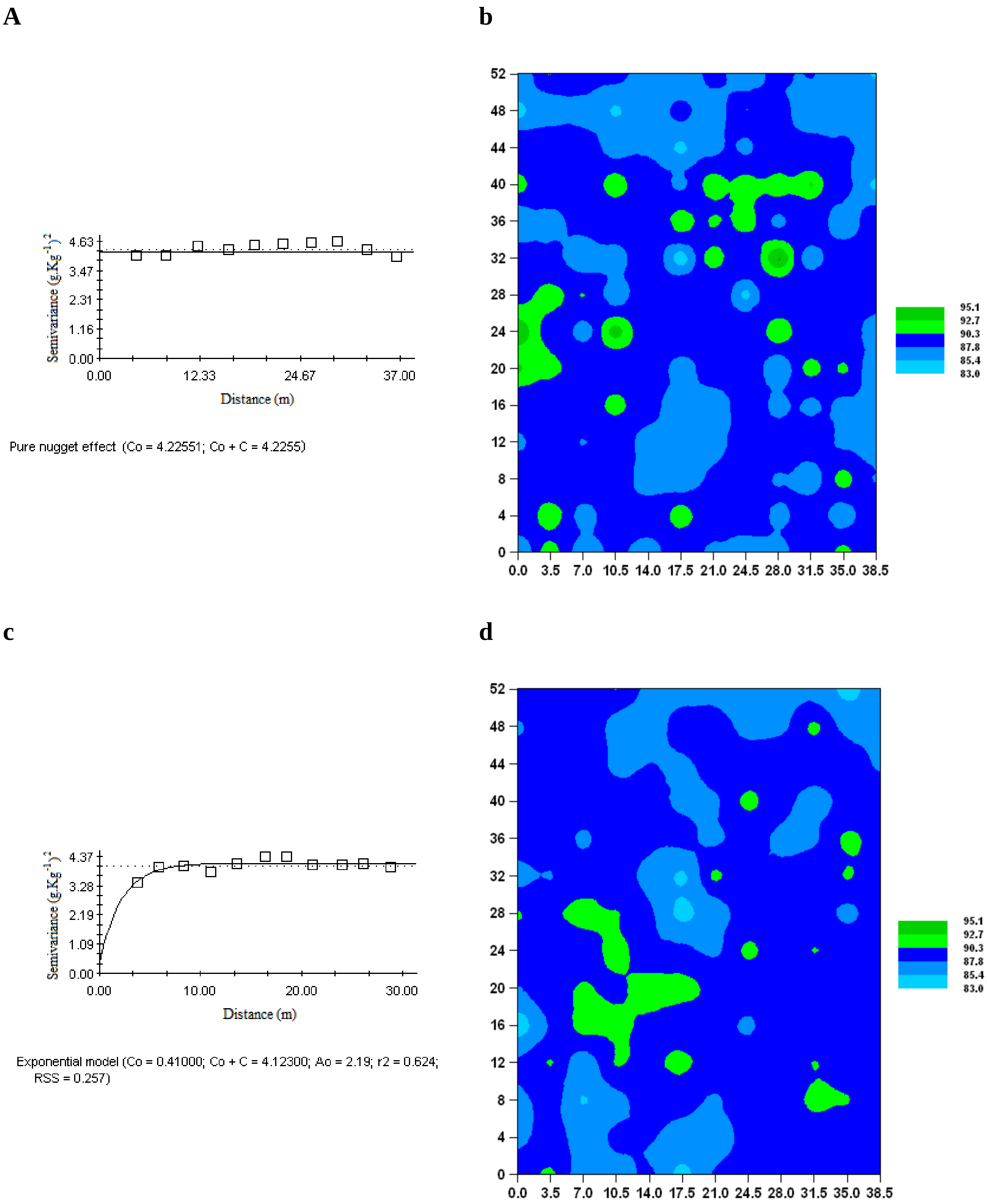


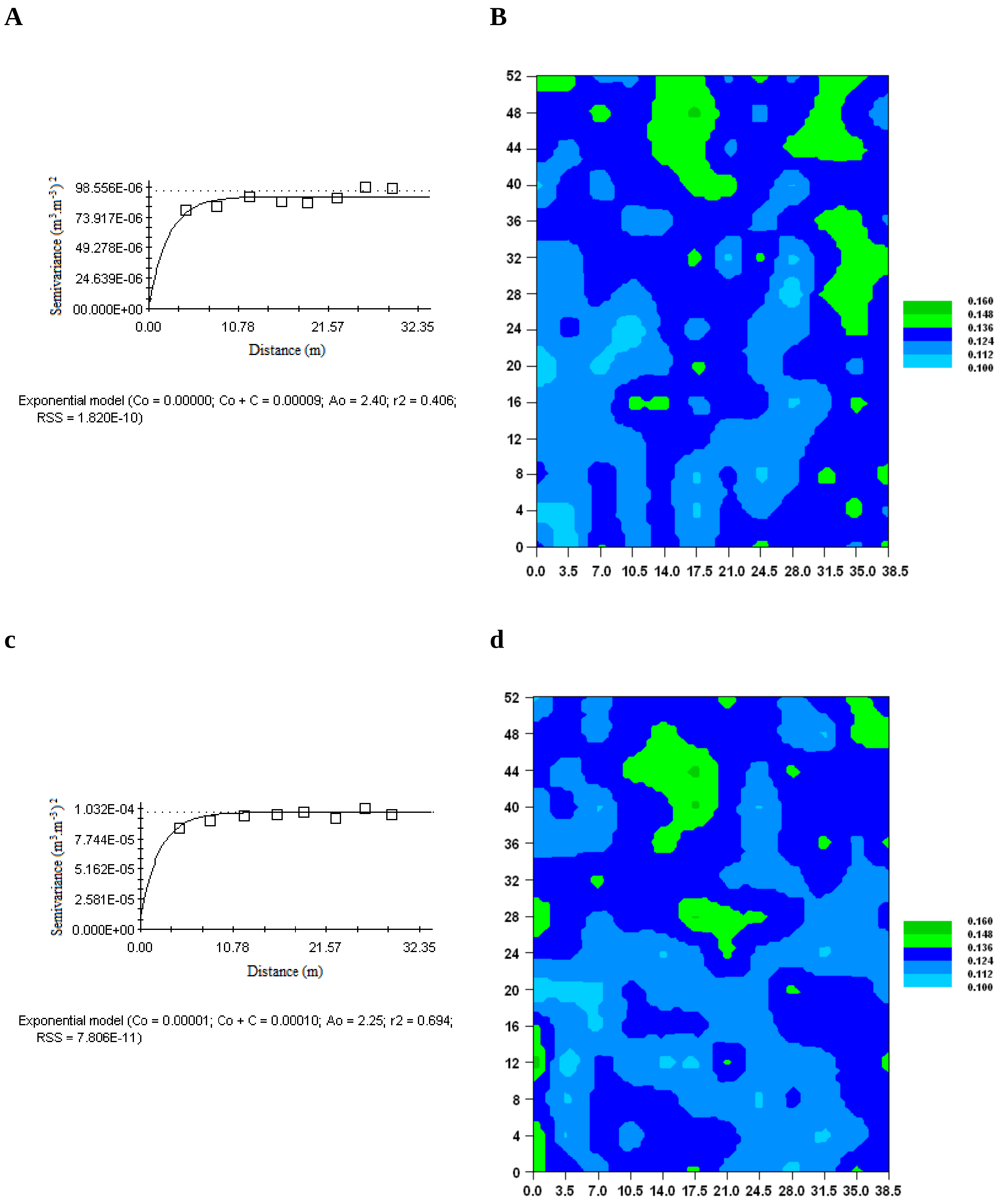
Figure 4. Experimental and theoretical isotropic semivariograms and contour maps of sand content at 0-0.20 m (a, b) and 0.20-0.40 m (c,d) soil layers.

