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Restrictions of the common bean productivity in direct seeding system in the brazilian cerrado

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ABSTRACT: The productivity of common bean in Brazil is considered low when compared to the productive potential of the cultivars used. Fertility conditions due to surface fertilization, and soil compaction in areas that adopt a direct seeding system, mainly irrigated, may be some of the factors limiting bean development. Thus, the objective of this study was to determine the spatial distribution and correlation of physical and chemical soil properties with the yield of irrigated beans in a direct seeding system. The study was conducted in an Typic Acrustox located in the municipality of Selvíria (MS), in the Cerrado biome. To determine properties of the soil and plant, a sampling grid was installed containing 121 points distributed over an area of 1815 m^2. There was variation in soil fertility, limiting bean yield. In places with higher values of pH, sum of bases, V% and organic matter yields were found to be the highest. In places with pH and V% below 4.6 and 34.11%, respectively, yields below 2900 kg ha^{-1} were observed. There were places where penetration resistance (PR) of the soil was less than 2 MPa, but also places with RP reaching values of 4.67 MPa, however, without correlation to bean yield.

Keywords: *Phaseolus vulgaris* L., agricultural sustainability, principal component analysis, soil fertility, soil compaction.

Restrições à produtividade do feijoeiro comum em sistema de semeadura direta no cerrado brasileiro

RESUMO: A produtividade do feijoeiro comum no Brasil é considerada baixa, quando comparada ao potencial produtivo das cultivares utilizadas. As condições de fertilidade, devido às adubações superficiais, e a compactação do solo em áreas que adotam o sistema de semeadura direta, principalmente irrigadas, podem ser alguns dos fatores que limitam o desenvolvimento do feijoeiro. Com isso, o objetivo deste estudo foi determinar a distribuição espacial e a correlação das propriedades físicas e químicas do solo com a produtividade do feijão irrigado em sistema de semeadura direta. O estudo foi realizado em um Latossolo Vermelho distroférrico localizado no município de Selvíria (MS), bioma Cerrado. Para a determinação das propriedades do solo e da planta, foi instalada uma malha de amostragem com 121 pontos distribuídos em uma área de 1815 m^2. Houve variação na fertilidade do solo, limitando o rendimento de feijão. Em locais com maiores valores de pH, a soma das bases, V% e matéria orgânica foram verificadas as maiores produtividades. Em locais com pH e V% abaixo de 4,6 e 34,11%, respectivamente, foram observados rendimentos abaixo de 2900 kg ha^{-1}. O solo apresentou locais com resistência à penetração (PR) inferiores a 2 MPa, mas também locais com RP atingindo valores de 4,67 MPa, entretanto, sem correlação com a produtividade do feijão.

Palavras-chave: *Phaseolus vulgaris* L., sustentabilidade agrícola, análise de componentes principais, fertilidade do solo, compactação do solo.

1. INTRODUCTION

The bean (*Phaseolus vulgaris* L.) is the most important food in the basic diet of Brazilians, due to its high protein content. In Brazil 3.4 million hectares were cultivated in the 2014/2015 harvest, with production recorded at 3.1 million metric tons and an average grain yield of 1,025 kg ha^{-1} (CONAB, 2016), which is considered low, since the production potential of bean cultivars is greater than 3,400 kg ha^{-1} (CONAB, 2013).

However, in the Midwest, third crop beans reached an average yield of 2,672 kg ha^{-1} in 2014/15 (CONAB, 2016). Among the essential techniques to ensure the highest yield in this period are the use of irrigation and cultivation in a direct seeding system (DSS), also associated with a lower incidence of pests and diseases in this period.

One of the limitations in the potential yield of beans is the soil fertility condition, which is normally less than ideal (DALCHIAVON et al., 2013). This is due to the fact that direct seeding brings about changes in the vertical and horizontal variability of soils, owing to fertilization of the surface and sowing line, especially for elements of lower mobility such as phosphorus (WILSON et al., 2016). Such vertical variation can also be due to the application of correctives to the surface, as reported by Crusciol et al. (2014), who found an acidity correction "front" at a depth proportional to the surface liming dosage and time.

