SEÇÃO I - FÍSICA DO SOLO

SPATIAL AND TEMPORAL VARIABILITY OF CROP YIELD AND SOME RHODIC HAPLUDOX PROPERTIES UNDER NO-TILLAGE(1)

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SUMMARY

Soil properties are closely related with crop production and spite of the measures implemented, spatial variation has been repeatedly observed and described. Identifying and describing spatial variations of soil properties and their effects on crop yield can be a powerful decision-making tool in specific land management systems. The objective of this research was to characterize the spatial and temporal variations in crop yield and chemical and physical properties of a Rhodic Hapludox soil under no-tillage. The studied area of 3.42 ha had been cultivated since 1985 under no-tillage crop rotation in summer and winter. Yield and soil property were sampled in a regular 10 x 10 m grid, with 302 sample points. Yields of several crops were analyzed (soybean, maize, triticale, hyacinth bean and castor bean) as well as soil chemical (pH, Soil Organic Matter (SOM), P, Ca^{2+}, Mg^{2+}, H + Al, B, Fe, Mn, Zn, CEC, sum of bases (SB), and base saturation (V %)) and soil physical properties (saturated hydraulic conductivity, texture, density, total porosity, and mechanical penetration resistance). Data were analyzed using geostatistical analysis procedures and maps based on interpolation by kriging. Great variation in crop yields was observed in the years evaluated. The yield values in the Northern region of the study area were high in some years. Crop yields and some physical and soil chemical properties were spatially correlated.

Index terms: crop yield maps, geostatistics, kriging.

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RESUMO: *VARIABILIDADE ESPACIAL E TEMPORAL DA PRODUTIVIDADE DE CULTURAS E ATRIBUTOS DE UM LATOSSOLO SOB SEMEADURA DIRETA*

Os atributos do solo condicionam a produção das culturas e, apesar das práticas adotadas, a variação espacial destes tem sido recorrentemente encontrada e descrita. A caracterização da variabilidade espacial dos atributos do solo e de seus efeitos sobre a produtividade das culturas pode ser utilizada como uma poderosa ferramenta para tomada de decisão em sistemas de manejo específico. O objetivo deste trabalho foi caracterizar a variabilidade espacial e temporal da produtividade de culturas e de atributos químicos e físicos de um Latossolo Vermelho distroférrico sob semeadura direta. A área estudada está localizada no Centro Experimental Central do Instituto Agronômico, em Campinas, SP, e vem sendo cultivada desde 1985 no sistema de semeadura direta com sucessão de culturas no verão e no inverno. As amostragens de produtividades e dos atributos do solo foram realizadas conforme uma grade regular de 10 x 10 m, totalizando 302 pontos. Para este estudo foram analisadas as produtividades de algumas culturas (soja, milho, triticale, labelabe e mamona) e de atributos químicos (pH, MOS, P, Ca, Mg, H + Al, B, Fe, Mn, Zn, CTC, SB e V %) e físico-hídricos (condutividade hidráulica saturada do solo, argila, densidade do solo, porosidade total e resistência mecânica do solo à penetração) do solo. Os dados foram analisados utilizando procedimentos de análise geoestatística, com cálculo de semivariogramas e interpolação de mapas por krigagem. Verificou-se que a produtividade das culturas apresentou alta variabilidade ao longo dos anos avaliados. A região norte da área apresentou repetição de altos valores de produtividade em alguns anos. Houve relação espacial entre as produtividades das culturas e alguns atributos físicos e químicos do solo.

Termos de indexação: mapa de produtividade, geoestatística, krigagem.

INTRODUCTION

In recent decades, many changes have taken place in Brazilian agriculture, mainly related to soil management. Particularly significant were the implementation of the no-tillage system and precision agriculture. From the conceptual point of view, these are no new technologies. No-tillage is based on the reproduction of a natural process, i.e., the continuous deposition of plant remains on the soil surface where they decompose, giving rise to organic compounds and recycling (Machado et al., 2004). Precision agriculture in turn has a long history; since ancient times recognized the benefits of differentiated manure application and liming according to the soil type (Kellogg, 1957; Coelho, 2003) in the manual management of small areas, dealing with each plant or small parts of a field individually (Werner, 2004). These technologies contribute significantly to agricultural production, mainly in relation to erosion control and the rational use of supplies, resulting in increased crop yields and reduced environmental impacts of agriculture.

The degree of variability in soils is typically high, due to the combined effects of physical, chemical and biological processes that operate at different intensities and scales (Goovaerts, 1998). For this reason, a new component came to be considered in the management of agricultural production: spatial variation. Knowledge about spatial variation of soil properties is important because it could indicate alternative soil management practices to reduce the effects of these variations on crop yields (Carvalho et al., 2002; Corá et al., 2004).

One of the most recent approaches to quantifying spatial variations for specific land management is based on the division of the field into land management zones according to yield level (Khosla et al., 2002). This analysis of yield maps is a fundamental tool in the investigation and understanding of the causes of yield and crop quality variations, and may become a decision procedure for land management (Molin, 1997; Amado et al., 2007).

Studying spatial variations of soil properties, Mzuku et al. (2005) verified that it was possible to separate low response from high response zones based on soil density, organic C, sand, silt, porosity, and moisture. From this data they could delimit areas in the field with low and high yield potential. Analyzing soil chemical properties and yield in maize, Ortega (1997) observed that the best maize yields were obtained in areas with high levels of organic matter and low pH and calcium carbonate values. Vieira & Gonzalez (2003) studied spatial variations of different crop yields in an Ultisol and observed that crop yield variations between one year and the following suggest that the causes of variability can change over time.

Spatial variability of soil and plant properties is normally determined by geostatistics, which is based on the concept that values sampled close to one another are more similar than those collected further apart (Yamagishi et al., 2003). Geostatistics has been cited as an efficient support tool for land management decisions since it is helpful in the interpretation of the variation structure shown in semivariograms and maps by characterizing spatial and temporal variations of soil and plant properties (Vieira, 2000; Carvalho et al., 2002; Vieira et al., 2002).

Jiang & Thelen (2004) stated that knowledge about the spatial variability of soil properties and their effects on crop yield is a critical component in specific land management systems. For this reason, the objective of this research was to characterize spatial and temporal variability of crop yield and physico-chemical property variations in a Rhodic Hapludox soil under no-tillage.

MATERIAL AND METHODS

The experimental area at the Experimental Center of the Instituto Agronômico in Campinas (22 º 53 ' S and 47 º 04 ' W), State of São Paulo, covers 180 x 200 m (total of 3.42 ha) with an average slope of 10 %, at about 630 m asl and with a mean annual precipitation of 1,430 mm. The soil was classified as a Rhodic Hapludox with moderate clay texture (Embrapa, 2006). According to Köeppen's international climate classification, the region of Campinas is a transition between the climate types Cwa and Cfa, characteristic of tropical mountain climate, with a dry period from April to September and a wet period from October to March.