The semivariograms of clay content (0-0.20 m) and sand content (0.20-0.40 m) data sets (Figures 2a and 4c), showed that for both variables the exponential model was best adjusted (r^2=0.700 Figure 2a; r^2=0.624 Figure 4c). The clay content (Figure 2a) presented a spatial dependence range of 8.3 m, while for the sand (Figure 4c) a range of 6.6 m was observed. Both variables presented a DD=9.9%, which represents a strong spatial dependence degree (Cambardella *et al*. 1994). Variables with strong dependence are more influenced by intrinsic soil attributes (Cambardella *et al*. 1994). The possibility to incorporate the spatial correlation structure among neighbors to predict values in non-sampled sites allows kriging to provide a better interpolation estimates (Vieira 2000, Nielsen & Wendroth 2003). Besides that, the random errors can be reduced through plot control associated to spatial dependence (Mello *et al*. 2003). Hence, contour maps of clay content were constructed for the 0-0.20 m (Figure 2b) and of sand content for 0.20-0.40 m (Figure 4d). Analyzing Figures 2, 3 and 4, it is possible to realize that there was a trend on soil texture variables to present nugget effects in this study, i.e., a randomized spatial distribution of the data.

The soil presented mean values of sand, clay and silt contents of 885 $g.kg^{-1}$, 79 $g.kg^{-1}$ and 36 $g.kg^{-1}$, respectively, for the 0-0.40 m soil layer (Table1). Due to its high sand content, according to Kiehl (1979) and Topp *et al.* (1997), it has some special characteristics like low soil particle specific surface, low soil particle cohesion and low organic matter content. Topp *et al.* (1997) reported that the nature and relative proportion of rock, mineral fragments, and organic matter, the soil aggregates determine the morphology, the continuity and the level of interaction of the space inside and between soil particles, and consequently they are factors related to the spatial dependence structure of a specific soil attribute. These features can be an explanation for the predominantly randomized behavior of soil texture. Nevertheless, it is important to mention that the spatial dependency structure of clay content for the 0-0.20 m soil layer (Figure 2a) can be explained by the frequent manure application to soil surface, knowing that organic matter plays a role as a cementing agent (Kiehl 1979, Reichardt & Timm 2008).

The experimental and theoretical isotropic semivariograms and contour maps of soil water contents at θ_{FC} and θ_{WP} in the 0-0.20 m and 0.20-0.40 m soil layers (Figures 5 and 6), showed that θ_{FC} values were spatially dependent up to 7.2 m (exponential model, r^2=0.406; Figure 5a) in the upper soil layer and up to 6.8 m in the lower soil layer (exponential model; r^2=0.694; Figure 5c). Based on this, θ_{FC} contour maps were constructed for both soil layers, using ordinary kriging (Figures 5b and 5d). On the other hand, for the construction of θ_{WP} contour maps (Figure 6b: 0-0.20 m soil layer; Figure 6d: 0.20-0.40 m soil layer), the inverse distance weighing interpolator was used because θ_{WP} did not present a spatial dependence structure, as shown in Figures 6a and 6c, indicating that the θ_{WP} data were spatially independent in both soil layers. In general, semivariograms present this independence trend as the soil dries out (Wendroth *et al*. 1999, Grego *et al*. 2006, Timm *et al*. 2006).

