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Correlations of soybean yield with soil porosity and bulk density of an Oxisol[1]

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ABSTRACT

The spatial variability of soil physical attributes is important to indicate management practices that best suit agricultural areas. This study aimed to analyze spatial correlations between soybean grain yield and soil mass-volume relationships, in order to select which attribute is correlated with yield, as well as to evaluate the spatial variability of soil attributes and yield components of this crop, in an Oxisol under no-tillage system. The soil attributes analyzed (0.0-0.10 m and 0.10-0.20 m) were the following ones: soil bulk density (paraffin-coated clod and volumetric ring methods), particle density (volumetric flask and modified volumetric flask methods) and total porosity. The soybean yield components were evaluated as it follows: grain yield, number of pods per plant, number of grains per pod, mass of 100 grains, grain mass per plant, plant population and plant height. The total soil porosity, calculated by the relations between the bulk density (volumetric ring method) and particle density (volumetric flask), in the 0.10-0.20 m layer, was the best indicator of soybean grain yield under no-tillage conditions.

KEYWORDS: *Glycine max* L.; soil compaction; soil aeration; geostatistics; no-tillage management.

RESUMO

Correlações de rendimento de soja com a porosidade e densidade de um Latossolo

A variabilidade espacial dos atributos físicos do solo é importante para indicar o manejo localizado, em áreas agrícolas. Objetivou-se analisar correlações espaciais entre o rendimento de grãos de soja e atributos da relação massa/volume do solo, visando a selecionar qual atributo está correlacionado com o rendimento, bem como avaliar a variabilidade espacial dos atributos do solo e componentes de produção desta cultura, em Latossolo Vermelho distroférrico manejado sob plantio direto. Os atributos do solo analisados (0,0-0,10 m e 0,10-0,20 m) foram: densidade (métodos do anel volumétrico e do torrão parafinado), densidade de partícula (métodos do balão volumétrico e do balão volumétrico modificado) e porosidade total. Os componentes de produção da soja avaliados foram: rendimento de grãos, número de vagens por planta, número de grãos por vagem, massa de cem grãos, massa de grãos por planta, população de plantas e estatura de plantas. A porosidade total do solo, calculada pela relação entre a densidade do solo (método anel volumétrico) e a densidade de partícula (método do balão volumétrico), na camada de 0,10-0,20 m, foi o melhor indicador de rendimento de grãos de soja sob plantio direto.

PALAVRAS-CHAVE: *Glycine max* L.; compactação do solo; aeração do solo; geoestatística; sistema plantio direto.

INTRODUCTION

The biomass production in an agricultural ecosystem depends, in principle, on environmental factors such as solar radiation, CO_2, climate, water and soil nutrients for the photosynthesis process. The physical characteristics of the ecosystem and the interaction between ecological factors (geology, relief, hydrography, climate, soils and vegetation) determine the potentialities, fragilities and limitations of each environment, and should be considered for a sustainable biomass production. This means that the farther the agricultural ecosystem is from its natural state, the more dependent a sustainable production will be on human management actions.

With the intensification of agricultural mechanization, cultivation is often carried out under conditions that compromise the conservation

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of edaphic resources, leading, for example, to a soil compaction process and its advancement in extensive regions of the country, with impacts on agricultural yield. Thus, mapping the soil physical attributes of an agricultural area is of utmost importance, both for the recommendation of management practices and for the evaluation of agricultural effects on environmental quality (Andreotti et al. 2010).

In geostatistics, maps made from estimates of a studied variable can represent the spatial variability. Studies related to soil compaction, which use its bulk density as an indicator attribute, have shown that its increase may cause, in general, a decrease in agricultural yield (Lima et al. 2007, Queiroz et al. 2011). In view of that, this study aimed to compare methods for determining soil porosity and density, as well as to analyze correlations between soybean grain yields with some attributes of soil mass-volume relationships, in order to indicate those that were more efficiently related to soybean yield, as well as to study the spatial variability of soil attributes and yield components of this crop.

MATERIAL AND METHODS

The study was carried out in Selvíria, Mato Grosso do Sul state, Brazil (20º18'05"S and 20º18'28"S; 52º39'02"W and 52º40'28"W), where the precipitation and average annual temperature are 1,300 mm and 23.7 ºC, respectively (Figure 1). The climate is Aw, characterized as humid tropical, with a rainy season in the summer and dry in the winter. The experiment was cultivated under a no-tillage system for five years, with successive sowings of corn in the first two years (2005/2006 and 2006/2007), and, in the last three years, sorghum in the second crop and soybean in the summer, respectively.

