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SPATIAL VARIABILITY OF IRRIGATED COMMON BEAN YIELD CORRELATED WITH THE FERTILITY OF A SANDY SOIL

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KEYWORDS

precision agriculture, geostatistics, soil management, irrigation, (*Phaseolus vulgaris* L.).

ABSTRACT

The common bean is widely cultivated in Brazil. In the 2016–2017 growing season, an experiment was carried out in a Typic Quartzipsamment (or Neossolo Quartzarênico) soil in the municipality of Cassilândia, MS, Brazil, with the aim of characterizing specific aspects of soil management, using a linear and spatial correlation between the irrigated yield of common beans and the chemical properties of the soil. Soil samples were collected from layers at depths 0.00–0.10 and 0.10–0.20 m, within a grid of 117 georeferenced points. A data analysis was carried out using statistical and geostatistical techniques. A multiple regression analysis showed that about 31% of the grain yield variability of the irrigated common bean crop could be attributed to the spatial variability in the chemical properties of the soil. These properties have a spatial dependence that is classified as moderate and strong, with a predominantly Gaussian-type semivariogram model. Soil properties such as $pH_{(1)}$, $pH_{(2)}$, $S_{(2)}$ and $V\%_{(2)}$ can be considered potential indicators of the grain yield of an irrigated common bean crop when cultivated in a sandy soil under a no-tillage system.

INTRODUCTION

The common bean (*Phaseolus vulgaris* L.) is widely cultivated in Brazil, and is an essential and nutritious component of the diet of the Latin-American population, mainly due to its high content of proteins and minerals. In the 2019–2020 harvest, the total area of common bean cultivation was 2.909 million hectares, with a production of 3.022 million tons, which resulted in an average grain yield (GY) of 1,039 kg ha^{-1} (Conab, 2020). With the advent of precision agriculture in Brazil, the geostatistical study of the components of crop production in relation to yield has intensified (Oliveira et al., 2018, Tavanti et al., 2020a, b).

Fertilizers and correctives can be applied at varying rates in conjunction with geostatistics. This is one of the tools of precision agriculture that allows for the study of the spatial variability of soil properties, and can indicate alternative approaches to soil management in order to minimize the effect on crop yield of the variability in the soil properties. Thus, after analyzing the spatial variability of soil properties of agricultural interest, it is possible to create maps of spatial variability without trend and with minimum variance using kriging interpolation (Lima et al., 2017a).

The hypothesis of this work is that it is possible to produce common beans in a sustainable way in sandy soils, when combined with the study of specific soil management zones. In this context, the objective of this study was to characterize specific areas of soil management, using the linear and spatial correlation between the irrigated yield of common beans and the chemical properties of a Brazilian Cerrado sandy soil, in order to identify the properties that are most closely related to the increase in yield.

MATERIAL AND METHODS

Our study was carried out in an area with a center-pivot irrigation system, located at Flor Jardim Farm in Cassilândia, Mato Grosso do Sul State, Brazil, at geographic coordinates 356381.383 m W; 7893667.280 m S (UTM) (Figure 1). The regional climate, according to the Köppen classification, is Aw, i.e. characterized as tropical, with hot summers and a tendency toward high rainfall

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levels, and dry winters, with a dry season between May and September. The mean annual temperature is 24.2ºC, with a minimum of 16.4ºC (July) and a maximum of 28.6ºC (January), and a mean annual rainfall of 1,500 mm.

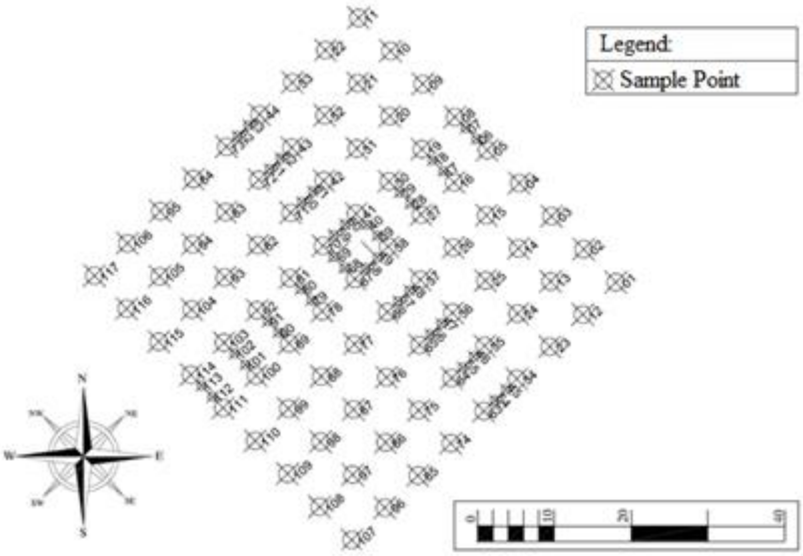

FIGURE 1. Detail of the sampling grid used at Flor Jardim Farm in Cassilândia, Mato Grosso do Sul State, Brazil, for cultivating common beans.

The experimental grids were installed in a deep sandy soil, classified as Neossolo Quartzarênico Órtico latossólico - RQo (Embrapa, 2018) or Typic Quartzipsamment. The results of the physical and chemical analyses are shown in Table 1.

TABLE 1. Physical and chemical properties[1] of Brazilian Cerrado sandy soil used for the cultivation of common beans.

Depth	Particle size			Chemical properties											
	Sand	Silt	Clay	pH	P	OM	K^+	Ca^{2+}	Mg^{2+}	H+Al	Al^{3+}	S	CEC	V%	m%
m	-----g kg^{-1} -----				mg dm^{-3}	g dm^{-3}	-------------- $mmol_c$ dm^{-3} --------------							--- % ----	
0.0-0.20	946	11	43	5.4	8	13	0.2	17	8	13	0	25.2	38.2	66	0
0.20-0.40	932	20	48	5.1	12	10	0.5	7	2	15	1	9.5	24.5	39	10

Particle size analysis was performed by the pipette method; pH in 0.01 mol L^{-1} $CaCl_2$; soil:solution ratio (1:2.5). OM: Organic matter, Walkley-Black method. P, K, Ca, Mg and Al were extracted by the resin method. S: Sum of bases (S = Ca + Mg + K). CEC: cationic exchange capacity. V%: soil base saturation. m%: Al^{3+} saturation.

The experiment was conducted under a no-tillage system in an area with a center-pivot irrigation system. The weeds in the experimental area were desiccated with glyphosate herbicide WG (2.0 kg ha^{-1}) at a spray volume of 200 L ha^{-1}. The common bean *cv. Elite* was sown mechanically on July 7th, 2016, in rows 0.45 m apart, with a density of 11 seeds m^{-1} (or 246,914 seeds per hectare). The management of weeds, pests, and diseases was carried out according to the needs and technical recommendations for the crop. Harvesting was performed manually on October 15th, 2016, 95 days after the emergence of plants.