The area had been cultivated since 1985 in a no-tillage system with crop rotation. Soil properties and crop yield were sampled in a 10 x 10 m grid with a total of 302 sample points. Yields of the following chronological crop rotation were evaluated: Hyacinth bean (*Dolichos lablab* L.) in 2002, maize (*Zea mays* L.) in 2003, triticale (*Triticum secale* L.) in 2004, castor bean (*Ricinus communis* L.) in 2005, popcorn (*Zea mays* L.) in 2006, triticale (*Triticum secale* L.) in 2007 and soybean (*Glycine max* (L.) Merr.) in 2008. Yields were measured in 2.0 x 2.5 m sample patches at each sampling point and later transformed into kg ha^{-1}. Equation 1 (Eastman, 2003) was utilized to normalize results of this variable to allow comparison between yields of different crops.

$$VN = \left(\frac{VP - VMin}{VMax - V\min} \right) 100 \qquad (1)$$

in which *VN* is the normalized adimensional value, *VP* the yield value at the sample point, *VMin* the minimum yield value and *VMax* the maximum yield value of all sampled points, all expressed in kg ha^{-1}. The different yields were graded with values from 0 to 100 and classified as low, average, high and very high, respectively, according to the intervals 0–25, 26–50, 51–75 and > 75, as a decision-making criterion.

Soil samples were collected from the 0–0.20 m layer in January 2008 with a Dutch auger, air-dried and sieved through 2 mm mesh and tested for: pH; soil organic matter (SOM); exchangeable K, P available, Ca and Mg; potential acidity (H + Al); B; Fe; Mn; and Zn according to the methods described by Raij et al. (2001). The following properties were also determined: cation exchange capacity (CEC), sum of bases (SB) and base saturation (V %).

The following soil physical properties were tested: saturated soil hydraulic conductivity (Ks), penetration resistance (PR), clay content (texture), soil density (SD) and total porosity (TP). Saturated soil hydraulic conductivity (Ks) was measured in the field with a constant head permeameter (IAC model) (Vieira, 1998) in January 2008, at depths of 0.20 and 0.40 m, and calculated according to Reynolds et al. (1992). Penetration resistance (PR) was measured in the field with a IAA/Planalsucar model impact penetrometer, according to Stolf (1991), in February 2008, to a depth of 0.20 m. Soil density and total porosity were determined by the volumetric ring and the clay content by the pipette method, in the 0–0.20 m layer, as described by Camargo et al. (1986).

To characterize spatial variations of soil properties and crop yields, data were analyzed by semivariograms underlying geostatistical methods, according toVieira (2000), based on the assumption of an invariable intrinsic hypothesis. The spatial correlation between neighboring areas was calculated by means of semivariance γ(h), as in equation 2:

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

in which *N(h)* is the number of measured values of pairs $Z(x_i)$, $Z(x_i + h)$, separated by vector *h*.

Equation 2 generates γ(h) values corresponding to distances h and, according to Vieira (2000), measurements carried out in areas that are close to one another are expected to be more similar to each other than those further apart, that is, γ(h) increases with distance until a maximum value, after which it stabilizes at a rank corresponding to the spatial dependence distance limit, which is the range.

Fitting models to the experimental semivariograms was based on the highest value of coefficient determination and the lowest value of the root mean square error. The best-fitting model was chosen utilizing a technique known as jack-knifing, according to Vieira et al. (2002).

From the fittings of the mathematical model to the experimental semivariograms, parameters were defined as: a) nugget effect (C_0), which is value γ when h = 0; b) spatial dependence range (a), which is the distance at which γ(h) remains approximately constant, after increasing with the increase of h and c) rank (C_0 + C1), which is value γ(h) based on the range which approximates the data variance, if existing.

The degree of spatial dependence (DD) was used to express spatial dependence of a variable, measuring the proportion of the nugget effect (C_0) in relation to the rank ($C_0 + C_1$) and can be calculated by equation 3:

$$DD = \left(\frac{C_0}{C_0 + C_1} \right) \cdot 100 \qquad (3)$$

According to Cambardella et al. (1994), DD can be used to classify spatial dependence as strong (DD < 25 %), moderate (26 < DD < 75 %) and weak (DD > 75 %). Once the spatial autocorrelation between samples was proven by means of semivariogram analysis, contour maps were created using kriging interpolation. Kriging is a geostatistical technique of estimating values for non-sampled areas, resulting in an estimate without trends and with minimal variance (Vieira, 2000). SURFER 7.0 (Golden Software, 1999) was used for the construction of isoline maps.

RESULTS AND DISCUSSION

Crop yield

In all study years, crop yields (Table 1) the coefficients of variation (CV) were high, between 30.08 % for maize in 2003 and 53.72 % for castor bean in 2005. These values exceed those reported by Milani et al. (2006) for soybean and by Amado et al. (2007) for maize, soybean and wheat under no-tillage. According to the classification proposed by Warrick & Nielsen (1980), values above 30 % are considered high. Kravchenko & Bullock (2000) pointed out that elevated crop yield variations could be a reflection of the influence of interactions between different factors, including the soil-related, which justifies the implementation of some type of localized treatment to reduce the differences.

Normalized average yields varied greatly, and no tendency was observed in the evaluation period. The normalized yield, which was high for maize 2003 (54.73), was average in the case of the other crops, varying from 36.44 for hyacinth bean in 2002 to 44.93 for triticale in 2004. The representativeness of the average values could be verified by observing asymmetry and Kurtosis coefficients, which indicate normal frequency distribution when close to zero. In this case, the sample mean is an adequate indicator of the population that originated the data.

The crop yields between 2002 and 2008 had a spatially dependent structure described by semivariograms with a defined rank fitting to the spherical model (Table 2). The degree of spatial dependence found for yields was moderate according to the classification scheme of Cambardella et al. (1994) and similar to that verified by Amado et al. (2007) for maize, soybean and wheat under no-tillage. The range is another important parameter of interpretation of semivariograms and spatial variations in general, indicating the limit distance at which a sample point has influence over another point, i.e., the maximum distance up to which sample points are correlated. All points located within a circle with radius equal to the range can be used to estimate values with smaller spacing (Vieira & Lombardi Neto, 1995). Points located at distances beyond the range have no defined spatial dependence but are randomly distributed, behaving independently. Spatial dependence range values varied from 15 m for triticale 2004 to 57 m for soybean 2008 (Table 2). This means that areas in the field that produce greater and lower quantities of grain tend to group together in regions whose size is approximately constant over time, even if the regions shift according to the different crops.