The soil under study, where the experimental plots were settled, is a typical clayey Dystrophic Oxisol (Haplustox), with 660 g kg^{-1} of clay, 220 g kg^{-1} of silt and 120 g kg^{-1} of sand. Before the experiment was installed, the soil presented the following characteristics (0-0.10 m and 0.0-0.20 m of depth, respectively): organic matter = 27.0 g dm^{-3} and 20.0 g dm^{-3}; Ca = 19.0 mmol$_c$ dm^{-3} and 16.0 mmol$_c$ dm^{-3}; K = 4.4 mmol$_c$ dm^{-3} and 1.0 mmol$_c$ dm^{-3}; Mg = 17.0 mmol$_c$ dm^{-3} and 10.0 mmol$_c$ dm^{-3}; Al = 1.0 mmol$_c$ dm^{-3} and 2.0 mmol$_c$ dm^{-3}; H + Al = 33.0 mmol$_c$ dm^{-3} and 31.0 mmol$_c$ dm^{-3}; sum of bases = 40.4 mmol$_c$ dm^{-3} and 28.0 mmol$_c$ dm^{-3}; cation exchange capacity = 73.4 mmol$_c$ dm^{-3} and 59.0 mmol$_c$ dm^{-3}; base saturation = 55 % and 47 %; P = 15.0 mg dm^{-3} and 11.0 mg dm^{-3}; and pH($CaCl_2$) = 5.1 and 5.0.

Soybean of the commercial variety Conquista was sown on December 21 and 22, 2009, with a space of 0.45 m between rows and density of 18 seeds m^{-1}, fertilized at sowing with 300 kg ha^{-1} of the formulation 00-20-20 (N-P-K). The soybean seeds were previously inoculated with *Bradyrhizobium*

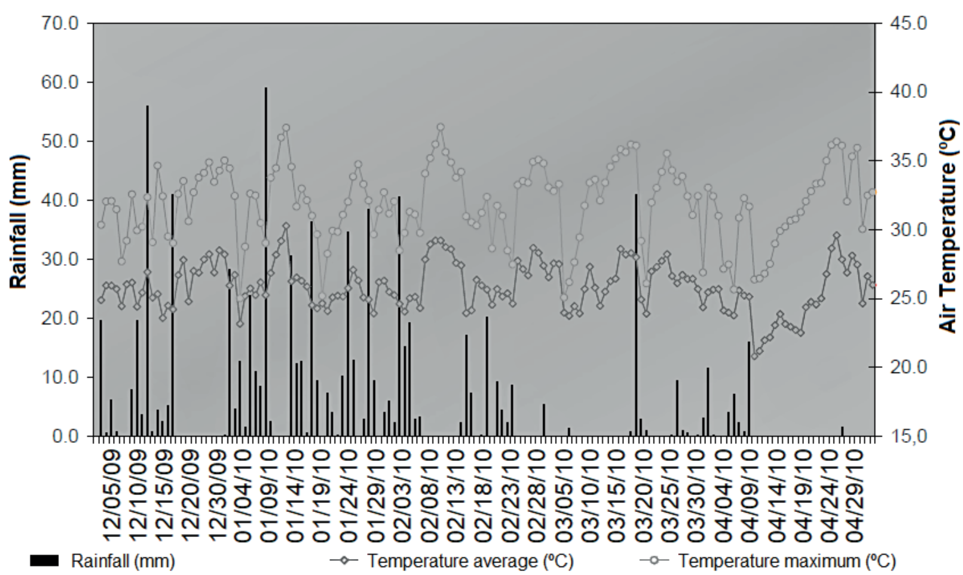

Figure 1. Maximum and average rainfall and temperature, during the evaluation period of the experiment.

japonicum, using the commercial liquid inoculant Masterfix®, containing SEMIA 5079 and SEMIA 5019 strains (minimum concentration of 5 × 10^9 viable cells mL^{-1}).

The statistical mesh was established in an area of 10 ha using the *x* and *y* directions of the Cartesian coordinate system in the largest launcher of the crop, performing random staking of the mesh at the time of planting and soil data sampling. In the direction of the *x*-axis, 18 lines were spaced at 39.0 m apart, with the number of 18 variable sample points in each of them and distances ranging between 18.0 m and 21.0 m in the direction of the *y*-axis, so that within the area 99 sampling points were distributed, obtaining an average of 10 sampling points per hectare.

The soybean yield components and soil physical attributes were collected around each sampling point. For the collection, 10 plants positioned in the central part of the points and their surroundings were used for the analysis of the soybean yield components. For the determination of grain yield, all the plants of the useful area were harvested, which, after dried, were submitted to manual tracking and, then, the mass of these grains, corrected to 13 % of humidity, was determined. The useful area of each sampling point was the result of the harvesting of four sowing rows, spaced at 0.45 m, totaling a width of 1.80 m and a length of equal value, totaling 3.24 m^2. The soybean yield components were the following ones: grain yield (GY), number of pods per plant, number of grains per pod, mass of 100 grains, grain mass per plant (GMP), plant population and plant height.

The soil samples collected at each of the 99 mesh points, obtained at the 0.00-0.10 m and 0.10-0.20 m layers (respectively indicated by even and odd numbers), were as it follows: soil bulk density (Embrapa 1997) - volumetric ring method (BD1 and BD2); soil bulk density (Blake & Hartge 1986) - paraffin-coated clod method (BD3 and BD4); particle density (Kiehl 1979) - volumetric flask method (PD1 and PD2); particle density (Gubiani et al. 2006) - modified volumetric flask method (PD3 and PD4); and total soil porosity (TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8), calculated by the relations TP1 = (1 - BD1/PD1); TP2 = (1 - BD2/PD2); TP3 = (1 - BD1/PD3); TP4 = (1 - BD2/PD4); TP5 = (1 - BD3/PD1); TP6 = (1 - BD4/PD2); TP7 = (1 - BD3/PD3); and TP8 = (1 - BD4/PD4). Both the plant harvest and soil sample collection took place in the final ten-days of April 2010.