According Valadão et al. (2015) and Wilson et al. (2016), the application of fertilizer in the line or on the surface also alters the rate of decomposition of organic material left on the surface, as well as the nutrient release, further contributing to the formation of a gradient in chemical properties beginning at the soil surface.

Another limiting factor to bean yield in DSS, especially in irrigated areas, may be surface soil compaction. According to Collares et al. (2008), bean yield was reduced by 17% in a no-till area with additional compaction when compared to a no-till area of 6 years without additional compaction. The authors observed that the growth of the root system was limited at the soil surface due to the adverse physical conditions, limiting the growth of shoots and productivity.

Due to the greater heterogeneity in the chemical and physical properties of soils submitted to DSS, the mapping of these properties, as well as crop yield, becomes a fundamental tool for maintaining agricultural production systems. Allowing technicians and producers to create management zones, identify sites of low yield, fertility, and compaction, and manage and correct soil limiting factors locally generates economic as well as environmental benefits.

Given the above, the objective of this study was to determine the spatial distribution and correlation of physical and chemical properties of soil with bean yield in direct seeding, using, jointly, the techniques of principal component analysis and geostatistics, seeking a greater understanding of soil/plant relationships.

2. MATERIAL AND METHODS

The experiment was conducted at the Farm of Teaching, Research and Extension at the Faculty of Engineering of Ilha Solteira - UNESP, located in Selvíria, eastern Mato Grosso do Sul state, Brazil, at the geographical coordinates 20°22'02"S and 51º25'08"W, biome Cerrado region, with an average altitude of 357 m. The climate of the region is of the Aw hot and humid tropical type, according to the Köppen classification, with two well defined seasons (rain in summer and dry in winter). The soil is classified as "Latossolo Vermelho distroférrico típico muito argiloso, A moderado, hiperdistrófico, álico, caulinítico, férrico, muito profundo, moderadamente ácido" (EMBRAPA, 2013), being equivalent to Typic Acrustox - Soil Survey Staff, with homogeneous slope of 0.055 m m^{-1}, and values of 620 g kg^{-1} clay, 100 g kg^{-1} silt, 60 g kg^{-1} of coarse sand and 220 g kg^{-1} sand in the 0-0.20 m layer.

The area where the study was conducted was cleared in 1978, when the trees of economic interest were removed and subsequently the native vegetation was burned. The area was used as pasture (*Brachiaria spp.*) until 1994. Since then a succession of annual crops has been cultivated in the area: corn (*Zea mays* L.) and soybean (*Glycine max* L.) in summer and irrigated beans (*Phaseolus vulgaris* L.) in winter. In 1998 and 2003, the soil was treated with lime and crop residues to a depth of 0.30 m, followed by leveling of the ground. For the past 12 years, the area has been cultivated in a direct seeding system (DSS), preserving the succession scheme of corn/beans or soybeans/beans.

The sowing of beans was done on April 10, 2012, using the cultivar IAC Alvorada, at spacing of 0.45 m, resulting in a population density of 16 plants per meter. Fertilization at the time of sowing used 250 kg ha^{-1} of 08-26-16 fertilizer. Topdressing was done 20 days after seedling emergence, with application of 200 kg ha^{-1} of a 20-00-20 formulation. The crop management practices were applied homogeneously throughout the experimental area.

To map the chemical and physical soil properties a rectangular sampling grid was constructed, containing 11 rows and columns. The spacing was 5 m in the direction of the line and 3 m between the lines, totaling 121 points distributed over an area of 1,815 m^2 (Figure 1).

At each point of the grid, using a Dutch auger, a sample was taken at a depth of 0-0.20 m for determination of pH, P, K, Ca and Mg, sum of bases (SB), exchangeable acidity (Al), potential acidity (H+Al), cation exchange capacity at pH 7 (T), base saturation (V%), aluminum saturation (m%), need for liming (NL) and the content of organic matter (OM). Analyses were performed according to the methodology described by van Raij et al. (2001).