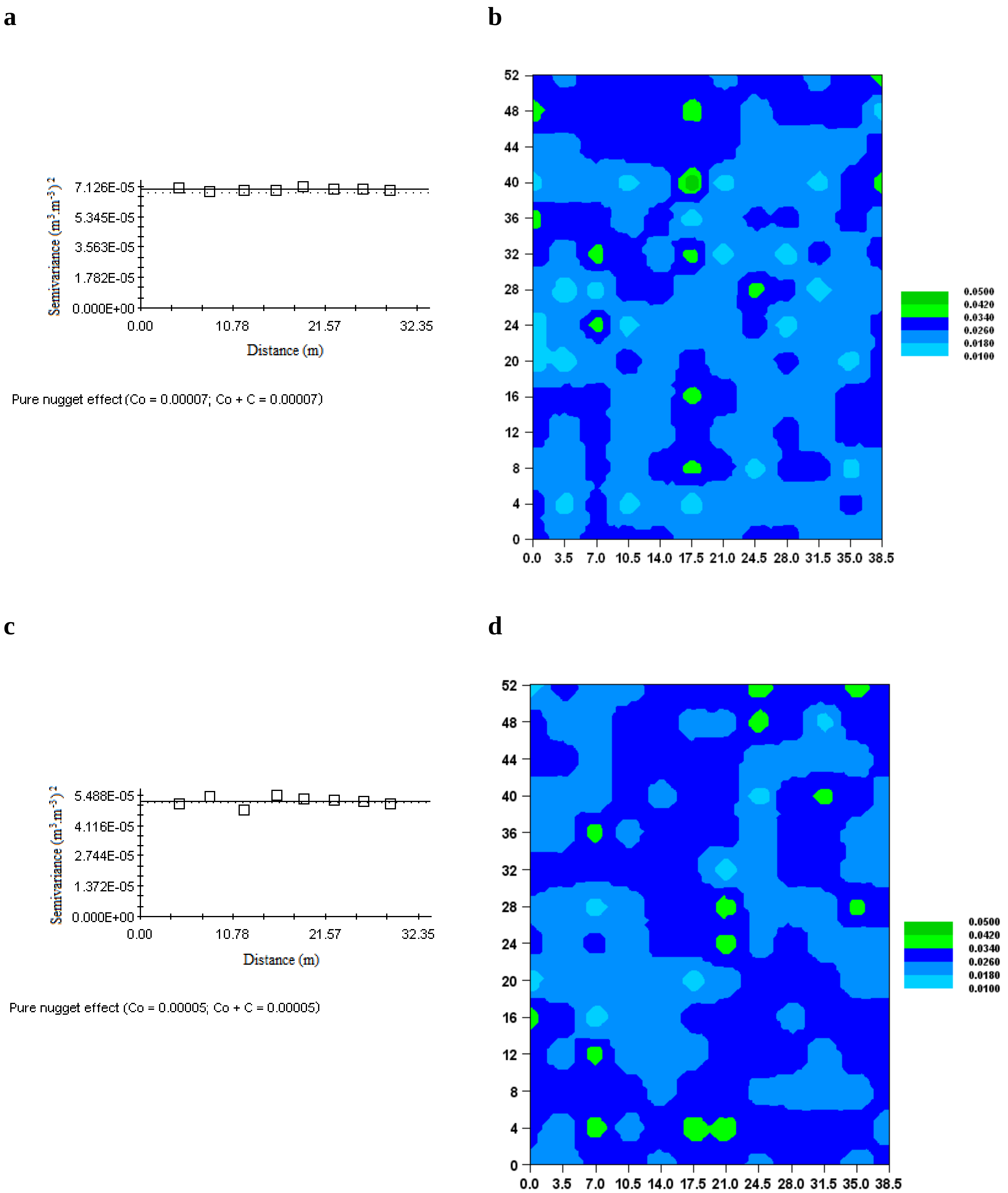
The spatial variability of physical and hydraulic attributes related to the retention, storage and movement of soil water, soil compaction and root system development is a result of soil genesis processes and soil management practices (McGraw 1994, Sousa *et al*. 1999). Until a few years ago, soil attribute variability was evaluated using classical statistics, which implies that observations are independent of each other, not considering their position in the field, and attributes were assumed having a randomized spatial distribution (Vieira 2000, Reichardt & Timm 2008). In this case, experiments are carried out disregarding the structure of spatial variability and the spatial dependence is ignored. This shows that Fisher´s classical methods are not always applied correctly, since the normality and independence hypotheses are not tested, and the independence is assumed even before data sampling, and all variability presented by the data are considered as residual. When the spatial variability of an attribute is analyzed by the theory of geostastistics (Figures 1 to 6) coupled to classic statistics, questions not clarified by one theory are analyzed by the other, not in an excluding but in a complementary way (Reichardt & Timm 2008). Based on the contour maps of the soil attributes analyzed herein, a soil water monitoring strategy can be developed to specify which management zone (wetter or drier), based on its extension, can be considered for adjustments or decisions on time and amount of water to be applied through irrigation systems to the grapevines. For the table grape production system of Brazilian semi-arid region, it is desirable to hold less water in the root zone to reduce plant vigor in some vegetative development stages or to avoid reduction of total soluble solids content in berries during reproductive development stages (ripening). Restart of irrigation events when some rainfall occurs during the growing season is dependent on soil water storage and different soil management zones should have different amounts of water in the crop root zone. Also, soil management zones indicate where soil water sensors should be installed, which is a common and crucial doubt from