The statistical analysis was performed using the SAS software (SAS Institute 2010). The descriptive analysis of the attributes was performed by calculating the average, median, minimum and maximum values, standard deviation, coefficient of variation, kurtosis, skewness and frequency distribution analysis, using the Shapiro & Wilk test at 1 % of error probability. The soil attributes variability and soybean yield components were classified according to the magnitude of their coefficients of variation (CV), which, according to Pimentel-Gomes & Garcia (2002), are classified as low (CV < 10 %), average (10 % < CV < 20 %), high (20 % < CV < 30 %) and very high (CV > 30 %). The correlation matrix was built among all the attributes studied, containing all the possible matched combinations, in order to detect the existence of significant correlations between the components of plant yield (dependent variables) and soil attributes (independent variables). The geostatistical analysis was done using the Gamma Design Software 7.0 (GS^+ 2004). For each attribute, the spatial dependence was analyzed by means of semivariogram calculation. The aim was to analyze correlations between soybean yield and soil, seeking to select which attribute was correlated with yield, as well as to study the spatial variability of the soil attributes and the yield components of this crop.

RESULTS AND DISCUSSION

According to Pimentel-Gomes & Garcia (2002), the yield components, regarding the number of soybean grains per pod and mass of 100 grains, indicated a low variability, with coefficient of variation values of 5.7 % and 6.4 %, respectively, whereas plant height, plant population and grain yield indicated an average variability (11.3 %, 12.2 % and 19.9 %); in turn, grain mass per plant and number of pods per plant indicated a high variability (22.6 % and 23.5 %) (Table 1). The values determined for number of pods per plant, number of grains per pod, grain mass per plant and plant population agreed with the magnitude of those obtained by Dalchiavon et al. (2011), except for grain yield, which showed an average variability of the data (19.9 %) and the aforementioned high variability (21.8 %).

When any statistical variable has a frequency distribution of the normal type, the most suitable central tendency measure to represent it should be the average. On the other hand, it should be represented

Table 1. Descriptive analysis of the crop production components of soybean in an Oxisol.

Crop production component[(a)]	Descriptive statistical measures									
	Average	Median	Value		Standard deviation	Coefficient			Test probability[(b)]	
			Minimum	Maximum		Variation (%)	Kurtosis	Asymmetry	Pr < w	FD
NPP	25.0	24.0	14.1	39.2	5.9	23.5	-0.624	0.160	0.157	LN
NGP	2.0	2.0	1.7	2.4	0.1	5.7	1.513	0.128	0.007	UN
MOG (g)	15.8	16.1	13.1	17.7	1.0	6.4	-0.050	-0.394	0.084	NO
GMP (g)	6.9	6.9	3.7	10.7	1.6	22.6	-0.568	0.312	0.093	NO
POP (pl m^{-2})	36.5	37.1	26.6	43.6	4.4	12.2	-0.911	-0.427	0.001	UN
HEI (cm)	75.8	76.6	48.9	94.5	8.5	11.3	0.169	-0.308	0.751	NO
GY (kg ha^{-1})	2,659	2,563	1,365	4,179	528.7	19.9	0.497	0.537	0.051	NO

[(a)] NPP = number of pods per plant; NGP = number of grains per plant; MOG = mass of 100 grains; GMP = grain mass per plant; POP = plant population; HEI = plant height; GY = grain yield. [(b)] FD = frequency distribution; UN = undetermined; NO = normal; LN = lognormal.

by the median or by the geometric average, in case it is lognormal (Dalchiavon et al. 2011). Therefore, except for the number of pods per plant, number of grains per pod and plant population, the components indicated a frequency distribution of the normal type and had their respective central tendency measures represented by the average (Table 1).

For the yield components, the average values for number of pods per plant, number of grains per pod, mass of 100 grains, grain mass per plant, plant population and plant height were, respectively, 25, 2.0, 15.8 g, 6.9 g, 36.5 plants m^{-2} and 75.8 cm, different from those obtained by Dalchiavon et al. (2011), who evaluated the soybean grain yield under no-tillage, in the region of Selvíria, and lower in terms of number of pods per plant, number of grains per pod and grain mass per plant attributes, whose values corresponded, respectively, to 72.2 g, 2.2 g and 23 g. The number of pods per plant was lower than that of 36.6 obtained by Queiroz et al. (2011), who studied the soybean grain yield in an Oxisol, in a crop rotation with brachiaria pasture, and of 72.2 observed by Dalchiavon & Carvalho (2012), evaluating soybean grain yield cultivated in a Oxisol under no-tillage. Possibly, the number of pods per plant was lower due to the increase in the soil bulk density, since, under stress conditions, the plant formed few grains in the pods, because the main biological objective of the crop is the dissemination of the species (Carvalho et al. 2004).