To determine soil penetration resistance (PR) an impact penetrometer was used. At each sampling point PR was determined at a depth of 0-0.20 m. Concomitantly, samples of deformed structure were collected with a Dutch auger in the same layer and position for gravimetric determination of soil moisture (GM), the GM was quantified by the method proposed by EMBRAPA (2011). Subsequently, the PR was calculated according to the equation:

$$PR = \left\{5.6 + 6.89\left[\frac{N}{(A-B)}10\right]\right\}0.0981$$

where in PR is the soil penetration resistance (MPa), N the number of impacts with the hammer performed to obtain reading, and B and A are the readings before and after the impacts (cm).

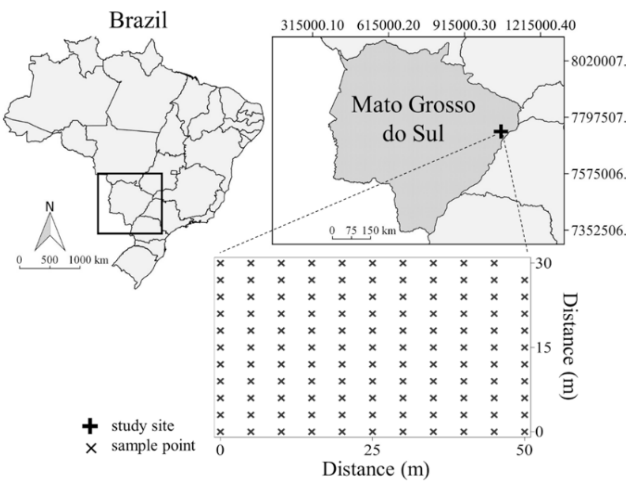

Figure 1. Study site location and the illustration of the sampling grid with 120 georreferenced points.

Figura 1. Local do estudo e ilustração da malha amostral contento 120 pontos georreferenciados.

Grain yield (GY) was determined with plants collected in the vicinity of each sampling point. The useful collection area was 3.24 m^2 (1.8 x 1.8 m) with allocation of the sampling point positioned at its center, which always contained four lines of beans. Subsequently yield was extrapolated to the area of one hectare, considering moisture of 13%.

Initially a descriptive data analysis was done by calculating the mean, median, range, standard deviation, variance, coefficient of variation, skewness and kurtosis. Normal distribution was checked by Shapiro-Wilk test.

The chemical and physical properties of the soil were standardized to present mean 0 and variance 1 and then subjected to principal component analysis (PCA) to identify the set of properties that explain most of the variability in the area. The selection of the number of principal components was based on the analysis criterion of the quality of approximation of the correlation matrix, known as the Kaiser or Latent Root method, using components associated with eigenvalues greater than 1 (SILVA et al., 2010).

The GY data and PC scores obtained from the linear combination of the original variables were then submitted to geostatistical analysis, which consisted of modeling of the semivariograms. Classification of the evaluator of spatial dependence (ESD) was based on the ratio of the nugget effect to the level (C/C+Co), according to which ESD ≤ 25% indicates weakly dependent spatial variable; 25% <ESD≤ 75% indicates moderately dependent spatial variable; and ESD> 75% indicates strongly dependent spatial variable (MONTANARI et al., 2010). The final criterion of the semivariogram decision model and the number of neighbors used in predicting the best fit was obtained by cross-validation, or adjustments with the slope closest to 1 and the linear coefficient closest to 0. Once the semivariograms were adjusted, there was ordinary kriging of the data and the composition of the maps. In the end, the obtaining of semivariogram crossed between the PCs and the GY was tested.

3. RESULTS

3.1. Descriptive analysis

According to the classification proposed by Pimentel-Gomes; Garcia (2002), GY had a mean variability with a coefficient of variation (CV) of 13.63% (Table 1). The average yield was 2644.71 kg ha^{-1}, similar to the average for the third bean crop in the Midwest region, which was 2543 kg ha^{-1} in 2015 (CONAB, 2016). According to Montanari et al. (2010) bean productivity in Mato Grosso do Sul may be more than 3000 kg ha^{-1} when subjected to an appropriate technological level, which can be confirmed by the amplitude of the data (Table 1). It was observed that GY reached 3564 kg ha^{-1} in some locations. However, yields below the average for the Midwest were observed, reaching the minimum of 1744 kg ha^{-1}.