According to Carvalho et al. (2001), the nugget effect (C_0) indicates spatial discontinuity of data for distances less than the distance between samples. The greatest C_0 values were observed for triticale 2004, castor bean 2005 and triticale 2007, and the lowest for hyacinth bean 2002, maize 2003, popcorn 2006 and soybean 2008, indicating greater continuity of their spatial variations. This did not influence the degree of spatial dependence because all yields studied had a moderate degree of dependence.

Table 1. Descriptive statistical parameters of normalized yields of seven crops in a rotation system under no-tillage

Crop	Mean	Variance	CV (%)	Skewness	Kurtosis
Hyacinth bean 2002	36.44	367.90	52.64	0.40	0.05
Maize 2003	54.73	270.90	30.08	-0.61	1.71
Triticale 2004	44.93	321.40	39.90	0.29	-0.09
Castor bean 2005	41.67	501.00	53.72	0.20	-0.57
Popcorn Maize 2006	37.97	308.90	46.29	0.37	-0.14
Triticale 2007	43.78	305.70	39.93	0.12	-0.07
Soybean 2008	42.62	344.90	43.57	0.64	-0.09

CV: coefficient of variation.

Table 2. Parameters of semivariographic analysis of normalized yields of seven crops in a rotation system under no-tillage

Yield	Model	C_0	C_1	a	DD	Class
Hyacinth bean 2002	Spherical	120	228	41	34	Moderate
Maize 2003	Spherical	100	95	35	51	Moderate
Triticale 2004	Spherical	205	100	15	67	Moderate
Castor bean 2005	Spherical	244	254	36	49	Moderate
Popcorn Maize 2006	Spherical	100	140	33	42	Moderate
Triticale 2007	Spherical	217	85	49	72	Moderate
Soybean 2008	Spherical	143	167	57	46	Moderate

C_0: nugget effect, C_1: structured variance, a: range, DD: degree of dependence.

The spatial variation of crop yields was high and the normalized yield was classified as average (25–50) for most of the study area. These results could be partially attributed to rainfall variations and partially to factors that seem to have changed over time from one crop to another, such as: weather, disease, pests, weeds, and soil. Specifically, the normalized yield of hyacinth bean 2002 was high in a patch in the North, low in the East and average in the rest of the area. In 2003, only the normalized yield map of maize showed predominantly high yields with a patch of very high yield in the Northern area. This could be explained by the strong response capacity of maize, as reported by Molin (2002), with less variation than soybean (Eghball & Varvel, 1997).

In the northern area there was a certain tendency of higher yields, as observed for hyacinth bean 2002, maize 2003, castor bean 2005, popcorn 2006, and triticale 2007 (Figure 1). This behavior was not verified for triticale 2004 because there was a severe attack of the *Pseudaletia sequax* Franclemlont (wheat caterpillar) described by Grego et al. (2006). The soybean 2008 yield map had the same behavior as triticale 2004, due to weed occurrence in the area. It can therefore be concluded that from 2002 to 2007, spatial yield variations were more structured, indicating that the northern region could be managed homogeneously. Molin (2002) and Kaspar et al. (2004) point out that the higher the number of harvests monitored in the same area, the more precise and easier is the definition of differentiated land management zones. This corroborates the results reported here, since five of the seven harvests analyzed indicated the northern area as high-yield management zone.

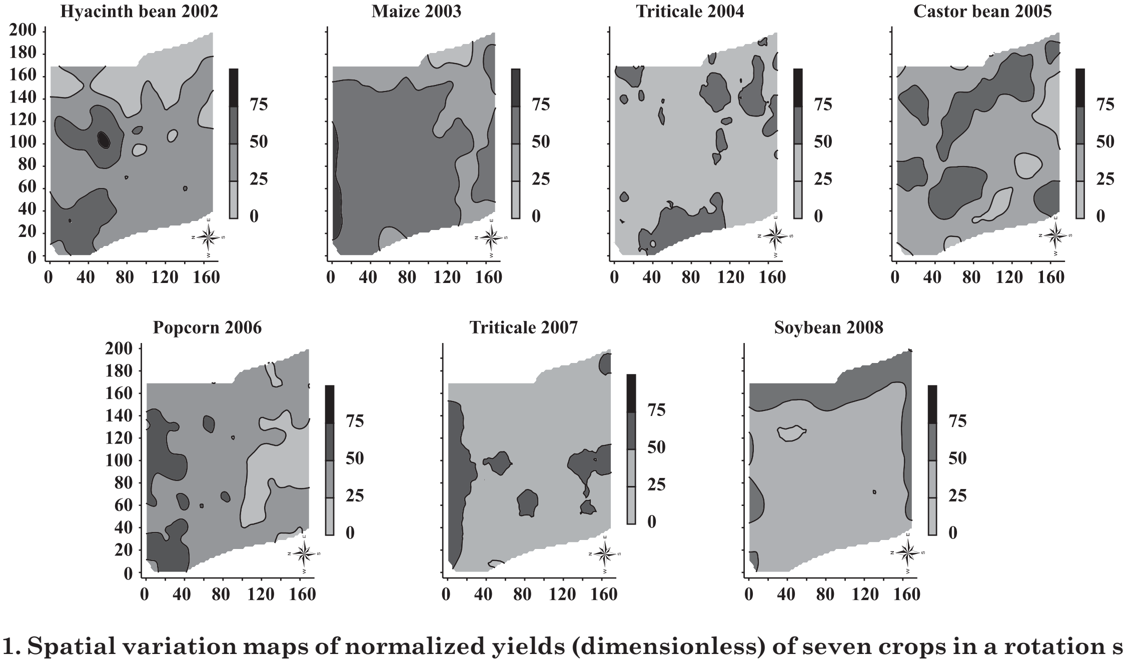

Figure 1. Spatial variation maps of normalized yields (dimensionless) of seven crops in a rotation system under no- tillage, 2002-2008.

Soil chemical properties

Analyses of skewness and kurtosis coefficients (Table 3) allow inferences about data frequency distribution. Following this line, note that most of the properties studied had normal frequency distribution, in disagreement with Montezano et al. (2006), who found that only pH, Ca, Mg, SB, and CEC had normal log frequency distributions in the analysis of chemical properties of soil under no-tillage.

The coefficient of variation (CV) indicated wide variations of soil chemical properties. There was a high degree of heterogeneity in CV values, with the lowest value for pH (6.85 %) and the highest for P (75.68 %), which could be a reflection of lime and phosphate fertilizer application. The former is distributed over the whole area, which might dilute variations, and the second is almost always applied in the furrow. According to the classification system proposed by Warrick & Nielsen (1980), only pH and CEC had low CV, that is, less than 12 %, corroborating the results of Souza et al. (2004), Pontelli (2006) and Silva et al. (2007). Soil organic matter, K, Mg, H + Al, V %, B, and Fe had CV classified as average (12 < CV < 24 %). The other properties were classified as high (Ca, SB, Mn, and Zn) and very high (P) CV. These high and very high CV values could be ascribed to the residual effects of earlier fertilizer treatments and to sampling as reported by Montezano et al. (2006) and Cavalcante et al. (2007), as well as to the fact that soil was not tilled, which might favor the formation of nutrient gradients in the area.