The *x* and *y* directions of the Cartesian coordinate system were defined, and at the end of the phenological cycle of the common bean (October 5th, 2016), the experimental grid was staked out. Each grid consisted of nine transects of 48 × 48 m. These transects were spaced 6.0 m apart, with sample points squared in 6.0 × 6.0 m, containing 81 of them. However, they were also allocated within a larger grid, with a spacing of 2.0 m between points (i.e. a grid with a higher density). This higher-density grid contained 36 points, giving a total of 117 sample points throughout the study area (Figure 1). This type of sampling, using grids with higher density within a larger grid, has also been used in previous studies (Montanari et al., 2013a, b).

The GY was individually determined at each sampling point, which was composed of four rows of plants of length 1.8 m, giving a total area of 3.24 m^2. Grains were cleaned and weighed, and the GY (in kg ha^{-1}) was estimated after the correction of grain weights to 13% of moisture.

At each sampling point, soil samples were collected from the 0.0–0.10 and 0.10–0.20 m layers using a hole-type auger. After collection, samples were air-dried, passed through a sieve with mesh size 2.0 mm, and submitted to chemical analysis in the Soil Fertility Laboratory of the Federal University of Mato Grosso do Sul, in Chapadão do Sul, MS, Brazil. The pH of the soil was determined potentiometrically in a 0.01 mol L^{-1} $CaCl_2$ solution, with a soil:solution ratio of 1:2.5, using a combined calomel reference glass electrode and pH meter. Phosphorus (P) was extracted using an ion-exchange resin and determined using the colorimetric method at a wavelength of 725 nm. Basic cations (Ca^{2+}, Mg^{2+}, and K^{+}) were extracted by ion-exchange resin and determined by atomic absorption spectrophotometry. Exchangeable aluminum (Al^{3+}) was extracted using an ion-exchange resin and determined by titration with 0.025 mol L^{-1} NaOH. The cation exchange capacity (CEC) was estimated by the summation method (CEC = H + Al + Ca + Mg + K). From this data, we also calculated the soil base saturation (V%), soil aluminum saturation (m%), and the amount of limestone needed (LN) to increase the soil base saturation to 70%. All the chemical properties of the soil were determined by adopting the standard procedures recommended by Teixeira et al. (2017).

For all the chemical properties of the soil and the GY of common beans, a descriptive analysis was carried out using RBio statistical software (Bhering, 2017). The average, median, minimum and maximum values, standard deviation, coefficient of variation, kurtosis, and asymmetry were calculated. A frequency distribution analysis was also performed. Thus, a test at 5% of significance was used to test the hypothesis of normality or lognormality of the chemical properties of the soil (x). This statistical test allowed us to test the null hypothesis, which was assumed to be a sample from a population with a normal distribution.

In order to characterize the structure and magnitude of the spatial dependence of the chemical properties of the soil and the GY, semivariogram adjustments and a semivariance estimation were performed to estimate the coefficients of the theoretical model; these coefficients are called the nugget effect (C_0), the sill (C_0+C), and the range (A_0). After the semivariograms were adjusted, the data were interpolated by kriging in order to allow visualization of the spatial distribution patterns of the soil properties using maps. Standard error maps of kriging prediction were generated. These maps refer to the standard deviation of the prediction for any individual point, and are obtained to gather information on the confidence in the interpolated values in the study area. Cross-validation is a tool that is used to evaluate alternative models of simple and crossed semivariograms, which will perform kriging and cokriging, respectively. In this analysis, each point contained within the spatial domain was removed individually, and its value was estimated as if it did not exist. In this way, a graph of estimated versus observed values could be constructed for all points.

RESULTS AND DISCUSSION

The results of this descriptive analysis of the chemical properties of the soil are shown in Table 2. The pH was the only characteristic that had a low value of the coefficient of variation for the two depths sampled, with values of $pH_{(1)}$ 8.7% and $pH_{(2)}$ 6.8%. Dalchiavon et al. (2011) evaluated the spatial variability of the common bean as a function of the chemical properties of a Latossolo Vermelho distroférrico soil with a no-tillage system, and also observed a low coefficient of variation (7.3%) for the soil pH at a depth of 0.0–0.20 m.

TABLE 2. Initial descriptive statistics of the yield of common beans and the main chemical and physical properties of a Brazilian Cerrado sandy soil, Cassilândia, MS, Brazil.

Properties [(a)]	Average	Minimum	Maximum	Standard deviation	Coefficient of variation	Kurtosis	Asymmetry	Pr>F	FD [(b)]
GY	1,089.0	328.0	1,992.0	340.50	31.3	–0.193	0.197	0.6540	NO
$pH_{(1)}$	4.9	3.8	6.1	0.42	8.7	–0.012	0.263	0.2110	NO
$pH_{(2)}$	5.3	4.3	6.0	0.36	6.8	0.135	–0.533	0.0070	ID
$P_{(1)}$	6.2	0.9	23.4	4.28	68.7	5.606	2.23	0.0001	ID
$P_{(2)}$	16.3	2.0	39.9	11.21	68.6	–0.625	0.825	0.0001	ID
$K^{+}_{(1)}$	1.0	0.1	2.4	0.50	48.1	0.060	0.828	0.0001	ID
$K^{+}_{(2)}$	0.9	0.2	2.8	0.54	58.1	1.103	1.245	0.0001	ID
$Ca^{2+}_{(1)}$	13.6	2.0	23.6	3.61	26.6	0.824	–0.382	0.1440	NO
$Ca^{2+}_{(2)}$	9.2	0.1	15.4	3.18	34.5	1.404	–1.028	0.0001	ID
$Mg^{2+}_{(1)}$	2.7	0.0	7.6	1.60	59.2	–0.119	0.432	0.0440	TN
$Mg^{2+}_{(2)}$	6.5	0.1	28.1	7.14	110.6	0.346	1.128	0.0001	ID
$H+Al_{(1)}$	14.0	4.1	24.8	4.73	33.8	–0.554	0.063	0.0740	NO
$H+Al_{(2)}$	14.2	4.1	25.9	5.09	35.8	–0.921	0.146	0.0160	ID
$Al^{3+}_{(1)}$	0.6	0.6	1.2	0.12	19.6	18.345	4.448	0.0001	ID
$Al^{3+}_{(2)}$	0.6	0.6	3.9	0.32	49.7	91.205	9.173	0.0001	ID
$S_{(1)}$	17.3	2.5	30.7	4.89	28.3	0.316	–0.325	0.2020	NO
$S_{(2)}$	16.6	0.5	37.4	7.80	47.0	0.000	0.387	0.0830	NO
$CEC_{(1)}$	31.3	15.7	44.8	5.02	16.1	0.890	–0.224	0.2590	NO
$CEC_{(2)}$	30.8	12.1	53.1	8.30	26.9	–0.137	0.272	0.2100	NO
$V\%_{(1)}$	55.3	10.1	83.8	13.88	25.1	0.288	–0.384	0.2500	NO
$V\%_{(2)}$	52.3	3.8	84.1	17.19	32.9	0.670	–0.666	0.0020	ID
$m\%_{(1)}$	3.7	1.9	8.0	1.09	29.7	1.105	1.018	0.0001	ID
$m\%_{(2)}$	6.2	1.3	80.8	11.13	180.3	28.336	5.165	0.0001	ID
$LN_{(1)}$	0.5	0.0	1.8	0.43	78.6	–0.297	0.528	0.0001	ID
$LN_{(2)}$	0.6	0.0	1.9	0.47	79.7	–0.455	0.502	0.0001	ID