The Acrustox presented a mean PR of 2.79 MPa with a high coefficient of variation, resulting in an amplitude in the PR of 1.54 to 4.67 MPa. To determine PR in the field with an impact penetrometer, it is recommended that the soil has two thirds of its micropores filled with water, that is, is of a friable soil condition, which was addressed by the average GM of 0.23 kg kg^{-1} (Table 1). Another factor that should be considered when using an impact penetrometer is that soil moisture should be constant, because of its influence on PR values, i.e., the higher the soil moisture the lower your PR will be and vice versa. Therefore, the soil moisture condition was ideal for determining the PR in the field, which can be confirmed by the low CV of 4.34%.

To characterize the soil fertility we used the criteria established by van Raij et al. (1996) in lows for pH and V%; mediums for P, K, Mg; and high for Ca. Due to the low pH of the soil, reflecting a high active soil acidity, content of Al and H+Al was also determined and found to be 7.54 and 43.35 $mmol_c$ dm^{-3}, respectively, resulting in an aluminum saturation of 27.52%.

Despite the levels of K and Mg having been classified as medium and the Ca content classified as high, the BS showed an average value of 21.24 $mmol_c$ dm^{-3}, resulting in a low average value for V%.

It was found that the saturation values for Ca, Mg and K were 17.05%, 11.43% and 4.36%, respectively. Therefore, the saturation by Ca and Mg was less than optimal. Thus, due to the low pH, V% and Ca and Mg saturation an average NL value of 3.19 Mg/ha was found.

The coefficient of variation was classified as low for the pH; medium for H+Al, T and MO; high for V%; and very high for P, K, Ca, Mg, Al, BS and m% (Table 1). Because of the CV a high amplitude in the soil chemical properties was also observed.

The Shapiro-Wilk test confirmed the normal distribution of the GY and GM. Although the test was significant for most properties, indicating deviations from normality, it was considered that the data presented a distribution tending towards normality. This can be explained by the low coefficients of kurtosis and skewness, and the proximity between the mean and median of these properties (Table 1).

3.2. Multivariate analysis

According to criteria established in the materials and methods, soil chemical and physical properties were subjected to principal component analysis (PCA). With this, three components were extracted that explained 76.53% of the total variability in the data (Table 2). It was found that all the properties of plant and soil showed eigenvectors of weight greater than or equal to 0.50, being considered highly significant (SILVA et al., 2015) in some of the three PCs, with this all of the soil properties were maintained in the analysis.

The first principal component (PC1) was responsible for explaining 50.55% of the total variance, being positively correlated with the properties K, Ca, Mg, SB, V%, pH and OM and negatively with the properties Al, m% and NC.

The second principal component (PC2) explained 18.55% of the variance in the data, correlating positively with the properties P, H+Al, T and NC, and showing positive correlation between P, potential acidity, T and NC.

The third principal component (PC3), here called the physical condition of the soil, explained only 7.43% of the total variance, correlating positively with PR and negatively with GM. It was observed that the soil physical properties explained little of the total variability of the data in the multivariate analysis.

3.3. Geostatistical analysis

The geostatistical analysis was performed in order to map the GY and PC scores of the multivariate analysis. Thus, spatial dependence was observed only for PC1, PC2 and GY, adjusting the spherical and exponential models (Table 3).

It was observed that the PC3 did not present spatial dependence, its variability being random in the area. Therefore,

Table 1. Descriptive analysis of some physical and chemical properties of an Typic Acrustox cultivated with irrigated bean in direct seeding system.
Tabela 1. Análise descritiva de algumas propriedades físicas e químicas do Latossolo Vermelho distroférrico cultivado com feijão irrigado em sistema de semeadura direta.