Exponential model (Co = 0.00000; Co + C = 0.00009; Ao = 2.40; r2 = 0.406; RSS = 1.820E-10)

Exponential model (Co = 0.00001; Co + C = 0.00010; Ao = 2.25; r2 = 0.694; RSS = 7.806E-11)

Figure 5. Experimental and theoretical isotropic semivariograms and contour maps of soil water content at field capacity (θFC) at 0-0.20 m (a, b) and 0.20-0.40 m (c,d) soil layers.



Pure nugget effect (Co = 0.00007; Co + C = 0.00007)

Pure nugget effect (Co = 0.00005; Co + C = 0.00005)

Figure 6. Experimental and theoretical isotropic semivariograms and contour maps of soil water content at wilting point (θWP) at 0-0.20 m (a, b) and 0.20-0.40 m (c,d) soil layers.

irrigators when they decide to use them. Use of these criteria should contribute to higher crop water use efficiency. Reichardt *et al*. (2001), in an experiment carried out in a Kandiudalfic Eutrudox, found CV values ranging from 3 to 4 % for soil water content data distribution before the irrigation. However, when a net irrigation water depth was calculated based on the mean θ_{FC} a net water depth of 18 mm was obtained (CV=29.3%), with minimum and maximum values of 9 mm and 41 mm, respectively, showing that some portions of the grid area would receive an excessive water application of 23 mm (128% above the mean value) and other portions a deficit water application of 9 mm (50% below the mean value).

CONCLUSIONS

In the semi-arid region of Northeast Brazil, a soil with predominance of coarse particles exhibited spatial dependence structures of soil attributes in the 0- 0.40 m layer, and contour maps were obtained using an ordinary kriging interpolator. When this spatial dependence was not observed, contour maps of soil attributes were constructed using the inverse distance weighting interpolator. In both cases, distinct management zones were defined and the knowledge of their extension in a soil attribute contour map allows the analysis of their correlation or not with plant features related to the contour map. Also, they can be helpful in soil water monitoring throughout the growing seasons, by indicating where water content sensors should be installed and which zone, wetter or drier, should be taken into account to help irrigation scheduling.

REFERENCES

ARYA LM, PARIS JF (1981) A physicoempirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data. Soil Sci. Soc. Am. J. 45: 1023-1030.

BASSOI LH, AQUINO LS, RECKZIEGEL NL, TIMM LC, VAZ CMP, MANIERI JM, TAVARES VEQ (2007) Mapas de contorno da capacidade de água disponível em solo cultivado com videiras irrigadas. In: CONGRESSO BRASILEIRO DE CIÊNCIA DO SOLO, 31., 2007, Gramado. Anais. Porto Alegre: Sociedade Brasileira de Ciência do Solo, 2007. CD-Rom.

BASSOI LH, HOPMANS JW, JORGE LAC, ALENCAR CM, SILVA JAM (2003) Grapevine root distribution for drip and microsprinkler irrigation. Sci. Agric. 60: 377-387.

CAMBARDELLA CA, MOORMAN TB, NOVAK JM, PARKIN TB, KARLEN DL, TURCO RF, KONOPKA AE (1994) Field-scale variability of soil properties in Central Iowa soils. Soil Sci. Soc. Am. J. 58: 1501-1511.

COELHO AM (2003) Agricultura de precisão: manejo da variabilidade espacial e temporal dos solos e das culturas. In: CURI, N.; MARQUES, J.J.; GUILHERME, L.R.G.; LIMA, J.M.; LOPES, A.S.; ALVAREZ, V.H. (Eds.). Tópicos em ciência do solo. Viçosa: Sociedade Brasileira de Ciência do Solo, 2003. p. 249-290.