(a) GY: grain yield (kg ha^{-1}); the subscripts $_{(1)}$ and $_{(2)}$ for each soil property refer to the depth of the layer from which samples were collected, i.e. 0.00–0.10 and 0.10–0.20 m, respectively. $pH_{(1)}$ and $pH_{(2)}$: pH value in $CaCl_2$; $P_{(1)}$ and $P_{(2)}$: phosphorus content (mg dm^{-3}); $K^{+}_{(1)}$ and $K^{+}_{(2)}$: potassium content ($mmol_c$ dm^{-3}); $Ca^{2+}_{(1)}$ and $Ca^{2+}_{(2)}$: calcium content ($mmol_c$ dm^{-3}); $Mg^{2+}_{(1)}$ and $Mg^{2+}_{(2)}$: magnesium content ($mmol_c$ dm^{-3}); $H+Al_{(1)}$ and $H+Al_{(2)}$: potential acidity ($mmol_c$ dm^{-3}); $Al^{3+}_{(1)}$ and $Al^{3+}_{(2)}$: aluminum content ($mmol_c$ dm^{-3}); $S_{(1)}$ and $S_{(2)}$: sum of bases ($mmol_c$ dm^{-3}); $CEC_{(1)}$ and $CEC_{(2)}$: values of cation exchange capacity ($mmol_c$ dm^{-3}); $V\%_{(1)}$ and $V\%_{(2)}$: values of the soil base saturation (%); $m\%_{(1)}$ and $m\%_{(2)}$: values of the aluminum saturation of the soil; and $LN_{(1)}$ and $LN_{(2)}$: amount of limestone needed (t ha^{-1}). (b) FD: frequency distribution, where NO: normal type, TN: tending to normal, and ID: indeterminate.

The common bean GY showed a very high coefficient of variation (31.3%). Dalchiavon et al. (2011) and Silva et al. (2017) analyzed the crop yield of common beans in a dystrophic Red Latosol soil with a no-tillage system, using grids of 135 and 124 sampling points, and also found high values of variability (20.3% and 22.2%, respectively) for the GY. However, contradictory results were reported by Montanari et al. (2013b), who evaluated the common bean GY for the same soil and climatic conditions and obtained a mean value for the spatial variability of 18.3%.

The phosphorus content in the 0.0–0.10 ($P_{(1)}$) and 0.10–0.20 m ($P_{(2)}$) layers had very high values for the coefficient of variation of 68.7% and 68.6%, respectively. Dalchiavon et al. (2011) also obtained very high values for the coefficient of variation (64.5%) for the P content at a depth of 0.0–0.20 m. The potassium content in the 0.0–0.10 ($K^{+}_{(1)}$) and 0.10–0.20 m ($K^{+}_{(2)}$) layers showed very high coefficients of variation of 48.1% and 58.1%. Montanari et al. (2016) similarly obtained very high coefficients of variation for the K content at depths of 0.0–0.10 m (CV = 51.2%) and 0.10–0.20 m (CV = 41.9%).

The calcium content at a depth of 0.0–0.10 m ($Ca^{2+}_{(1)}$) had a high variability of 26.6%, while in the 0.10–0.20 m layer ($Ca^{2+}_{(2)}$), it had a very high variability of 34.5%. The magnesium content in the two sampled depths showed a very high variability of 59.2% ($Mg^{2+}_{(1)}$) and 110.6% ($Mg^{2+}_{(2)}$). Similar results were reported by Montanari et al. (2016) and Dalchiavon et al. (2011), who also obtained very high values for the coefficient of variation for the Ca^{2+} and Mg^{2+} contents at depths of up to 0.20 m.

The potential acidity of the soil in the 0.0–0.10 m ($H+Al_{(1)}$) and 0.10–0.20 m ($H+Al_{(2)}$) layers showed very high values of variability of 33.8% and 35.8%, respectively. For a Red Latosol, Dalchiavon et al. (2011) observed a high variability (CV = 20%) for the potential soil acidity. The exchangeable aluminum content had a medium variability (CV = 19.6%) in the 0.0–0.10 m layer, while the variability in the 0.10–0.20 m layer was very high (CV = 49.7%). The sum of bases had high variability (CV = 28.3%) in the 0.0–0.10 m layer ($S_{(1)}$) and very high variability (CV = 47.0%) in the 0.10–0.20 m layer ($S_{(2)}$). Dalchiavon et al. (2011) also reported very high values (CV = 30.4%) for the variability of the sum of soil bases. The cation exchange capacity in the 0.0–0.10 m layer ($CEC_{(1)}$) showed medium variability (CV = 16.1%), while in the 0.10–0.20 m layer ($CEC_{(2)}$), the variability was high (CV = 26.9%). For a Red Latosol, Dalchiavon et al. (2011) also observed high variability (CV = 20.4%) for the cation exchange capacity in the 0.0–0.20 m layer. The soil base saturation had high (CV = 25.1%) and very high variability (CV = 32.9%) for the layers at 0.0–0.10 m ($V\%_{(1)}$) and 0.10–0.20 m ($V\%_{(2)}$), respectively. The aluminum saturation (m%) had high variability (CV = 29.7%) in the 0.0–0.10 m layer, while the variability in the 0.10–0.20 m layer was very high (CV = 180.3%). Montanari et al. (2016) similarly observed very high variability for base saturation (V%) and aluminum saturation (m%). The amount of limestone needed for soil correction at the two depths sampled here showed very high variability, with values of 78.6% ($LN_{(1)}$) and 79.7% ($LN_{(2)}$).

The medium to very high values of variability observed for most of the chemical properties of the soil and the grain yield may be because the studied soil (Neossolo Quartzarênico Órtico latossólico - RQo) has a sandy texture and low levels of nutrients (see Table 1).

The frequency distributions of the soil properties $pH_{(2)}$, $P_{(1)}$, $P_{(2)}$, $K_{(1)}$, $K_{(2)}$, $Ca^{2+}_{(2)}$, $Mg^{2+}_{(2)}$, $H+Al_{(2)}$, $Al^{3+}_{(1)}$, $Al^{3+}_{(2)}$, $V\%_{(2)}$, $m\%_{(1)}$, $m\%_{(2)}$, $LN_{(1)}$, and $LN_{(2)}$ were indeterminate (Table 2). Montanari et al. (2016) likewise reported an indeterminate frequency distribution for $pH_{(2)}$, $P_{(1)}$, $P_{(2)}$, $K_{(1)}$, $K_{(2)}$, $Ca^{2+}_{(2)}$, $Mg^{2+}_{(2)}$, $Al^{3+}_{(1)}$, $V\%_{(2)}$, and $m\%_{(1)}$, supporting the results obtained in this study. Of the soil properties measured here, a normal frequency distribution was observed for GY, $pH_{(1)}$, $Ca^{2+}_{(1)}$, $H+Al_{(1)}$, $S_{(1)}$, $S_{(2)}$, $CEC_{(1)}$, $CEC_{(2)}$, and $V\%_{(1)}$, with respective asymmetries of 0.197, 0.263, −0.382, 0.063 , −0.325, 0.387, −0.224, 0.272, and −0.384, which were shown to be significant by the normality test, since their values varied between 0.0740 and 0.6540 (Table 2).