The mass of 100 grains (15.8 g) was very close to that of 15.9 g obtained by Lovera (2015) and less than the 16.4 g obtained by Carvalho et al. (2004), studying the effect of soybean cultivated under no-tillage in an Oxisol, because, according to the authors, the mass of 100 grains is the one that presents the lowest percentage variation due to changes in the growing environment. The plant height (75.8 cm) was higher than that of 68.0 cm verified by Queiroz et al. (2011). It is noteworthy that, when it exceeds 65 cm, it is indicated as the desired height of plants for mechanical harvesting (Bonetti 1983).

Grain yield was low (Table 1), with an average value of 2,659 kg ha^{-1}, lower than the national average of 3,362 kg ha^{-1} (Conab 2017) and also lower in relation to that reported by Rosa Filho et al. (2009) of 3,317.5 kg ha^{-1}, by Queiroz et al. (2011) of 3,270 kg ha^{-1} and by Dalchiavon et al. (2011) of 4,639.4 kg ha^{-1}. However, it is much higher than that of 1,215 kg ha^{-1} found by Lovera (2015), all carried out in the same soil under no-tillage in the region of Selvíria. It should be noted that the soybean sowing took place in late December and it was summer throughout the crop cycle, both of which were determinants for the low grain yield. Despite the total rainfall of 645 mm, there was an irregular distribution of rainfall, with 72 % of the total concentration in the months of December and January. Considering that the rainfall levels in the months of February and March were, respectively, 76.7 mm and 72.9 mm (Figure 1), and based on the soil water requirement for soybean from 7 mm day^{-1} to 8 mm day^{-1} in the period of the flowering-grain filling, there were hydric deficits in the period, since rainfall levels of 196 mm and 248 mm would be necessary for the mentioned months.

The variability of soil bulk density and particle density attributes, in the two layers evaluated, were low, with coefficient of variation values between 3.9-7.2 % and 1.9-3.0 %, respectively (Table 2). The coefficient of variation data for soil bulk density were of the same magnitude as those obtained by Santos et

Table 2. Initial descriptive analysis of the Oxisol attributes.

Attribute[(a)]	Descriptive statistical measures									
	Average	Median	Value		Standard deviation	Coefficient			Test probability[(b)]	
			Minimum	Maximum		Variation (%)	Kurtosis	Assimetry	Pr < w	FD
BD1 (kg dm^{-3})	1.442	1.446	1.153	1.666	0.104	7.2	0.348	-0.522	0.088	NO
BD2 (kg dm^{-3})	1.460	1.462	1.300	1.604	0.066	4.5	-0.474	-0.038	0.677	NO
BD3 (kg dm^{-3})	1.545	1.548	1.293	1.688	0.073	4.7	0.517	-0.457	0.193	NO
BD4 (kg dm^{-3})	1.539	1.539	1.407	1.685	0.059	3.9	-0.062	0.221	0.430	NO
PD1 (kg dm^{-3})	2.582	2.597	2.354	2.703	0.077	3.0	0.320	-0.974	10^{-4}	UN
PD2 (kg dm^{-3})	2.615	2.632	2.410	2.732	0.062	2.4	0.503	-0.738	2.10^{-4}	UN
PD3 (kg dm^{-3})	2.571	2.575	2.385	2.721	0.065	2.5	0.604	-0.339	0.131	NO
PD4 (kg dm^{-3})	2.600	2.600	2.477	2.728	0.048	1.9	0.162	0.144	0.733	NO
TP1 (m^3 m^{-3})	0.441	0.443	0.326	0.562	0.048	11.0	0.043	0.621	0.621	NO
TP2 (m^3 m^{-3})	0.441	0.438	0.366	0.504	0.030	6.7	-0.437	-0.001	0.679	NO
TP3 (m^3 m^{-3})	0.438	0.435	0.337	0.554	0.046	10.5	0.158	0.278	0.375	NO
TP4 (m^3 m^{-3})	0.438	0.437	0.379	0.500	0.030	6.8	-0.642	0.119	0.217	NO
TP5 (m^3 m^{-3})	0.401	0.401	0.301	0.516	0.038	9.4	0.153	0.012	0.862	NO
TP6 (m^3 m^{-3})	0.410	0.409	0.301	0.467	0.028	6.8	1.517	-0.478	0.054	NO
TP7 (m^3 m^{-3})	0.398	0.398	0.335	0.508	0.035	8.7	-0.044	0.427	0.059	NO
TP8 (m^3 m^{-3})	0.408	0.410	0.326	0.466	0.028	6.8	0.392	-0.404	0.222	NO

[(a)] BD1 and BD2 and BD3 and BD4 are respectively the bulk densities determined by the methods of the ring and clod; PD1 and PD2 and PD3 and PD4 are respectively the particle density determined by the methods of the volumetric flask and modified volumetric flask; and TP1 to TP8 are respectively the total porosities of the soil determined by the abovementioned methods, sampled at the 0.00-0.10 m and 0.10-0.20 m layers (respectively indicated by even an odd numbers). [(b)] FD = frequency distribution; UN = undetermined; NO = normal; LN = lognormal.