Variable[1]	Value					Coefficient[3]			Prob.[4]	
	Mean	Median	Min.	Max.	SD[2]	CV (%)	Kurtosis	Asymmetry	Pr < W	FD
Plant properties										
GY	2644.71	2612	1744	3565	360.26	13.62	-0.03	0.23	0.745	NO
Soil physics properties										
PR	2.79	2.73	1.54	4.67	0.70	25.08	-0.30	0.48	0.016	TN
GM	0.23	0.23	0.20	0.26	0.01	4.34	-0.38	-0.16	0.695	NO
Soil chemical properties										
pH	4.43	4.40	4.00	5.00	0.22	4.96	-0.30	0.42	0.002	TN
P	23.15	21.00	8.00	54.00	11.25	48.59	0.13	0.89	0.000	TN
K	2.82	2.70	0.90	5.20	1.04	36.87	-0.54	0.35	0.032	TN
Ca	11.02	11.00	4.00	19.00	4.10	37.20	-1.00	0.36	0.000	TN
Mg	7.39	7.00	3.00	14.00	2.61	35.31	-0.65	0.45	0.001	TN
Al	7.54	7.00	1.00	16.00	3.64	48.27	-0.91	0.23	0.004	TN
H+Al	43.35	42.00	31.00	58.00	6.58	15.17	-0.61	0.31	0.006	TN
SB	21.24	20.10	8.70	36.20	7.21	33.94	-0.94	0.39	0.001	TN
T	64.60	63.70	46.70	93.60	9.13	14.13	0.16	0.55	0.002	TN
V%	32.46	32.00	15.00	49.00	8.53	26.27	-0.86	0.12	0.036	TN
m%	27.52	25.00	3.00	65.00	14.54	52.83	-0.78	0.30	0.006	TN
NL	3.19	3.15	1.75	4.63	0.71	22.25	-0.86	0.07	0.065	TN
OM	22.45	23.00	17.00	28.00	2.82	12.56	-0.75	0.02	0.013	TN

[1] GY: Bean grain yield (kg ha^{-1}); PR: Soil penetration resistance (MPa); GM: Gravimetric moisture (kg kg^{-1}); P: Soil phosphorus (mg dm^{-3}); K: Soil potassium ($mmol_c$ dm^{-3}); Ca: Soil calcium ($mmol_c$ dm^{-3}); Mg: Soil magnesium ($mmol_c$ dm^{-3}); SB: Sum of bases ($mmol_c$ dm^{-3}); Al: Soil aluminum ($mmol_c$ dm^{-3}); H+Al: Hydrogen + aluminum soil ($mmol_c$ dm^{-3}); T: Potencial cation exchange capacity ($mmol_c$ dm^{-3}); pH: Hydrogen potential; V%: Base saturation; m%: Aluminum saturation; NL: Need liming (Mg ha^{-1}); OM: Soil organic matter (g dm^{-3}). [2] SD: Standard deviation. [3] CV: Coefficient of variation. [4] Prob: Probability referring to the normality of Shapiro-Wilk test; FD: Distribution of frequencies, NO = normal and TN = tending to normal.

Table 2. Summary of the principal components obtained in the multivariate analysis of some physical and chemical properties of an Typic Acrustox cultivated with irrigated bean in direct seeding system.
Tabela 2. Sumário dos componentes principais obtidos na análise multivariada de algumas propriedades físicas e químicas do Latossolo Vermelho distroférrico cultivado com feijão irrigado em sistema de semeadura direta.

Principal component[1]	PC1	PC2	PC3
Eigenvalue	7.58	2.78	1.11
Explained variance (%)	50.55	18.55	7.43
Variable	**Correlation[2]**		
PR	-0.132	-0.109	0.652*
GM	0.037	-0.058	-0.765*
P	0.193	0.534*	0.153
K	0.631*	0.296	0.086
Ca	0.905*	0.272	0.076
Mg	0.902*	0.246	0.017
SB	0.933*	0.287	0.062
Al	-0.849*	0.316	0.078
H+Al	-0.388	0.880*	-0.079
T	0.461	0.863*	-0.008
pH	0.856*	-0.325	-0.061
V%	0.968*	-0.098	0.070
m%	-0.965*	0.101	0.038
NL	-0.714*	0.641*	-0.094
OM	0.658*	0.155	-0.181