The average yield of common beans (winter growing season) in this experiment differed from the average yield of the main producing regions for common beans across Brazil during the 2019–2020 season. The average GY in this study (1,089 kg ha^{-1}) was higher than in the northern and northeastern regions, which had average yields of 933 kg ha^{-1} and 431 kg ha^{-1}, respectively; however, it was lower than the midwestern and southeast regions, which had average yields of 1786 kg ha^{-1} and 1592 kg ha^{-1}, respectively (Conab, 2020). This means that the average GY in the present study was 60% higher than the average for the northeast region and 39% lower than the average for the midwestern region, where this study was conducted.

The respective values for $pH_{(1)}$ and $pH_{(2)}$ of 4.9 and 5.3 indicate that the pH increased with soil depth (Table 2). This effect was also observed for the Mg^{2+} content (from 2.7 to 6.5 $mmol_c\ dm^{-3}$) and the P content (from 6.2 to 16.3 mg dm^{-3}). Differing results were reported by Lima et al. (2017b), who observed a decrease in nutrient content in a Cerrado sandy soil fertilized with lime sludge and oxyfertil. The potassium content ($K^+_{(1)}$ = 1.0 $mmol_c\ dm^{-3}$ and $K^+_{(2)}$ = 0.9 $mmol_c\ dm^{-3}$) and calcium ($Ca^{2+}_{(1)}$ = 13.6 mmolc dm^{-3} and $Ca^{2+}_{(2)}$ = 9.2 $mmol_c\ dm^{-3}$) decreased with the soil depth, which was in agreement with the results of Lima et al. (2017b). These results may be due to the soil being sandy and having high macroporosity, which can facilitate the leaching of these nutrients. The values of the potential acidity ($H+Al_{(1)}$ = 14.0 $mmol_c\ dm^{-3}$and $H+Al_{(2)}$ = 14.2 $mmol_c\ dm^{-3}$) and aluminum saturation ($m\%_{(1)}$ of 3.7% and $m\%_{(2)}$ of 6.2%) increased with the depth of the soil. Similar results were also reported by Montanari et al. (2016). The values for the sum of bases ($S_{(1)}$ = 17.3 $mmol_c\ dm^{-3}$ and $S_{(2)}$ = 16.6 $mmol_c\ dm^{-3}$), soil base saturation ($V\%_{(1)}$ = 55.3% and $V\%_{(2)}$ = 52.3%), and cation exchange capacity ($CEC_{(1)}$ = 31.3 $mmol_c\ dm^{-3}$ and $CEC_{(2)}$ = 30.8 $mmol_c\ dm^{-3}$) were reduced with depth, a result that also agreed with those of Montanari et al. (2016). The amount of limestone needed ($LN_{(1)}$ = 0.5 t ha^{-1} and $LN_{(2)}$ = 0.6 t ha^{-1}) was higher for the deeper layer than the superficial layer. This indicates that the technique used for the application of liming must be carried out with criteria and in an appropriate way so that limestone can be efficiently incorporated into the soil profile.

From a study of Pearson's linear correlation between the yield and the chemical properties of the soil (Figure 2), it was found that there was a positive and highly significant correlation of GY with $pH_{(1)}$ (r = 0.412; p = 0.01), $Mg^{2+}_{(1)}$ (r = 0.266; p = 0.01), $Mg^{2+}_{(2)}$ (r = 0.306; p = 0.01) and $V\%_{(2)}$ (r = 0.324; p = 0.01), and a negative correlation with $H+Al_{(2)}$ (r = −0.364; p = 0.01).

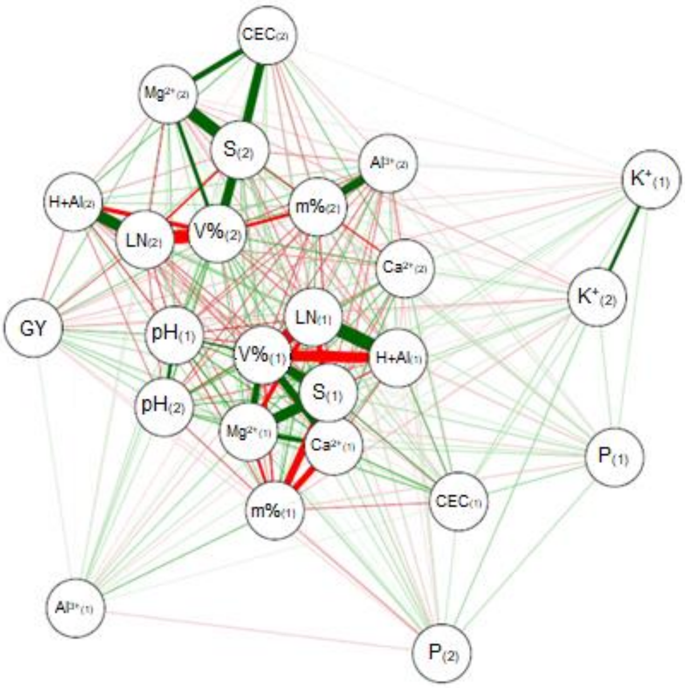

FIGURE 2. Correlation network of common bean grain yield and some chemical properties of a Brazilian Cerrado sandy soil, Cassilândia, MS, Brazil.

For the simple correlation between the GY and the chemical properties of the soil, a regression equation with GY as a function of $pH_{(1)}$ was represented by a direct linear model (Eq. 1, Table 3 and Fig. 3a). This indicates a direct variation between cause and effect, and when the $pH_{(1)}$ values reach a minimum (3.79), the estimated minimum GY will be 638.33 kg ha^{-1}. Dalchiavon et al. (2011) also reported a direct relationship between the GY of common beans and the soil pH. The expression for GY as a function of $LN_{(2)}$ was represented by an indirect exponential model (Eq. 2 and Fig. 3b), with a correlation coefficient value of 0.453 (p = 0.01). Hence, the GY variation of the common bean crop can be explained by 45.3% of the variation in the LN data at a depth of 0.10–0.20 m ($LN_{(2)}$). When $LN_{(2)}$ is increased from 0 to 1,930 t ha^{-1}, the GY may decrease from 1,249.6 to 568.9 kg ha^{-1}. In turn, the expression for GY as a function of $V\%_{(2)}$ was represented by a direct exponential model (Eq. 3 and Fig. 3c), with a correlation coefficient value of 0.349 (p = 0.01). Thus, the variation in GY can be explained by 34.9% of the variation in the base saturation value at a depth of 0.10–0.20 m. Hence, when $V\%_{(2)}$ is increased from 3.8% to 84.1%, GY may increase from 638.3 to 1,229.7 kg ha^{-1}. From the expression of GY as a function of $H+Al_{(2)}$, represented by a quadratic model (Eq. 4 and Fig. 3d), it can be observed that when $H+Al_{(2)}$ is increased from 4.1 to 25.9 $mmol_c$ dm^{-3}, GY may decrease from 1,116.86 to 561.03 kg ha^{-1}, reaching a point of maximum yield (1,214.36 kg ha^{-1}) when the potential acidity is 10.17 $mmol_c$ dm^{-3}. The expression for GY as a function of $Mg^{2+}_{(2)}$ content was represented by a direct potential model (Eq. 5 and Fig. 3e), and when $Mg^{2+}_{(2)}$ is increased from 0.1 to 28.1 $mmol_c$ dm^{-3}, GY may increase from 903.1 to 1,270.3 kg ha^{-1}.