According to the criteria established for the interpretation of soil chemical properties in the State of São Paulo (Raij et al., 1997) the means of the properties pH, P, K, Ca, and Mg were high and V % was average. And among the micronutrients, the values of B and Fe were considered average and Mn and Zn high.

The predominantly high nutrient values observed in the no-tillage system agree with results of Cavalcante et al. (2007) for this land management system. Although the mean values of the chemical properties were considered high they should not underlie decisions on land management, since the CV indicated wide variations for these properties in the study area. Consequently, the use of mean values of chemical properties as reference could result in over- or underdosage of fertilizer and lime.

The semivariograms of all chemical properties indicated spatial dependence (Table 4 and Figure 2) and fitted to the spherical model.

The lowest C_0 values were observed for P, K, B, which were equal to zero, followed by pH (0.05), Zn (0.11), Fe (0.17), Mg (3.0), and SOM (9.0). These properties were spatially continuous than SB, Ca, CEC, V %, and Mn, with C_0 values of 132.3, 121.0, 85.2, 50.0, and 37.9, respectively. These results show that the slightly mobile soil properties tended to a lower C_0 than the more mobile. The nugget effect (C_0) is an expression of the unexplained variations due to sampling distance, area variations, analysis errors, and sampling errors (Trangmar et al., 1985; Cavalcante et al., 2007). Since it is impossible to quantify the individual contribution of these errors, the nugget effect could be expressed as percentage of the sill, thus facilitating a comparison of the spatial dependence of soil chemical properties. By analysis of the $C_0/(C_0 + C_1)$ ratio the proportion of the random component (C_0) in total variance ($C_0 + C_1$) was quantified, known as degree of spatial dependence (DD). In this analysis, the classification proposed by Cambardella et al. (1994) was used. Thus all chemical properties analyzed had a strong or moderate spatial dependence degree. Similar results were found by Silva et al. (2003), Machado et al. (2007) and Zanão Júnior et al. (2007), which highlights the importance of knowledge on spatial dependence structures.

Table 3. Descriptive statistical parameters of soil chemical properties using a no-tillage system

Property	Unit	Mean	Variance	CV (%)	Skewness	Kurtosis
SOM	g dm^{3}	30.64	18.01	13.85	1.00	0.13
pH	n/a	5.10	0.073	5.34	2.30	7.98
P	mg dm^{-3}	52.69	1603.0	75.99	1.13	0.46
K	mmol$_c$ dm^{-3}	5.14	1.202	21.33	-0.52	0.47
Ca	mmol$_c$ dm^{-3}	32.17	106.4	32.07	3.45	15.48
Mg	mmol$_c$ dm^{-3}	8.00	2.63	20.27	3.46	16.09
H + Al	mmol$_c$ dm^{-3}	33.86	36.81	17.92	-0.97	0.96
SB	mmol$_c$ dm^{-3}	45.31	149.0	26.94	3.39	15.14
CEC	mmol$_c$ dm^{-3}	79.26	86.94	11.76	3.60	16.93
V	%	56.48	94.71	17.23	0.96	1.23
B	mg dm^{-3}	0.31	0.003	16.04	0.26	-0.33
Fe	mg dm^{-3}	7.11	2.62	22.74	0.33	0.08
Mn	mg dm^{-3}	33.81	127.1	33.35	0.16	-0.40
Zn	mg dm^{-3}	1.37	0.49	51.13	1.16	0.96

CV: coefficient of variation; SOM: soil organic matter; pH: activity of hydrogen ions; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; H + Al: potential acidity; SB: sum of bases; CEC: cation exchange capacity; V %: base saturation; B: boron; Fe: iron; Mn: manganese and Zn: zinc.

Table 4. Parameters of semivariographic analysis of soil chemical properties under no-tillage

Property	Model	C_0	C_1	a	DD	Class
SOM	Spherical	9.00	3.80	116.50	70.0	Moderate
pH	Spherical	0.05	0.08	77.80	38.0	Moderate
P	Spherical	0.00	3300.00	70.00	0.0	Strong
K	Spherical	0.00	1.20	85.00	0.0	Strong
Ca	Spherical	121.00	251.80	79.30	32.0	Moderate
Mg	Spherical	3.00	7.00	60.00	30.0	Moderate
H + Al	Spherical	20.00	32.00	53.00	38.0	Moderate
SB	Spherical	132.30	382.30	75.00	26.0	Moderate
CEC	Spherical	85.20	212.10	80.40	29.0	Moderate
V%	Spherical	50.00	90.00	65.00	36.0	Moderate
B	Spherical	0.00	0.00	80.00	37.0	Moderate
Fe	Spherical	0.17	2.15	72.00	7.0	Strong
Mn	Spherical	37.90	76.20	96.50	33.0	Moderate
Zn	Spherical	0.11	0.32	84.70	26.0	Moderate

C_0: nugget effect; C_1: variance structure; a: range; DD: Spatial dependence degree; SOM: soil organic matter; pH: activity of hydrogen ions; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; H + Al: potential acidity; SB: sum of bases; CEC: cation exchange capacity; V%: base saturation; B: boron; Fe: iron; Mn: manganese and Zn: zinc.