al. (2006), Lima et al. (2007), Rosa Filho et al. (2009), Montanari (2009), Andreotti et al. (2010) and Lovera (2015), evaluating an Oxisol in the region of Selvíria, which ranged between 3 % and 10 %. The variability of the soil bulk density values was affected by the crop soil management, which is essentially mechanized. The pressure exerted on the soil by the machines and the implements used in the cultivation and harvesting of soybean may generate additional compaction of the soil in certain regions in the place, mainly when under conditions of high soil moisture. Regarding particle density, the low variability of the data attested by the variation coefficient between 1.9 % and 3.0 % agreed with the findings of Santos et al. (2006) with values of 2.5-3.0 %, and Montanari (2009) with 4.6-5.5 %. The lower variability of the particle density data is consistent, because the soil pore volume is not considered in its determination, only that of the solid fraction, what makes it impossible to detect changes in the soil structure (Brady 1990) due to crop management. Probably, the variability of the particle density is more related to errors due to its determination than to the variations of the constituents of the solid fraction of the soil.

In general, the total soil porosity presented a low variability, corroborating the findings of Andreotti et al. (2010) and Lovera (2015), with coefficients of variation of 1-6.5 % and 6.9-8.9 %, respectively (Table 2). However, the attributes TP1 and TP3 indicated the average variability of the data, with coefficients of variation of 11 % and 10.5 %, respectively, agreeing with those found by Montanari (2009), with values of 11.5-14.3 %. It should be noted that the same considerations made to base the variability of the data determined from soil bulk density are plausible for the total soil porosity attribute, whose calculation considers the pore space in the soil.

The average values of the soil physical attributes were different in the layers, with an increase in the soil bulk density when determined by the ring method (BD1 and BD2) and in particle density for the evaluated methods (PD1 and PD2, PD3 and PD4) (Table 2). The average values were 1.442 kg dm^{-3} and 1.460 kg dm^{-3} for BD1 and BD2, respectively, and 1.545 kg dm^{-3} and 1.539 kg dm^{-3} for BD3 and BD4, respectively. This indicates a soil compaction in the studied layers, since they are larger, in relation to those determined by Oliveira & Moniz (1975) for a Dystroferric Oxisol under natural forest (0.980 kg dm^{-3} and 1.130 kg dm^{-3}). The bulk density values found in the present study were higher than those observed by Lovera (2015) of 1.359 kg dm^{-3} and 1.411 kg dm^{-3}, respectively at the 0.00-0.10 m and

0.10-0.20 m layers, in the same area and the same soil classification as in the present study, indicating that, maybe, there was an increase in soil compaction due to the no-tillage system. The higher soil compaction in the superficial layer for the no-tillage system, as a consequence of the movement of machines in the area, without the subsequent rotation, could increase the degree of packing of particles, thus reducing the volume of voids and increasing the soil bulk density (Portugal et al. 2012, Sales et al. 2016).

The higher soil bulk density values obtained using the paraffin-coated clod method (BD3 and BD4), if compared to those using the ring method, have been reviewed in the literature (Pires et al. 2011). The penetration of paraffin in small cracks in the clod and in the macropores, besides the loss of them during the clod sampling, are among the probable causes of the higher values obtained by the analysis method. According to Van Remortel & Shields (1993), the values are generally 0.07-0.09 kg dm^{-3} higher than those determined by the volumetric ring method. In the present study, they were higher at 0.103 kg dm^{-3} and 0.079 kg dm^{-3} for the layers of 0.00-0.10 m and 0.10-0.20 m, respectively. Pires et al. (2011) found an increase of 0.15 kg dm^{-3} of the clod method, in relation to the volumetric ring, due to the procedure of clod collecting, in which only the denser ones had a structure to be prepared and analyzed in the laboratory. The total soil porosity was lower than that recommended as ideal, which is of 0.500 m^3 m^{-3} of its total volume (Kiehl 1979), indicating a compaction of the layers evaluated by the mechanized activities in the area. The values ranging from 0.398 m^3 m^{-3} (TP7) to 0.441 m^3 m^{-3} (TP1 and TP2) were lower than those determined by Lovera (2015) of 0.489 m^3 m^{-3} and 0.467 m^3 m^{-3}, respectively in the layers of 0.00-0.10 m and 0.10-0.20 m. However, the reduction of total soil porosity did not result in lower grain yields, since they were superior to those obtained by Lovera (2015).

According to Dalchiavon (2010), when between any two attributes, there is a high and significant Pearson's correlation coefficient and both result in a semivariogram, and co-kriging will certainly exist. However, if they present a low and non-significant Pearson's correlation coefficient and both present a semivariogram, co-kriging may or may not exist. In this context, Table 3 displays the parameters of the cross-semivariograms adjusted between some attributes of grain yield.

In Figure 2, which represents the map of the grain yield simple kriging, the highest values for grain yield were found in the southwest and northeast regions, ranging from 2,623 kg ha^{-1} to 3,069 kg ha^{-1} in the form of halos of light color. On the other hand, the northwest and southeast regions of the map presented the lowest values for grain yield (2,027-2,474 kg ha^{-1}) in the form of halos of dark color.