TABLE 3. Regression equation model for common bean grain yield as a function of some chemical properties of a Brazilian Cerrado sandy soil, Cassilândia, MS, Brazil.

Mathematical model	Adjustment coefficients					Equation
	a	b	c	R	r^2	
$GY = a + b.(pH_{(1)})$	-531.23	331.94**	-	0.412**	0.170**	[1]
$GY = a.EXP^{b.LN(2)}$	1253.6	-0.332**	-	0.453**	0.205**	[2]
$GY = a.EXP^{b.V\%(2)}$	717.02	0.007**	-	0.349**	0.122*	[3]
$GY = a + b.(H+Al_{(2)}) – c.(H+Al_{(2)})^2$	940.85	52.763	-2.642*	-	0.174*	[4]
$GY = a.(Mg^{2+}_{(2)})^b$	989.95	0.063**	-	0.371**	0.137**	[5]

GY: grain yield (kg ha^{-1}); $pH_{(1)}$: soil pH value in the 0.0–0.10 m layer; $LN_{(2)}$: amount of limestone needed (kg ha^{-1}) for the 0.10–0.20 m layer; $V\%_{(2)}$: soil base saturation (%) in the 0.10–0.20 m layer; $H+Al_{(2)}$: potential acidity ($mmol_c$ dm^{-3}) in the 0.10–0.20 m layer; $Mg^{2+}_{(2)}$: magnesium content ($mmol_c$ dm^{-3}) in the 0.10–0.20 m layer. ** and * represent values that are significant at 1% and 5%, respectively.

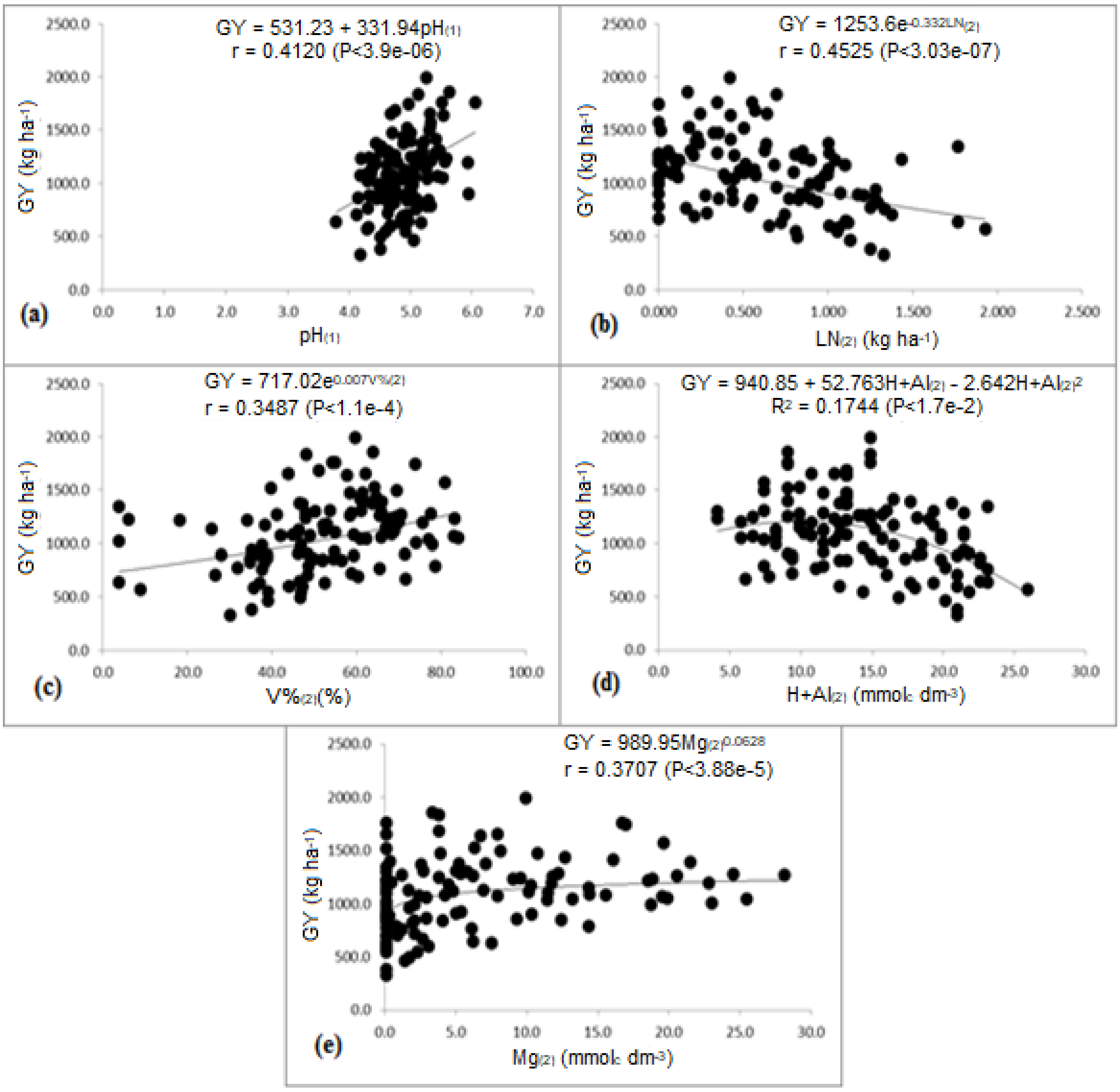

FIGURE 3. Regression equation for common bean grain yield (GY) as a function of: (a) soil pH in the 0.0–0.10 layer [$pH_{(1)}$]; (b) amount of limestone needed for the 0.10–0.20 m layer [$LN_{(2)}$]; (c) soil base saturation in the 0.10–0.20 m layer [$V\%_{(2)}$]; (d) potential acidity in the 0.10–0.20 m layer [$H+Al_{(2)}$]; and (e) magnesium content in the 0.10–0.20 m layer [$Mg^{2+}{}_{(2)}$] for a Brazilian Cerrado sandy soil, Cassilândia, MS, Brazil.