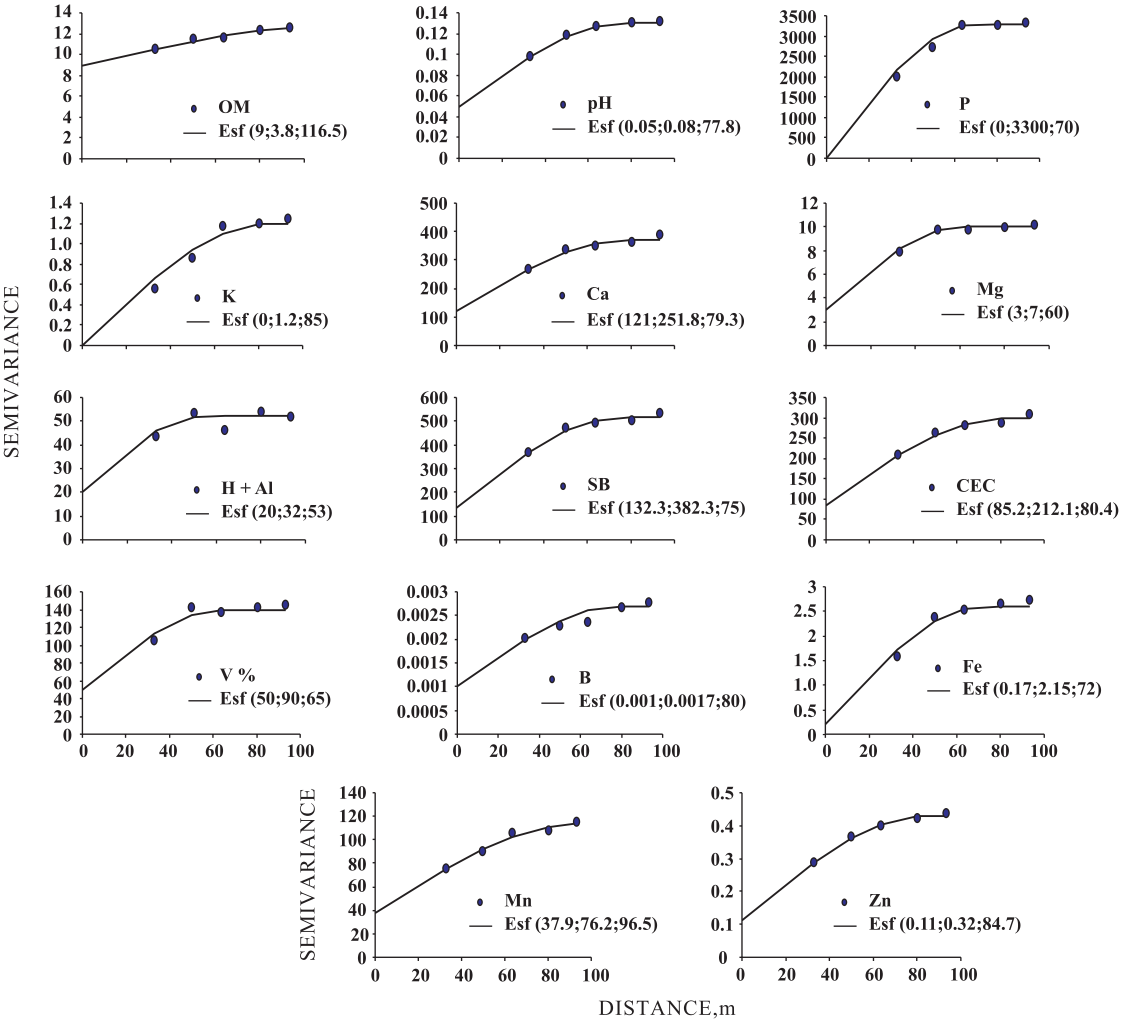

Figure 2. Semivariograms for soil chemical properties. OM: organic matter; pH: activity of hydrogen ions; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; H + Al: potential acidity; SB: sum of bases; CEC: cation exchange capacity; V %: base saturation; B: boron; Fe: iron; Mn: manganese and Zn: zinc.

The spatial dependence degree of available P and exchangeable K was zero, representing strong spatial dependence, despite the though higher CV of the two properties. It becomes clear, therefore, that the great variability of these properties did not influence the characterization of the structure of their variations. Spatial Dependence Degree (DD) values varied from 0 for P and K to 70 % for SOM, although with exception of the latter, the highest Spatial Dependence Degree (DD) value was 38 % for properties related to soil reaction (pH and H + Al).

Another important parameter of semivariogram interpretation is the range, which indicates the distance up to which sample points are spatially correlated. In general, chemical properties had high range values, which proves the effectiveness of the sampling grid in detecting spatial variations of the properties. The highest range value was observed for SOM with 116.5 m, and surprisingly, this was the property with the greatest DD (70 %), although this value is considered moderate. The lowest range value (53.0 m) was observed for H + Al, although variation predominated in the interval between 70.0 and 96.5 m. It is worth remembering that the similarity of C_0, C_1, and DD indicates the relationship of directly related properties, such as SB, CEC and V % (Table 4).

The contour maps (Figure 3) show mostly clear-cut, well-defined patches for all soil chemical properties. The SOM map shows that spatial distribution of SOM varied between 27.5 and 35.5 g dm^{-3}, indicating adequate levels in the area. The SOM values were highest in the eastern area and diminished gradually towards the west. The pH amplitude varied from 4.75 to 5.55 units, confirming the low variation indicated by the CV value, with one patch in the northern and one in the eastern area, with values between 5.15 and 5.55, and another in the south-central region with pH of 4.75–4.95. The spatial distribution of pH indicated highly acidic zones in most of the area (4.75 a 5.15), indicating the need for liming.

The spatial variation map of P levels shows a high amplitude of variation of 15–175 mg dm^{-3}. Nevertheless, visual analysis of the map revealed predominance of levels of 15–55 mg dm^{-3} in the study