DANTAS JA, SANTOS MC, HECK RJ (1998) Caracterização de Podzólicos Amarelos irrigados e não irrigados do Submédio São Francisco. R. Bras. Ci. Solo 22: 761-771.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (EMBRAPA) (1997) Manual de métodos de análise de solos. Rio de Janeiro, Embrapa Solos, 212 p.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA (EMBRAPA) (1999) Sistema Brasileiro de Classificação de Solos. Brasília: Embrapa Solos, 412 p.

FANTE JUNIOR L, OLIVEIRA JCM, BASSOI LH, VAZ CMP, MACEDO A, BACCHI OOS, REICHARDT K, CAVALCANTI AC, SILVA FHBB (2002) Tomografia computadorizada na avaliação da densidade de um solo do Semi-Árido brasileiro. R. Bras. Ci. Solo 26: 835-842.

GAMMA DESIGN SOFTWARE (2004) GS+ - Geostatistics for the Environmental Sciences. Gamma Design Software, Plainwell.

GREGO CR, VIEIRA SR (2005) Spatial variability of soil physical properties on an experimental plot. R. Bras. Ci. Solo 29: 169-177.

GREGO CR, VIEIRA SR, ANTONIO AM, DELLA ROSA SC (2006) Geostatistical analysis for soil moisture content under the no tillage cropping system. Sci. Agric. 63: 341-350.

GROSSMAN RB, REINSCH TG (2002) The solid phase: 2.1. Bulk density and linear extensibility. Chapter 2. In: DANE JH, TOPP GC (eds). Methods of soil analysis. Part 4. Physical methods. Soil Science Society American Book Series. 5. Madison: Soil Science Society of America, 201-228 pp.

HAUSENBUILLER RL (1978) Soil Science: principle and practices. WC Brown Co Publishers, Dubuque, 611 p.

ISAAKS EH, SRIVASTAVA RM (1989) An introduction to applied geostatistics. Oxford University Press, New York, 561 p.

KIEHL EJ (1979) Manual de edafologia. Agronômica Ceres, São Paulo, 262 p.

KUTÍLEK M, NIELSEN DR (1974) Soil Hydrology. Catena Verlag, Cremlingen Destedt, 370 p.

LANDIM PMB (2003) Análise estatística de dados geológicos. Editora UNESP, São Paulo, 253 p.

McGRAW T (1994) Soil test level variability in Southern Minnesota. Better Crops with Plant Foods 78: 24-25.

MELLO CR, LIMA LM, SILVA AM, MELLO JM, OLIVEIRA MS (2003) Kriging and inverse-square-distance for the interpolation of rainfall equation parameters. R. Bras. Ci. Solo 27: 925-933.

MZUKU M, KHOSLA R, REICH R, INMAN D, SMITH F, MACDONALD L (2005) Spatial variability of measured soil properties across site-specific management zones. Soil Sci. Soc. Am. J. 69: 1572-1579.

NAIME JM, SHINYA VT, VAZ CMP (2004) Programa para estimativa indireta da curva de retenção da água no solo. São Carlos: Embrapa Instrumentação Agropecuária, 2004. 3p. (Comunicado Técnico, 60).

NIELSEN DR, WENDROTH O (2003) Spatial and temporal statistics: sampling field soils and their vegetation. Catena Verlag, Reiskirchen, 398 p.

PARFITT JMB, TIMM LC, PAULETTO EA, SOUSA RO de, CASTILHOS DD, ÁVILA CL de, RECKIEGEL NL (2009) Spatial variability of the chemical, physical and biological properties in lowland cultivated with irrigated rice. R. Bras. Ci. Solo 33: 819-830.

REICHARDT K, SILVA JCA, BASSOI LH, TIMM LC, OLIVEIRA JCM, BACCHI OOS, PILOTTO JE (2001) Soil spatial variability and the estimation of the irrigation water depth. Sci. Agric. 58: 549-553.

REICHARDT K, TIMM LC (2008) Solo, planta e atmosfera: conceitos, processos e aplicações. Editora Manole, Barueri, 478 p.

REICHARDT K (1988) Capacidade de campo. R. Bras. Ci. Solo 12: 211-216.