In the multiple regression analysis of GY as a function of all soil chemical properties, the models tested (Equations 6 and 7) explained approximately 31.3% of the variation in the common bean GY for a depth of 0.00–0.10 m depth ($r^2 = 0.313$ **) and 31.1% for a depth of 0.10–0.20 m ($r^2 = 0.311$ **). Dalchiavon et al. (2011) reported that 22.1% of the variation in the common bean GY was explained by the characteristics of the 0.00–0.20 m layer of a Latossolo Vermelho eutroférrico.

$$GY = -2371.5 + 370.9\,pH_{(1)} + 0.7\,P_{(1)} - 1892.4\,K^{+}{}_{(1)} - 1728.7\,Ca^{2+}{}_{(1)} - 1629.1\,Mg^{2+}{}_{(1)} + 0.0\,H{+}Al_{(1)} - 236.8\,Al^{3+}{}_{(1)} + 1620.2\,S_{(1)} + 64.5\,CEC_{(1)} + 23.4\,V\%_{(1)} + 74.8\,m\%_{(1)} - 24.7\,LN_{(1)} \quad (6)$$

$$GY = 727.4 + 165.2\,pH_{(2)} - 0.5\,P_{(2)} - 4369.6\,K_{(2)} - 4296.7\,Ca^{2+}{}_{(2)} - 4266.6\,Mg^{2+}{}_{(2)} + 2650.9\,H{+}Al_{(2)} - 177.3\,Al^{3+}{}_{(2)} + 6855.2\,S_{(2)} - 2602.8\,CEC_{(2)} + 0.7\,V\%_{(2)} + 4.5\,m\%_{(2)} - 904.3\,LN_{(2)} \quad (7)$$

The geostatistical analysis (Table 3) showed that there were semivariograms spatial dependence for the following traits: GY, $pH_{(1)}$, $pH_{(2)}$, $Ca^{2+}{}_{(2)}$, $H+Al_{(1)}$, $S_{(2)}$, $m\%_{(1)}$, and $LN_{(2)}$. The cross-semivariograms GY = f[$pH_{(1)}$] and GY = f[$V\%_{(2)}$] were adjusted to a spherical model, while the simple semivariogram ($Mg^{2+}{}_{(1)}$ and $CEC_{(2)}$) and cross-semivariogram GY = f[$S_{(2)}$] were adjusted to an exponential model. Montanari et al. (2013b) also reported that spherical and exponential models were the most commonly used for soil and plant attributes. However, the chemical properties $P_{(2)}$, $K^{+}{}_{(1)}$, $K^{+}{}_{(2)}$, $Ca^{2+}{}_{(1)}$, $Mg^{2+}{}_{(2)}$, $Al^{3+}{}_{(1)}$, $Al^{3+}{}_{(2)}$, $S_{(1)}$, $CEC_{(1)}$, $V\%_{(1)}$, $V\%_{(2)}$, and $LN_{(1)}$, and the cross-semivariogram of GY = f[$pH_{(2)}$], were adjusted to a Gaussian model. These adjustments can be explained by the physical-chemical alterations of the soil, and mainly by the chemical properties, which are altered by correction and fertilization practices.

The values of the relative ranges (A_O) observed for the soil chemical properties and GY ranged from 9.0 m ($CEC_{(1)}$) to 51.0 m (GY) for the single semivariogram and 25.3 m [GY = f($pH_{(2)}$)] to 62.3 m [GY = f($pH_{(1)}$)] for the cross-semivariogram. In view of the way in which this research was conducted and using the same soil characteristics, it is suggested that the values of these ranges should be no less than 9.0 m, since this represents the distance within which the values of each property are consistent (Table 4).

TABLE 4. Estimated parameters for simple or cross-semivariogram of the common bean grain yield with some of the chemical properties of a Brazilian Cerrado sandy soil, Cassilândia, MS, Brazil.

Attributes[(a)]	Model[(b)]	Nugget	Sill	Range	r^2	SRS[(c)]	SDE[(d)]		Cross-validation		
		C_O	C_O+C	A_O (m)			%	Class	a	b	r
γ(h) Simple semivariogram – Plant attribute											
GY	sph	3.82×10^{4}	1.58×10^{5}	51.0	0.866	3.13×10^{9}	75.8	Strong	91.06	0.917	0.651
γ(h) Simple semivariogram – Soil attribute											
$pH_{(1)}$	sph	3.64×10^{-2}	2.00×10^{-1}	26.9	0.953	6.32×10^{-4}	81.8	Strong	0.19	0.960	0.716
$pH_{(2)}$	sph	7.44×10^{-2}	1.29×10^{-1}	17.0	0.612	1.32×10^{-2}	42.5	Moderate	0.03	0.997	0.474
$P_{(1)}$	pne	1.77×10^{1}	1.77×10^{1}	-	-	-	-	-	-	-	-
$P_{(2)}$	gau	8.00×10^{1}	1.33×10^{2}	18.2	0.789	7.56×10^{2}	40.1	Moderate	-0.03	1.013	0.455
$K^{+}_{(1)}$	gau	8.20×10^{-2}	2.25×10^{-1}	12.2	0.712	1.51×10^{-2}	63.6	Moderate	0.12	0.881	0.554
$K^{+}_{(2)}$	gau	2.15×10^{-1}	3.60×10^{-1}	43.0	0.239	5.00×10^{-2}	40.3	Moderate	0.00	1.010	0.498
$Ca^{2+}_{(1)}$	gau	6.00×10^{0}	1.50×10^{1}	11.0	0.768	2.50×10^{1}	60.6	Moderate	5.53	0.594	0.355
$Ca^{2+}_{(2)}$	sph	5.00×10^{0}	1.05×10^{1}	32.0	0.954	1.72×10^{0}	52.4	Moderate	0.20	0.979	0.556
$Mg^{2+}_{(1)}$	exp	1.15×10^{0}	2.55×10^{0}	13.0	0.546	4.55×10^{-1}	54.8	Moderate	0.79	0.723	0.324
$Mg^{2+}_{(2)}$	gau	3.00×10^{1}	5.70×10^{1}	26.0	0.819	1.94×10^{2}	47.4	Moderate	1.84	0.720	0.366
$H+Al_{(1)}$	sph	8.00×10^{0}	2.30×10^{1}	12.0	0.720	3.68×10^{1}	65.2	Moderate	1.86	0.853	0.439
$H+Al_{(2)}$	sph	1.57×10^{1}	2.86×10^{1}	34.3	0.855	2.26×10^{1}	45.2	Moderate	1.53	0.894	0.452
$Al^{3+}_{(1)}$	gau	3.00×10^{-3}	1.54×10^{-2}	11.0	0.790	2.91×10^{-5}	80.5	Strong	0.73	-0.161	0.105
$Al^{3+}_{(2)}$	gau	0.00×10^{0}	1.00×10^{-1}	12.0	0.554	6.86×10^{3}	100.0	Strong	0.58	0.110	0.148
$S_{(1)}$	gau	1.23×10^{1}	2.50×10^{1}	12.0	0.394	1.34×10^{2}	51.0	Moderate	5.13	0.706	0.412
$S_{(2)}$	sph	4.30×10^{1}	6.17×10^{1}	17.0	0.309	8.80×10^{2}	30.3	Moderate	8.60	0.485	0.145
$CEC_{(1)}$	gau	1.60×10^{1}	2.55×10^{1}	9.0	0.265	9.32×10^{1}	37.3	Moderate	13.39	0.569	0.237
CEC	exp	5.20×10^{1}	6.90×10^{1}	16.0	0.561	8.17×10^{1}	24.6	Weak	23.14	0.252	0.063
$V\%_{(1)}$	gau	7.77×10^{1}	1.88×10^{2}	10.7	0.512	6.73×10^{3}	58.6	Moderate	10.12	0.825	0.483
$V\%_{(2)}$	gau	1.70×10^{2}	2.94×10^{2}	12.0	0.588	3.20×10^{3}	42.2	Moderate	13.85	0.734	0.358
$m\%_{(1)}$	sph	6.20×10^{-1}	1.36×10^{0}	18.6	0.875	6.00×10^{-2}	54.5	Moderate	0.34	0.901	0.507
$m\%_{(2)}$	pne	1.09×10^{2}	1.09×10^{2}	-	-	-	-	-	-	-	-
$LN_{(1)}$	gau	9.68×10^{-2}	1.90×10^{-1}	13.0	0.461	6.49×10^{-3}	49.0	Moderate	0.05	0.893	0.491
$LN_{(2)}$	sph	1.45×10^{-1}	2.36×10^{-1}	36.0	0.809	1.53×10^{-3}	38.6	Moderate	0.03	0.944	0.443
γ(h) Cross-semivariogram – [Plant = f(Soil attribute)]											
GY=f[$pH_{(1)}$]	sph	1.00×10^{-1}	1.06×10^{2}	62.3	0.926	7.89×10^{2}	99.9	Strong	324.50	0.961	0.715
GY=f[$pH_{(2)}$]	gau	6.80×10^{0}	3.20×10^{1}	25.3	0.905	5.97×10^{1}	78.6	Strong	285.50	0.739	0.622
GY=f[$S_{(2)}$]	exp	0.00×10^{0}	6.88×10^{2}	27.3	0.744	2.11×10^{5}	100.0	Strong	912.70	0.654	0.501
GY=f[$V\%_{(2)}$]	sph	4.19×10^{2}	2.32×10^{3}	36.7	0.884	3.98×10^{3}	81.9	Strong	532.60	0.791	0.603