[1] Correlations considered in the interpretation of the principal component. [2] PR: Soil penetration resistance; GM: Gravimetric moisture; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; SB: Sum of bases; Al: Aluminum; H+Al: Hydrogen + aluminum; T: Potential cation exchange capacity; V%: Base saturation; m%: Aluminum saturation; NL: Need liming; OM: Organic matter.

the variability of the PR in the area was random, not interfering with the GY. According to Moraes et al. (2014), PR values on the order of 3.5 MPa are accepted in no-till because the roots grow by continuous channels left by the soil fauna and the decomposed root system, as well as by the greater stability of aggregates due to increased release of root exudates and biological activity.

The semivariance stabilizes when the threshold is reached, thus defining the range, which for PC1, PC2 and GY was 37.4, 9.54 and 31.95 m, respectively. It was observed that PC1 and GY showed the highest ranges, indicating greater continuity of properties in space. The evaluator of spatial dependence (ESD) was rated high for PC2 and GY, and moderate for PC1.

Through cross-validation it was possible to verify the quality of the semivariogram adjustments (Table 3). PC1, PC2 and GY showed satisfactory kriging, since the angular coefficient (b) for the linear model between the observed and estimated values was greater than 0.90. The linear coefficients (a) were close to zero, except for GY.

The spatial correlation between the PCs and GY was tested by the formation of a cross-semivariogram, which was achieved by PC1 versus GY. With this, it was found that the spatial variability of GY directly correlated with the spatial distribution of PC1. The cross semivariogram fit the gaussian model with range of 8.67 m and high spatial dependence.

3.4. Kriging maps

Through models adjusted to simple semivariograms, PC1, PC2 and GY data were interpolated by ordinary kriging (Figure 2). By the distribution map for PC1 it was observed that scores below -0.2 corresponded to 29.16% of the area, indicating higher Al content in the soil, m% and NL. In this interval there was variation in Al content of 8 to 16 $mmol_c$ dm^{-3} and in m% of 21.86 to 64.78%, resulting in variation of NL from 3.20 to 4.63 Mg/ha.

Table 3. Parameters of simple and crossed semivariograms adjusted for the principal components obtained in the multivariate analysis and some physical and chemical properties of an Typic Acrustox cultivated with irrigated bean in no-till system.
Tabela 3. Parâmetros dos semivariogramas simples e cruzado ajustados para os componentes principais obtidos na análise multivariada das propriedades físicas e químicas do Latossolo Vermelho distroférrico cultivado com feijão irrigado em sistema de semeadura direta.

Variable [1]	Parameters adjustment [2]										
	Model	C_0	C_0+C	A (m)	R^2	SSR	ESD[3]		Cross-validation		
							%	Class	a	b	R^2
Simple semivariogram											
PC1	Sph	0.48	0.96	37.4	0.97	6.22×10^{-3}	50	MO	0.00	1.04	0.52
PC2	Exp	0.12	0.98	9.54	0.87	1.55×10^{-2}	88	HI	0.01	0.94	0.44
PC3	Epp	0.92	0.92	-	-	-	-	-	-	-	-
GY	Exp	40600	145600	31.95	0.96	2.84×10^{-8}	72	HI	77.90	0.96	0.62
Crossed semivariogram											
GY = f(PC1)	Gau	0.10	90.90	8.67	0.82	838	99	HI	0.02	0.58	0.42

[1] PC: Principal component; GY: Bean grain yield. [2] Sph: Spherical model; Gau: Gaussian model; Exp: Exponential model; Epp: Nugget effect; C_0, C_0+C and A they are respectively: nugget effect, sill and range; SSR: Sum of the squared residuals. [3] ESD: Evaluator of spatial dependence, MO: Moderate spatial dependence and HI: High spatial dependence.