After creating the kriging maps of the soil attributes (Figure 3), an inverse and high similarity was observed in the spatial behavior of the soil bulk density (Figure 3a) and its total soil porosity. The highest values for BD1 (1.46-1.54 kg dm^{-3}) were observed in the southwest region of the map in the form of dark halos, in which, on the other hand, the lowest values for TP1 (0.390-0.424 m^3 m^{-3}), TP2 (0.410-0.433 m^3 m^{-3}) and TP3 (0.390-0.420 m^3 m^{-3}) (Figures 3a, 3b and 3c) were found. The inverse

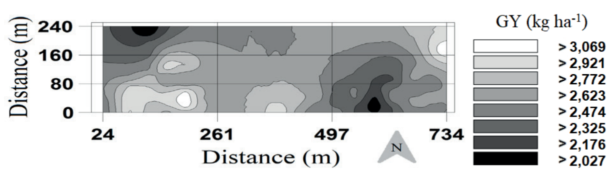

Figure 2. Kriging maps of soybean grain yield (GY) of an Oxisol.

Table 3. Parameters of cross-validation semivariograms adjusted for some attributes of the soybean grain yield (GY) and Oxisol.

Property[(a)]	Setting parameters										
	Model[(b)]	C_o	$C_o + C$	A_o (m)	r^2	RSS[(c)]	SDE[(d)]		Cross validation		
							%	Class	a	b	r
GY = f(GMP)	gau (406)	$1.00.10^{-1}$	$2.31.10^2$	308.3	0.304	$1.39.10^5$	100.0	MA	$6.60.10^3$	0.748	0.547
GY = f(BD1)	sph (297)	$2.60.10^{-1}$	$1.23.10^1$	490.0	0.363	$3.34.10^2$	97.9	MA	$1.01.10^3$	0.618	0.427
GY = f(TP2)	gau (574)	$1.00.10^{-2}$	4.27	401.8	0.478	2.17.10	99.8	MA	6.38.10	0.760	0.552
GY = f(TP3)	gau (408)	$6.40.10^{-1}$	-8.92	535.0	0.606	5.00.10	78.1	AL	$7.22.10^2$	0.726	0.516
GMP = f(BD1)	gau (375)	$1.00.10^{-4}$	$1.00.10^{-1}$	486.0	0.786	$4.29.10^{-3}$	99.8	MA	2.72	0.606	0.510

[(a)] The same as in Tables 1 and 2. [(b)] Sph = spherical; gau = gaussian, with the respective number of pairs of the first lag in brackets. [(c)] RSS = residue squares sum. [(d)] SDE = spatial dependence evaluator.

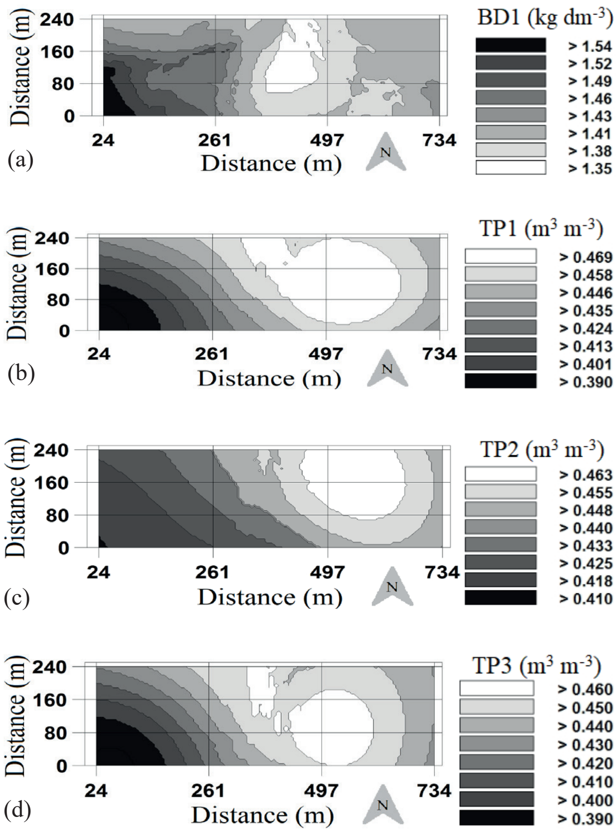

Figure 3. Kriging maps. Attributes: bulk density determined by the ring method (BD1; a); total porosity TP1 [(1 - BD1/PD1); b]; total porosity TP2 [(1 - BD2/PD2); c]; and total porosity TP3 [(1 - BD1/PD3); d], sampled at the 0.00-0.10 m and 0.10-0.20 m layers (respectively indicated by even an odd numbers) of an Oxisol.

behavior was also verified: the highest TP1 (0.435-0.469 m^3 m^{-3}), TP2 (0.440-0.463 m^3 m^{-3}) and TP3 (0.430-0.460 m^3 m^{-3}) values also occurred in the center-east region, in the form of light halos, in the lower values of BD1 (1.35-1.43 kg dm^{-3}) (Figures 3a, 3b and 3c).