[(a)] GY: grain yield (kg ha^{-1}); $pH_{(1)}$ and $pH_{(2)}$: pH values in the 0.0–0.10 and 0.10–0.20 m layers, respectively; $P_{(1)}$ and $P_{(2)}$: phosphorus content (mg dm^{-3}); $K^{+}_{(1)}$ and $K^{+}_{(2)}$ = potassium content ($mmol_c$ dm^{-3}); $Ca^{2+}_{(1)}$ and $Ca^{2+}_{(2)}$: calcium content ($mmol_c$ dm^{-3}); $Mg^{2+}_{(1)}$ and $Mg^{2+}_{(2)}$: magnesium content ($mmol_c$ dm^{-3}); $H+Al_{(1)}$ and $H+Al_{(2)}$: potential acidity ($mmol_c$ dm^{-3}); $Al^{3+}_{(1)}$ and $Al^{3+}_{(2)}$: aluminum content ($mmol_c$ dm^{-3}); $S_{(1)}$ and $S_{(2)}$: sum of bases ($mmol_c$ dm^{-3}); $CEC_{(1)}$ and $CEC_{(2)}$: cation exchange capacity ($mmol_c$ dm^{-3}); $V\%_{(1)}$ and $V\%_{(2)}$: soil base saturation (%); $m\%_{(1)}$ and $m\%_{(2)}$: soil aluminum saturation; and $LN_{(1)}$ and $LN_{(2)}$: amount of limestone needed (kg ha^{-1}). [(b)] sph: spherical, exp: exponential, pne: pure nugget effect, and gau: Gaussian. [(c)] SRS = sum of the residue square. [(d)] SDE = spatial dependence evaluation.

The variation in the simple semivariograms, analyzed based on the magnitude of the spatial determination coefficient (r^2), was as follows: a lower value was found for $K^+_{(2)}$ (0.239) and a higher value for $Ca^{2+}_{(2)}$ (0.954). For the spatial dependence evaluator (SDE), the relationship was lower for $CEC_{(2)}$ (24.6%) and higher for $Al^{3+}_{(2)}$ (100.0%). The attributes Ca and V% had a low value of r, that is, a low-quality interpolation presented by cross-validation, but even so it was possible to verify even if an existence of spatial dependence was low.

The performance of the cross-semivariograms (Table 4) in decreasing order, analyzed based on the spatial determination coefficient (r^2), was as follows: (i) [GY = f($pH_{(1)}$)] (0.926); (ii) [GY = f($pH_{(2)}$)] (0.905); (iii) [GY = f($V\%_{(2)}$)] (0.884); and (iv) [GY = f($S_{(2)}$)] (0.744). In decreasing order, analyzed based on the magnitude of the range (A_O), the results were as follows: (i) [GY = f($pH_{(1)}$)] (62.3) m; (ii) [GY = f($V\%_{(2)}$)] (36.7) m; (iii) [GY = f($S_{(2)}$)] (27.3) m; (iv) [GY = f($pH_{(2)}$)] (25.3) m.

In terms of cokriging, the best adjustments were between GY and $pH_{(1)}$, and GY and $pH_{(2)}$. It was observed that 92.6% ($pH_{(1)}$) and 90.5% ($pH_{(2)}$) of the spatial variability of the GY was explained by the spatial variability of the pH value of the soil, and the highest values for the yield were recorded in regions with higher soil pH values (Figure 4b and 4d). The spatial dependencies for these cokriging results were high (SDE = 99.9% [GY = f($pH_{(1)}$)] and 78.6% [GY = f($pH_{(2)}$)]), and the spherical and Gaussian types were adjusted to $pH_{(1)}$ and $pH_{(2)}$, respectively (Table 4, Figures 4b and 4d). Similar results for cokriging between GY and the soil pH value were also reported by Montanari et al. (2013c), who found that the SDE was high (99.0%), with a 13.0 m range and a Gaussian model adjustment. Figure 5 shows the kriging map of the common bean GY, which is very similar to the maps in Figure 4; the low productivity regions are in the northern region in all of the maps, and the regions with highest productivity are in the south.