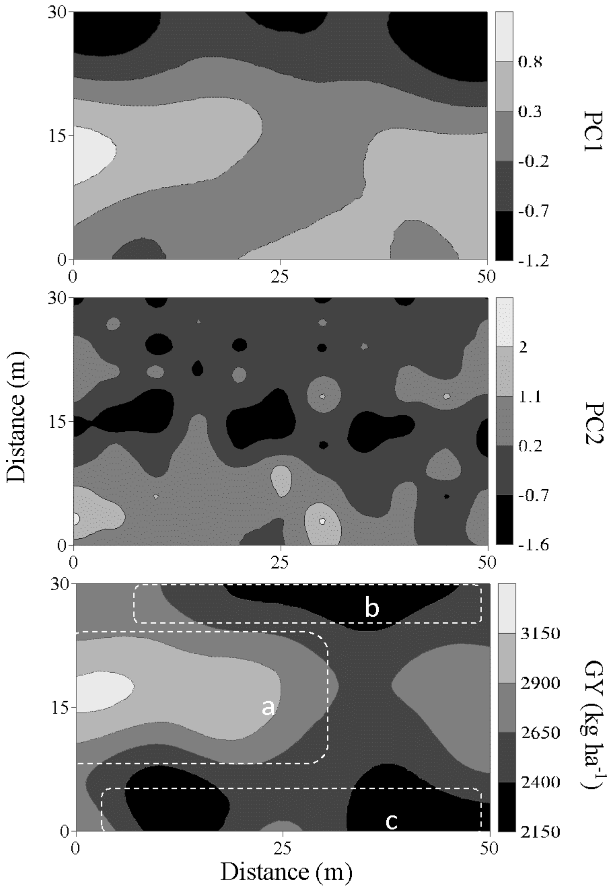

Figure 2. Maps of the principal components 1 and 2 of physical and chemical properties of an Typic Acrustox and bean grain yield.
Figura 2. Mapas dos componentes principais 1 e 2 das propriedades físicas e químicas do Latossolo Vermelho distroférrico e rendimento de grãos de feijão.

The PC1 map also showed that 31.54% of the area had scores greater than or equal to 0.3, representing the area with a better fertility condition. In this region K values varied between 3.30 to 5.20 $mmol_c\ dm^{-3}$; Ca between 12 to 19 $mmol_c\ dm^{-3}$; Mg between 10 and 14 $mmol_c\ dm^{-3}$; BS between 23.20 to 36.20 $mmol_c\ dm^{-3}$; V% from 34.11 to 48.79%; and pH between 4.2 to 4.6.

The GY kriging map showed that 57.06% of the area had yields below 2650 kg ha^{-1}; 27.62% from 2650 to 2900 kg ha^{-1}; and only 15.28% above 2900 kg ha^{-1}.

4. DISCUSSION

It is known that the direct seeding system (DSS) adds heterogeneity to soil physical properties when compared to conventional cultivation systems, mainly due to the absence of soil disturbance. The results obtained in this study are similar to those to Cavalcante et al. (2011) and Montanari et al. (2010). These authors found in DSS areas variations in PR of 0.54 to 5.40 MPa, and postulated that such amplitude was a result of the absence of soil disturbance, heavy machine traffic, deposition of fertilizers in the planting row and use of fertilizer shanks in different places.

Regarding the state of soil compaction, Montanari et al. (2013) concluded that PR values ranging from 0.54 to 5.05 MPa for the same soil did not limit the yield of the BRS Pérola bean cultivar. As already noted, PR values were found up to 4.67 MPa, which may have limited the GY, explaining the values below 2000 kg ha^{-1}.

Demonstrating heterogeneity regarding soil fertility, as well as PR, the variability of the chemical properties may have limited the GY. With respect to soil acidity, Dalchiavon et al. (2011) describes in his studies that the bean achieves maximum yield with pH values > 5.5, attributing these results to the increase in saturation by Ca, Mg and K in the soil CEC.