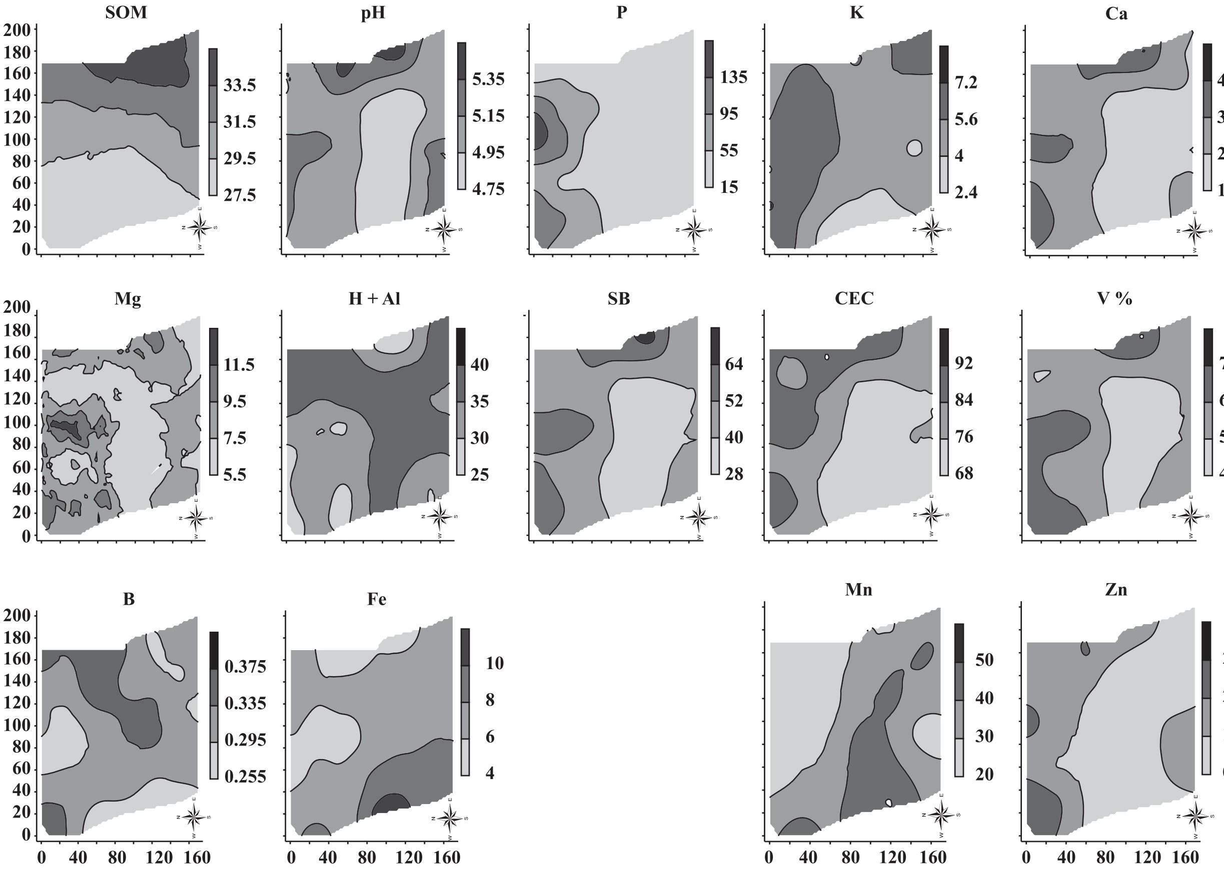

Figure 3. Spatial variation maps of soil chemical properties: SOM (g dm^{-3}): organic matter; pH (n/a): activity of hydrogen ions; P (mg dm^{-3}): phosphorus; K (mmol$_c$ dm^{-3}): potassium; Ca (mmol$_c$ dm^{-3}): calcium; Mg (mmol$_c$ dm^{-3}): magnesium (mmol$_c$ dm^{-3}); H + Al (mmol$_c$ dm^{-3}): potential acidity; SB (mmol$_c$ dm^{-3}): sum of bases; CEC (mmol$_c$ dm^{-3}): cation exchange capacity; V (%): base saturation; B (mg dm^{-3}): boron; Fe (mg dm^{-3}): iron; Mn (mg dm^{-3}): manganese and Zn (mg dm^{-3}): zinc.

area. On the northern side, there was a well-defined patch with a variation range of 55–175 mg dm^{-3}, which could be classified as a very high P level, according to Raij et al. (1997). The variation amplitude of K was 2.4–8.8 $mmol_c$ dm^{-3}. On the southwestern side was a low-K patch with levels from 2.4 to 4.0 $mmol_c$ dm^{-3}. In contrast, the rest of the area had levels of 4.4–7.2 $mmol_c$ dm^{-3}, which are considered high and very high (Raij et al., 1997). The variation amplitude of Ca was large; however analysis of the map shows two distinct and defined patches, one in the south with levels of 19–29 $mmol_c$ dm^{-3} and another in the northern area with 29 - 49 $mmol_c$ dm^{-3}.

Maps related to soil fertility for the properties SB, CEC and V % basically indicated two patches (Figure 3). There was a patch with SB values of 28–40 $mmol_c$ dm^{-3} (south) and another of 52–64 $mmol_c$ dm^{-3} (north). In the case of CEC, with exception of the northern area with levels between 84 and 92 $mmol_c$ dm^{-3}, values varied from 68–76 $mmol_c$ dm^{-3} in almost all the rest of the area. For V %, a patch with values below 52 % (central-south) and another with values of 52 - 70 % for the rest of the area were observed.

The soil micronutrient maps revealed considerable variations in concentrations across the study area (Figure 3). Predominant B values in the area were considered average values for this micronutrient (0.255–0.335 mg dm^{-3}). Iron had predominant levels between 4.0 and 8.0 mg dm^{-3} in the area, and small patch in the southwest with average values of 8–12 mg dm^{-3}. Manganese soil concentrations were the highest (20–50 mg dm^{-3}) and also had a differentiated distribution, since the Mn level increased in the area from the northeast to the central-west, from where it decreased to levels of 20–30 mg dm^{-3}. The Zn level in the area predominantly from 0.6 to 1.3 mg dm^{-3}, but there was a patch with high Zn (2.0–2.7 mg dm^{-3}) in the north.

The combined analysis of spatial variation maps (Figure 3) allowed the conclusion that geospatial distribution was similar for the following chemical properties: SOM, K, P, Ca, Mg, SB, CEC, V %, B, Mn, and Zn. On all maps, a patch with low values of these elements was verified on the south side. This indicates that soil chemical properties in this patch could be managed homogeneously to correct them to adequate levels for crop development.

On the north side, the spatial distribution of some properties was similar: pH, P, K, Ca, SB, CEC, V %, and Zn. The maps (Figure 3) of these properties indicate that this region of the area has the highest levels according to the classification of Raij et al. (1997). It is important to note that crop yields were highest at this very spot. Therefore, the highest yield values on this side could be partially justified by adequate levels of soil nutrients in this area. It is likely that these nutrient levels are also the result of residual fertilizer, since the area had been constantly fertilized for year-long cultivation.

Soil physical properties

Table 5 shows descriptive statistical parameters for the following physical properties: saturated soil hydraulic conductivity (Ks), texture, soil density (SD), total porosity (TP), and penetration resistance (PR).

The variability of a property can be classified according to the magnitude of its coefficient of variation (Freddi et al., 2006; Lima et al., 2007). Thus, of the properties analyzed, the variations of hydraulic conductivity were greatest. The highest CV value was 78.97 % for Ks 0.20 m, followed by Ks 0.40 m with 53.67 %. High CV values were found for hydraulic conductivity in an Ultisol by Abreu et al. (2003). Bosch & West (1998) also reported large variations for hydraulic conductivity in two sandy soils, and Rehfeldt et al. (1992) observed high variations of hydraulic conductivity in floodplain soil. Note that independent of the soil and management type, measurements of this property seem to be highly variable.

The CV value was low for clay (6.26 %), as similarly observed by Souza et al. (1997) and Abreu

Table 5. Descriptive statistical parameters of soil physical properties under no-tillage

Property	Unit	Mean	Variance	CV%	Skewness	Kurtosis
$Ks_{20\ 2008}$	m day^{-1}	0.93	0.54	78.97	2.26	6.18
$Ks_{40\ 2008}$	m day^{-1}	1.21	0.42	53.67	2.42	11.93
Clay	%	59.60	13.91	6.26	-0.28	-0.96
SD	kg dm^{-3}	1.30	0.0053	5.61	0.02	-0.05
TP	m^3 m^{-3}	0.54	0.0006	4.77	-0.04	-0.04
PR_{0-5}	Mpa	1.41	0.41	44.92	0.75	0.16
PR_{5-10}	Mpa	3.09	0.53	23.53	0.08	1.69
PR_{10-15}	Mpa	3.32	0.69	24.99	5.77	62.09
PR_{15-20}	Mpa	3.23	0.57	23.32	2.92	17.76

CV: coefficient; Ks: saturated soil hydraulic conductivity; SD: soil density; TP: total porosity and PR: penetration resistance.

et al. (2003), when studying clay levels. The CV values of the physical properties TP and SD were lowest, as similarly reported by Souza et al. (2004). This demonstrates a lower heterogeneity of these properties in the study area, as also stated by Grego & Vieira (2005) in an experiment under conventional tillage and by Lima et al. (2007), with no-tillage.