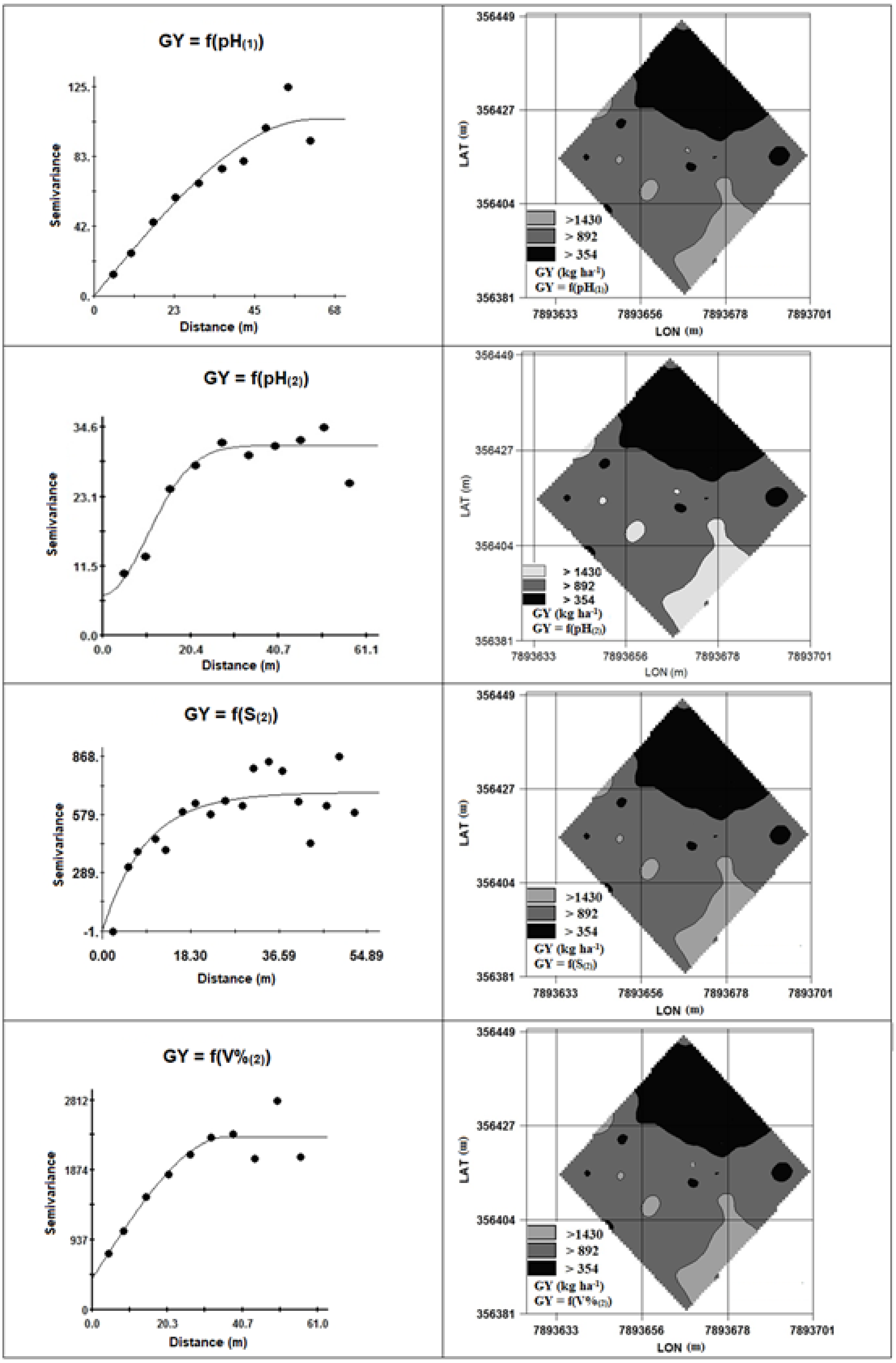

FIGURE 4. Cross-semivariograms and cokriging maps for common bean grain yield (GY) as a function of soil pH in the 0.0–0.10 layer [$pH_{(1)}$], soil pH in the 0.10–0.20 layer [$pH_{(2)}$], sum of bases in the 0.10–0.20 m layer [$S_{(2)}$], and soil base saturation in the 0.10–0.20 m layer [$V\%_{(2)}$] in a Brazilian Cerrado sandy soil, Cassilândia, MS, Brazil.

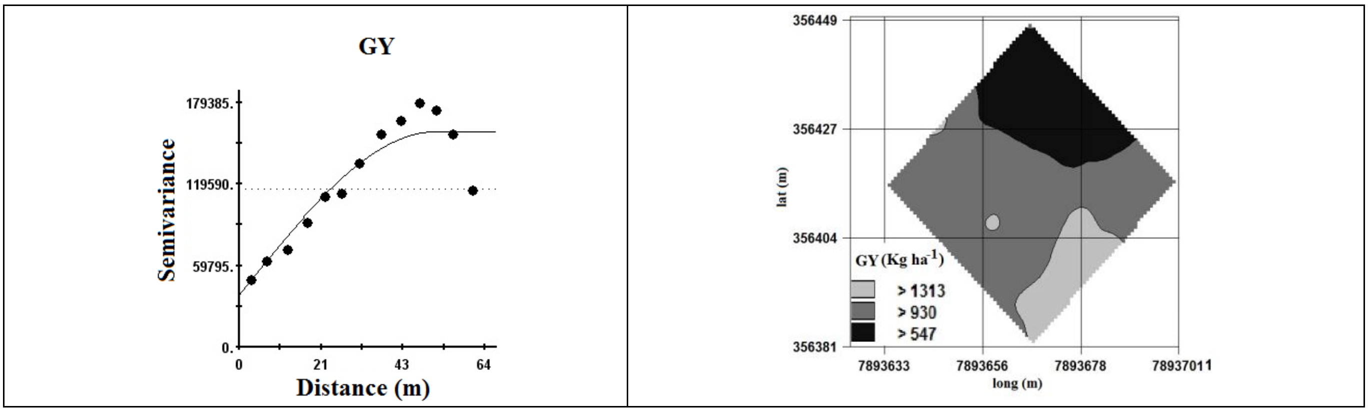

FIGURE 5. Semivariogram and kriging maps of common bean grain yield (GY) in a Brazilian Cerrado sandy soil, Cassilândia, MS, Brazil.

The cokriging results between GY and $S_{(2)}$ (r^2 = 0.744) and GY and $V\%_{(2)}$ (r^2 = 0.884) (Table 4) had exponential and spherical adjustments, respectively, for the cross-semivariograms, with ranges of 27.3 and 36.7 m, and a high SDE was found for both (100.0% and 81.9%). Thus, in relation to the properties GY = f($S_{(2)}$), and GY = f($V\%_{(2)}$), substantial elevations were found, with values ranging from 0.5 to 37.4 $mmol_c\ dm^{-3}$ for $S_{(2)}$ and 3.8 to 84.1% for $V\%_{(2)}$. The variation in the common bean GY was 328.2 to 1991.7 kg ha^{-1}.

It can be observed that the spatial variability between the chemical properties $pH_{(1)}$, $pH_{(2)}$, $S_{(2)}$, and $CEC_{(2)}$ with the GY of the common bean crop showed the same linear effect. Therefore, by cokrigagem of high significance, the GY of common beans can be estimated based on the direct effect of an increase in soil pH, the sum of exchangeable bases and the percentage of the soil base saturation of the sandy soils of the Brazilian Cerrado.

CONCLUSIONS

For the GY of an irrigated common bean crop during the winter season, a multiple regression analysis indicated that 31% of the variation in production can be attributed to the spatial variability in all the chemical properties of a sandy soil of the Cerrado.

The chemical properties of the soil have a spatial dependence that is classified as moderate and strong, with a predominantly Gaussian-type semisvariogram model.

Properties such as $pH_{(1)}$, $pH_{(2)}$, $S_{(2)}$ and $V\%_{(2)}$ can be considered potential indicators of the GY of an irrigated common bean crop when cultivated in sandy soil with a no-tillage system.

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