It is known that one of the main problems for crop development is the presence of Al in toxic amounts in the soil (SPERA et al., 2014). In this study, the average concentration of Al is considered restrictive to beans. However, the addition of straw to the soil surface provided by DSS favors a reduction in Al toxicity, mainly due to the action of organic binders and hydrolysis, resulting in complexation of this element (ALLEONI et al., 2010; NOLLA et al., 2007).

According Bissani et al. (2008), the optimal level of V% for beans is around 70%. Dalchiavon et al. (2011), studying beans in a clayey, dystroferric Red Latosol under DSS, suggested that for a good yield, the appropriate levels of Ca and Mg should be close to 53 and 18 $mmol_c\ dm^{-3}$, respectively.

The potential acidity is a component of T, which is determined with pH equal to 7. As the pH of the soil was considered low and the charges of Oxisols are of variable origin or pH dependent, it appears that a large part of the negative charges in the soil are occupied by H+ ions, representing non-exchangeable soil acidity, as well as exchangeable acidity (Al).

With the correction of pH by liming (NL) there was an increase in the effective soil cation exchange capacity (t) due to the dissociation process of OH^- radicals and neutralization of exchangeable acidity (Al), which explains the positive correlation between the potential acidity, T and NC. The analysis involving T and potential acidity should be viewed with caution, since T is, in the final analysis, the sum of K, Ca, Mg and H+Al and since soils with the same T value will present different H+Al values depending on the pH or quantity of bases present.

The positive correlation of P with H+Al and NC in CP2 can only be explained by fertilization, i.e., in the sites with the greater potential acidity and NL greater quantities of P were applied via fertilizers. That soils have varying charges when they present high concentrations of phosphate ions in solution (H2PO4-), from soluble sources suggests that much of this P can be quickly retained by the surfaces of oxydroxides or by the protonation of amines and carboxylic and phenolic groups derived from organic matter (ASSMANN et al., 2007).

Based on the cross semivariogram established between GY and the PC1 (Table 3), it can be said that soil fertility condition was one of the factors that influenced the variability of GY. This can be confirmed from the GY distribution map, in which region "a" presented the highest yields and these coincided with the highest scores on the PC1 map. In region "b" of the GY map the lowest yields were observed, and these coincided with the lowest scores of PC1.

However, there was a region "c" which had yields of less than 2650 kg ha^{-1} and did not coincide with poor soil fertility conditions, being designated as a region of uncertainty, i.e., in which the low GY cannot be explained by low soil fertility.

As a function of areas "a" and "b" of the GY map it can be inferred that K, Ca and Mg levels less than 3.30, 12 and 10 $mmol_c$ dm^{-3}, respectively, as well as V% and pH values below 34.11% and 4.6, respectively, as well as Al and m% values higher than 4 $mmol_c$ dm^{-3} and 16%, respectively, could limit the yield of irrigated beans.

However, according to the Grain and Fiber Center of the Agronomic Institute of Campinas the cultivar IAC Alvorada has genetic yield potential of 4351 kg ha^{-1}, while the highest GY value observed in the area was 3565 kg ha^{-1} with a V% of 49% and pH 5. Thus, higher yields could be obtained in the area as a function of NL, which would result in higher pH and V%.

With respect to PC2, it was found by the map that 33% of the area had scores above 0.2. In this region P content varied from 22 to 54 mg dm^{-3}. In the 67% where the scores were less than 0.2 the P values ranged from 8 to 21 mg dm^{-3}. There was no spatial correlation between PC2 and GY, and the P variation between these limits did not limit GY.

The multivariate analysis associated with geostatistics allowed summary, mapping and interpretation of the physical conditions and soil fertility. Correlating them to the spatial distribution of yield, and jointly identifying the limiting factors to GY, defines management zones for soil fertility. This highlights the importance of precision agriculture for the management of soil and crops.

5. CONCLUSIONS

Bean productivity and the principal components related to soil fertility showed moderate to high spatial dependence, with greater spatial continuity observed for the first principal component and the yield. There was a positive correlation between the spatial variability of grain yield and the first principal component. The highest yields were observed in conditions of higher base saturation and pH. Soil penetration resistance values of up to 4.67 MPa were not restrictive to bean yield.

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