The CV of PR was average to high (23.32–44.92 %). The CV value was highest for the surface layer to a depth of 0.05 m and was practically the same in the three subjacent layers (23.53, 24.99 and 23.32 %). Abreu et al. (2003) and Souza et al. (2006) reported similar behavior for the same depths. High CV values for PR had already been expected due to the wide variations of this variable and measurement errors that influence the value.

When a data set has nearly normal distribution, the coefficients of skewness and kurtosis approach zero and the average and median values are similar and can be efficiently used to characterize a sample population from which they had been removed. In this case, SD and TP had normal frequency distribution, agreeing with results of Souza et al. (2001). In addition to these properties and texture, the frequency of PR 0.05 m and PR 0.10 m also tended towards normality.

Average values allow some important inferences in relation to the set of soil physical properties. They indicate an increase in penetration resistance (PR) values with depth. This observation corroborates results of Souza et al. (2001). Nevertheless, Silva et al. (2004) reported higher mean spatial variations of penetration resistance in the surface layer of an Ultisol. Numerous cases of root-growth limiting PR values are reported in the literature. Camargo & Alleoni (1997) described that PR values of 1–2.5 MPa are not considered restrictive to root development. It can be verified that in this case, average PR in deeper layers is > 2.5 MPa. The same authors also stated a soil density value of 1.55 kg dm^{-3} as critical. Erickson (1982) claimed that total porosity below 0.10 m^3 m^{-3} is harmful to crops. With this, based on the average values, the sustainability of the no-tillage system with crop rotation is confirmed for the study area, since average density and porosity values were 1.30 kg dm^{-3} and 0.54 m^3 m^{-3}, respectively, which is not limiting.

By means of semivariograms, the spatial dependence between physical properties can be verified. If the semivariogram instead of increasing and depending on distance, has no baseline, there is total absence of spatial dependence, making it impossible to fit a model, which is called a pure nugget effect (Vieira, 2000). Only PR in the 0.10 m layer behaved in this way, indicating the need for a tighter sampling grid to detect spatial dependence. Abreu et al. (2003) also observed a pure nugget effect for PR in this layer, which they attributed to the wide PR variations. The spatial dependence structure of the other properties was well-defined, as can be seen in table 6 and figure 4.

All properties were fitted to the spherical mathematical model, confirming the predominance of this model in soil science research (Carvalho et al., 2003; Cavalcante et al., 2007; Siqueira et al., 2008). The nugget effect (C_0) reveals discontinuity of the semivariogram for distances shorter than the distance between samples (Vieira, 2000). When C_0 is smallest, spatial continuity is therefore the best of the properties analyzed. Amplitude of C_0 variation for study properties was 0.0–0.42. Therefore, it can be concluded from the analysis of C_0 that all properties have continuous spatial structure, especially texture (0.0), SD (0.0033) and TP (0.00044).

The range values showed that the patch of largest spatial variation is represented by the clay fraction with a 100 m range. Soil density and TP respectively had ranges of 62.0 and 66.0 m, which are much higher than the values found by Souza et al. (2001) and Lima

Table 6. Parameters of semivariographic analysis of soil physical properties in a no-tillage system

Property	Model	C_0	C_1	a	DD	Class
$Ks_{20\ 2008}$	Spherical	0.32	0.21	41.80	60.00	Moderate
$Ks_{40\ 2008}$	Spherical	0.31	0.18	67.10	63.00	Moderate
Clay	Spherical	0.00	32.00	100.00	0.00	Strong
SD	Spherical	0.0033	0.002	74.00	62.00	Moderate
TP	Spherical	0.00044	0.00023	72.00	66.00	Moderate
PR_{0-5}	Spherical	0.31	0.08	60.00	80.00	Weak
PR_{5-10}	Pure nugget effect					
PR_{10-15}	Spherical	0.42	0.20	50.00	68.00	Moderate
PR_{15-20}	Spherical	0.35	0.17	52.00	67.00	Moderate

C_0: nugget effect; C_1: structured variance; a: range; DD: degree of dependence spatial; Ks: saturated soil hydraulic conductivity; SD: soil density; TP: total porosity and PR: penetration resistance.

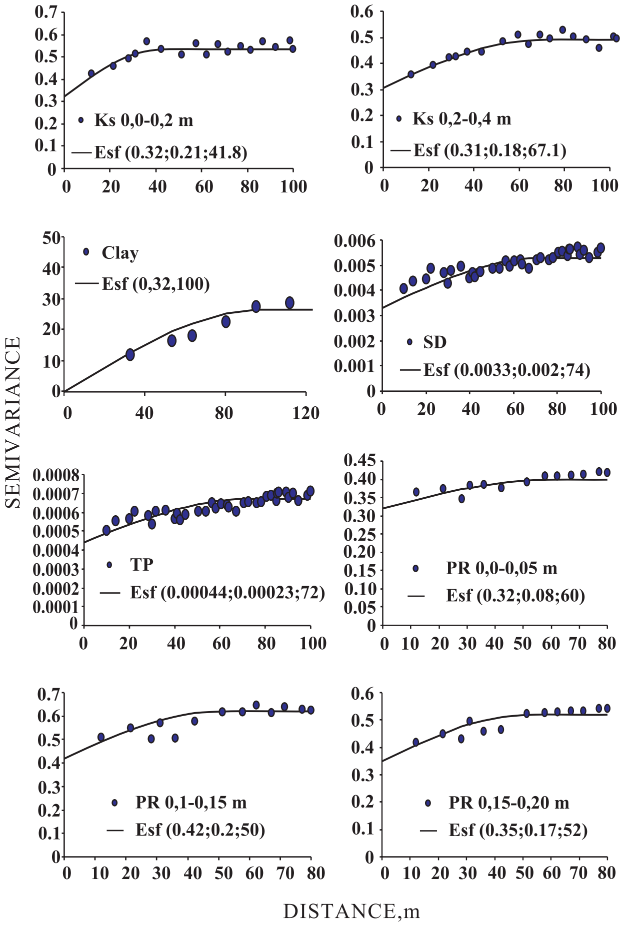

Figure 4. Semivariograms for soil physical properties. PR: penetration resistance; Ks: satured soil hydraulic conductivity; SD: soil density; TP: total porosity.

et al. (2007). Even with low C_0 values, the variation amplitude of DD of soil properties was wide. The lowest value was obtained for texture (0 %) and the highest for PR 0.05 m (80 %). With exception of texture, with strong DD, and PR 0.05 m, with weak DD, the other properties had moderate DD, agreeing with various authors who also studied soil physical properties (Mercante et al., 2003; Silva et al., 2004; Grego & Vieira, 2005; Souza et al., 2006; Siqueira et al., 2008). Predominance of moderate spatial dependence and strong dependence indicate that absence of tilling does not necessarily affect the varibility of soil properties.