SILVA MSL (2000) Caracterização e gênese do adensamento subsuperficial em solos de Tabuleiro do Semi-Árido do Nordeste do Brasil. 126f. Tese (Doutorado em Ciências do Solo) – Faculdade de Agronomia - Universidade Federal do Rio Grande do Sul, Porto Alegre.

SILVA FM, SOUZA ZM, FIGUEIREDO CAP, MARQUES JÚNIOR JM, MACHADO RV (2007) Spatial variability of chemical attributes and productivity in the coffee cultivation. Ci. Rural 37: 401-407.

SOUSA JR, QUEIROZ JE, GHEYI HR (1999) Variabilidade espacial de características físico-hídricas e de água disponível em um solo aluvial no semi-árido paraibano. R. Bras. Eng. Agríc. Amb. 3: 140-144.

TIMM LC, PIRES LF, ROVERATTI R, ARTHUR RCJ, REICHARDT K, OLIVEIRA JCM, BACCHI OOS (2006) Field spatial and temporal patterns of soil water content and bulk density changes. Sci. Agric. 63: 55-64.

TIMM LC, REICHARDT K, OLIVEIRA JCM, CASSARO FAM, TOMINAGA TT, BACCHI OOS, DOURADO NETO D (2003) Sugarcane production evaluated by the state-space approach. J. Hydr. 272: 226-237.

TIMM LC, REICHARDT K, OLIVEIRA JCM, CASSARO FAM, TOMINAGA TT, BACCHI OOS, DOURADO NETO D, NIELSEN DR (2004) State-space approach to evaluate the relation between soil physical and chemical properties. R. Bras. Ci. Solo 28: 49-58.

TOMINAGA TT, CASSARO FAM, BACCHI OOS, REICHARDT K, OLIVEIRA JCM, TIMM LC (2002) Variability of soil water content and bulk density in a sugarcane field. Austr. J. Soil Res. 40: 605-614.

TOPP GC, REYNOLDS WD, COOK FJ, KIRBY JM, CARTER MR (1997) Physical attributes of soil quality. In: GREGORICH EG, CARTER MR (eds). Soil quality. Amsterdam: Elsevier, 1997. p. 21-58.

USDA-NRCS (1999) Soil taxonomy – a basic system of soil classification of making and interpreting soil surveys. Government Printing Office, Washington DC.

VAZ CMP, IOSSI MF, NAIME JM, MACEDO A, REICHERDT JM, REINERT DJ, COOPER M (2005) Validation of the Arya and Paris model for water retention model for Brazilian soils. Soil Sci. Soc. Am. J. 69: 577-583.

VAZ CMP, NAIME JM, MACEDO A (1999) Soil particle size fractions determined by gamma-ray attenuation. Soil Sci. 146: 403-410.

VIEIRA SR (2000) Geoestatística em estudos de variabilidade espacial do solo. In: NOVAIS RF, ALVAREZ VH, SCHAEFER CEGR (eds). Tópicos em ciência do solo. Viçosa: Sociedade Brasileira de Ciência do Solo, 2000. p. 1-54.

VIEIRA SR, HATFIELD TL, NIELSEN DR, BIGGAR JW (1983) Geostatistical theory and application to variability of some agronomical properties. Hilgardia 51: 1-75.

WARRICK AW, NIELSEN DR (1980) Spatial variability of soil physical properties in the field. In: HILLEL D (ed). Applications of soil physics. New York: Academic Press, 1980. p. 319-344.

WEBSTER R, OLIVER MA (2001) Geostatistics for environmental scientists. John Wiley & Sons Ltd., Chichester, 271 p.

WENDROTH O, POHL W, KOSZINSKI S, ROGASIK H, RITSEMA CJ, NIELSEN DR (1999) Spatio-temporal patterns and covariance structures of soil water status in two Northeast-German field sites. J. Hydr. 215: 38-58.

WILDING LP, DREES LR (1983) Spatial variability and pedology. In: WILDING LP, SMECK NE, HALL GF (eds). Pedogenesis and soil taxonomy: 1. concepts and interactions. Amsterdam: Elsevier, 1983. p. 83-116.