Regarding the performance of the cross-semivariograms, the decreasing relation of them analyzed by the magnitude of the coefficient of spatial determination (r^2) (Table 3) was as it follows: GMP = f(BD1), r^2 = 0.786; GY = f(TP3), r^2 = 0.606; GY = f(TP2), r^2 = 0.487; GY = f(BD1), r^2 = 0.363; and GY = f(GMP), r^2 = 0.304. In relation to the evaluation of spatial dependence (Table 3), it was high (78.1 %) for GY = f(TP3) and very high for the other attributes; 97.9 % for GY = f(BD1); 99.8 % for GY = f(TP2) and GMP = f(BD1); and 100 % for GY = f(GMP).

The cross-semivariograms and the co-kriging maps between soybean yield components (plant *versus* plant) and between soybean yield components and soil attributes (plant *versus* soil) are shown in Figure 4. Thus, of the co-kriging attested by the coefficient of spatial determination (r^2), the GMP = f(BD1) presented a variographic adjustment of the direct Gaussian type (Table 3; Figure 4e) and a higher value of r^2, indicating that 78.6 % of the spatial variability of the grain mass per plant could be explained by the spatial variability of BD1. In other words, from a spatial point of view of the searched areas, in the halos in which BD1 presented values between 1.46 kg dm^{-3} and 1.54 kg dm^{-3}, the grain mass per plant of soybean of the commercial variety Conquista, planted in late December, ranged between 7.10 g and 8.16 g. However, in those where the BD1 ranged from 1.35 kg dm^{-3} to 1.43 kg dm^{-3}, the soybean mass of 100 grains ranged between 5.67 g and 6.74 g. A direct relationship was also observed for co-kriging between the grain mass per plant and soybean grain yield (Table 3; Figure 4a). Thus, in the halos of the map in which the soybean grain mass per plant presented values between 7.10 g and 8.16 g, the soybean grain yield varied between 2,623 kg ha^{-1} and 3,069 kg ha^{-1}.

The co-kriging of BD1 with soybean grain yield (Table 3; Figure 4b), with a direct relation to the spherical variographic adjustment indicated in the halos of the map in which BD1 presented the highest values, ranged between 1.46 dm^{-3} and 1.54 kg dm^{-3}, and the soybean grain yield increased, ranging between 2,623 kg ha^{-1} and 3,069 kg ha^{-1}, corroborating the fact that the increase between soil and root caused by higher BD1 was not sufficient to affect the soybean grain yield. According to Favaretto et al. (2006), nutritional and water stresses are necessary to plants between the emergence and maturation periods to affect the plant growth, what was not observed in the present study. Lovera (2015), who evaluated some soil physical attributes and soybean yield components in the same area as that of the present study, also verified such a direct behavior between the soil bulk density co-kriging and soybean grain yield. The variographic adjustment was of the Gaussian type, with r^2 = 0.813 and a reach of 35.0 m.

The co-kriging of TP3 and TP2 with grain yield (Table 3; Figures 4c and 4d) was adjusted to the Gaussian model and showed an indirect relation between them, indicating that the increase of total soil porosity resulted in a decrease of soybean grain yield. Thus, the co-kriging GY = f(TP3) (Table 3; Figure 4d)