Figure 5 shows maps of spatial variation in soil physical properties. The $Ks_{0.20}$ map showed a patch on the south side with values varying from 1.1 to 2.9 m day^{-1}, while in the rest of the area values were 0.5–1.1 m day^{-1}. Spatial distribution of $Ks_{0.40}$ had a patch from the south to the north with Ks values between 1.2 and 1.7 m day^{-1} and a south-central patch with higher values (1.7–2.7 m day^{-1}). Note that Ks values tended to be higher in the south at both depths. Spatial distribution of Ks values was similar to results of an evaluation of saturated soil hydraulic conductivity by Vieira et al. (1988).

The texture map shows that there are two patches with high values (between 61.4 and 65.2 %), although values between 57.6 and 61.4 % predominated. The SD map shows a patch on the north side with the lowest values (1.23–1.28 Mg dm^{-3}). The southwest had the highest SD (1.33–1.43 Mg dm^{-3}). In the rest of the area, SD values were between 1.28 and 1.33 Mg dm^{-3}, which is not restrictive to root development, according to Camargo & Alleoni (1997). Neither machine traffic nor the fact that the soil had not been tilled was enough to cause soil compaction in the 23 years of no-tillage, using SD values as a reference. An analysis of the TP map showed an inverse spatial behavior to SD. Note that practically the same patches appear on the SD map, with the difference that where SD had the highest values, TP was lowest. But it is worth pointing out that TP values in the order of 0.535–0.555 m^3 m^{-3} predominated, which is considered higher than ideal for soil porosity (Kiehl, 1979).

The map of PR at 0.05 m showed high spatial variations (0.9–2.1 MPa). Nevertheless, the predominant values in the area were between 0.9 and 1.5 MPa. PR values above 1.8 MPa were only observed in small patches in the northeast. Despite the high amplitude, PR values were between 2.8 and 3.7 MPa in practically the whole 0.10–0.15 m layer. High PR amplitude was also observed in the 0.15–0.20 m layer, although values of 2.5–3.3 MPa predominated, but in some places there were small patches with values of 3.3–4.1 MPa. For Camargo & Alleoni (1997), values > 2.5 MPa are considered restrictive to plant root development. For Torres & Saraiva (1999), restrictive values are in the range of 3.5–6.5 MPa. Based on this last interval, it can be said that there is no compaction problem down to a depth of 0.20 m. Nevertheless, if the first value is considered, plant development is restricted in all soil layers but the surface (0–0.05 m).

Analyzing SD and PR maps together, no similarity was noted in spatial distribution despite close relationships, as pointed out by Fidalski et al. (2006). On this subject, Torres & Saraiva (1999) reported that PR is more affected by the moisture level at sampling than by soil density. The SD and Ks maps were somewhat similar, since the values of these properties were highest in the south. In the case of PR, the maps were not similar to the geospatial pattern for the property evaluated.

Spatial distribution analysis of the soil physical properties indicated sustainability and viability of long-term maintenance of a no-tillage system. Thus, taking the higher yields in the north into account, it is possible to say that the yield and soil physical

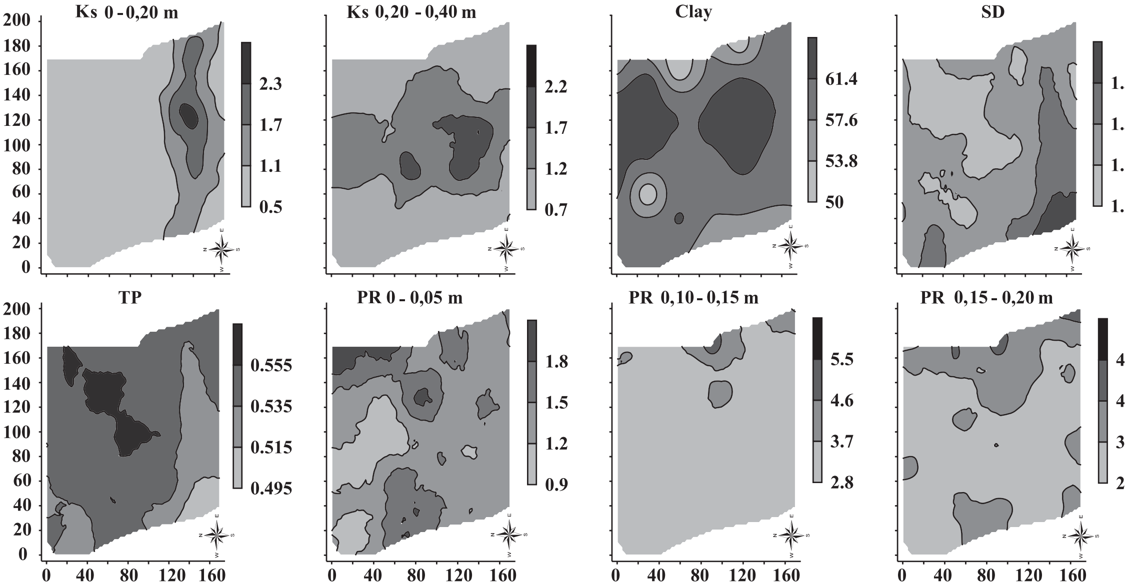

Figure 5. Spatial variation maps of soil physical properties: Ks (m dia^{-1}): saturated soil hydraulic conductivity, SD (kg dm^{-3}): soil density, TP (m^3 m^{-3}): total porosity, PR (MPa): penetration resistance.

properties were similar, since the highest texture and TP and lowest Ks and SD values were observed in the northern area. This shows the importance of considering spatial variations of physical properties in soil management.

CONCLUSIONS

1. The yield values in the northern area were repeatedly high (in 2002, 2003, 2005, 2006 and 2007), showing that in this case five yield maps were enough for a high response zone.

2. There was a spatial relationship between crop yields and some physical and soil chemical properties, indicating that the area could be divided into land management zones, defining two classes of behavior in the area: higher values in the northern and lower in the southwest area.

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