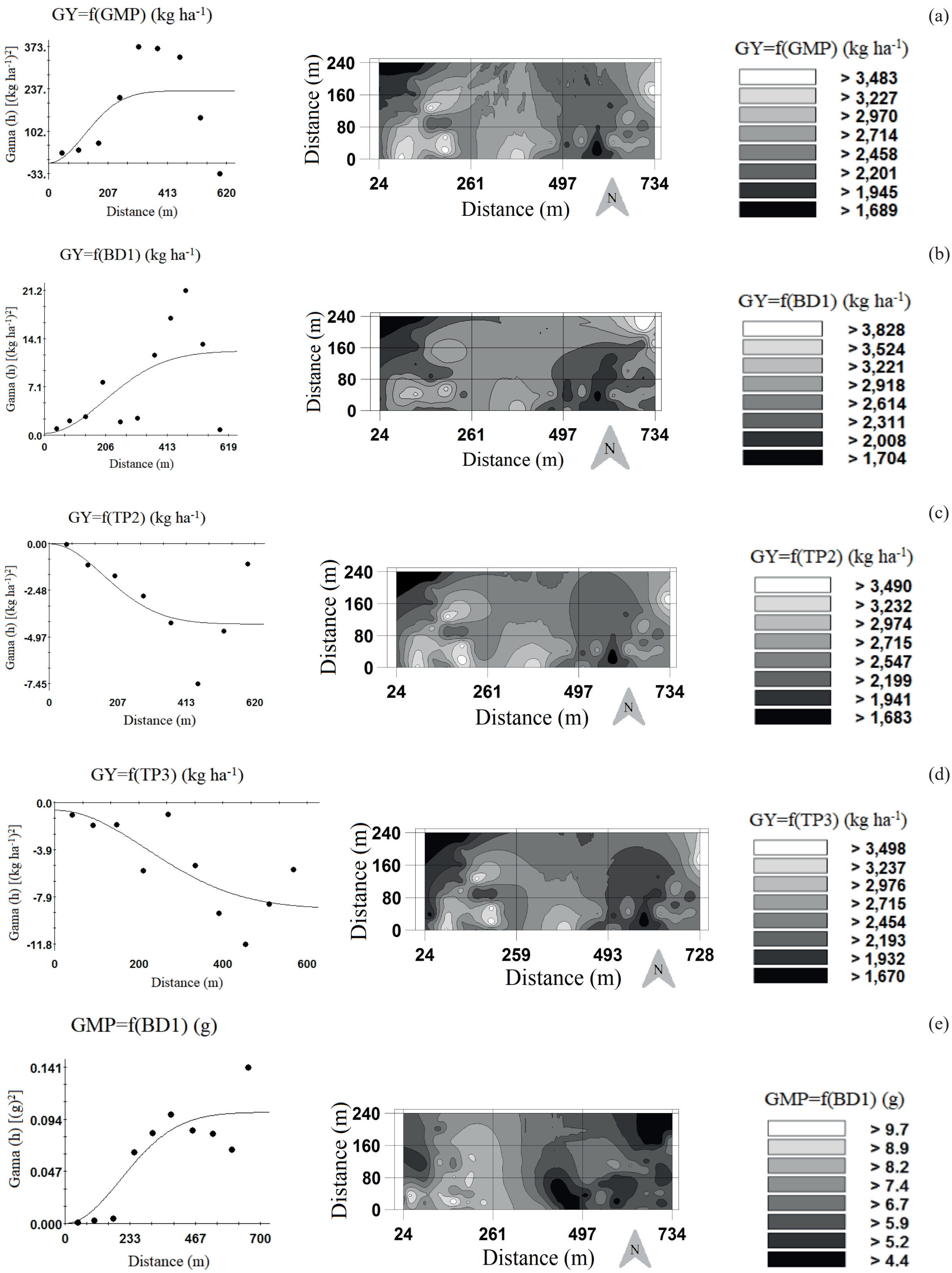

Figure 4. Cross-semivariogram and co-kriging map of soybean grain yield (GY), as a function of grain mass per plant (GMP; a), soil bulk density determined by the ring method (BD1; b), total porosity TP2 [(1-BD1/PD1); c] and TP3 [(1-BD1/PD3); d] and GMP of soybean due to BD1 (e), sampled at the 0.00-0.10 m and 0.10-0.20 m layers (respectively indicated by even an odd numbers) of an Oxisol.

indicated that, in the clearer halos, in which the TP3 values increased, there was a reduction in soybean grain yield and vice-versa. The calculated r^2 indicated that 60.6 % of the spatial variability of grain yield could be explained by the spatial variability of TP3. Thus, where the TP3 values ranged between 0.430 m^3 m^{-3} and 0.460 m^3 m^{-3}, the soybean grain yield ranged between 1,670 kg ha^{-1} and 2,454. On the other hand, in regions where TP3 presented values between 0.390 m^3 m^{-3} and 0.420 m^3 m^{-3}, the grain yield was between 2,623 kg ha^{-1} and 3,069 kg ha^{-1}. Probably, the decrease of the total soil porosity due to the increase of its soil bulk density contributed to the increase of water retention owing to the influence of the pore size distribution, both improving the efficiency of the water absorption by the soybean and providing a better soil-root contact. A similar behavior was observed by Beutler & Centurion (2003), when evaluating the yield of soybean in an Oxisol, who verified that the lowest yields were obtained in extremely loose soil, confirming what was observed in this study.

The values for the spatial dependence reach (A_o) (Table 3) in the cross-semivariograms found in the present study were 535.0 m for GY = f(TP3), 490.0 m for GY = f(BD1), 486.0 m for GMP = f(BD1), 401.0 m for GY = f(TP2) and 308.3 m for GY = f(GMP). The reach is important for the interpretation of semivariograms by indicating the distance up to where the sample points are correlated, i.e., the points located in an area whose radius is the range are more similar to each other than those separated by greater distances. The reach depends on the size of the sampled area and on the observation scale, being as large as the interval between measurements (Trangmar et al. 1985).

CONCLUSIONS

1. The total soil porosity (TP2) calculated by the soil bulk density determined by the volumetric ring method (BD2) and the particle density determined by the volumetric flask method (PD2) were the most promising indicators of grain yield;
2. The paraffin-coated clod method overestimated the soil bulk density values at both soil layers (0.00-0.10 m and 0.10-0.20 m);
3. The soil attributes showed a low data variability, except for the total soil porosity (TP1 and TP3) (average variability), while the plant attributes showed low (number of grains per pod and mass of 100 grains), medium (plant population, plant height and grain yield) and high (grain mass per plant and number of pods per plant) variability;
4. The studied attributes did not randomly range, because they followed well-defined spatial patterns;
5. The co-krigings found were of high agricultural importance. From the soil bulk density (BD1), total porosity (TP2 and TP3) and grain mass per plant, it was possible to estimate the spatial variability for grain yield.

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