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Sugarcane productivity correlated with physical-chemical attributes to create soil management zone

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ABSTRACT

The socioeconomic importance of sugar cane in Brazil is unquestionable because it is the raw material for the production of ethanol and sugar. The accurate spatial intervention in the management of the crop, resulting zones of soil management, increases productivity as well as its agricultural yields. The spatial and Person's correlations between sugarcane attributes and physico-chemical attributes of a Typic Tropustalf were studied in the growing season of 2009, in Suzanápolis, State of São Paulo, Brazil (20°28'10'' S lat.; 50°49'20'' W long.), in order to obtain the one that best correlates with agricultural productivity. Thus, the geostatistical grid with 120 sampling points was installed to soil and data collection in a plot of 14.6 ha with second crop sugarcane. Due to their substantial and excellent linear and spatial correlations with the productivity of the sugarcane, the population of plants and the organic matter content of the soil, by evidencing substantial correlations, linear and spatial, with the productivity of sugarcane, were indicators of management zones strongly attached to such productivity.

Key words: precision agriculture, geostatistical, management and conservation of soil, *Saccharum* spp., spatial variability.

RESUMO

Produtividade de cana-de-açúcar correlacionada com atributos físico-químicos do solo visando à criação de zonas de manejo

A importância socioeconômica da cana-de-açúcar para o Brasil é inquestionável por se tratar de matéria-prima destinada à produção de etanol e açúcar. A correta intervenção espacial na administração da lavoura decorrente das zonas de manejo do solo aumenta sua produtividade e a lucratividade agrícola. No ano de 2009, no município de Suzanápolis, no Estado de São Paulo (20° 28' 10'' S lat.; 50° 49' 20'' W long.), foram empregadas correlações (espaciais e de Pearson) entre atributos da cana-de-açúcar e alguns físico-químicos de um Argissolo Vermelho eutrófico, visando encontrar aquele que melhor se correlacionasse com a produtividade agrícola. Para tanto, instalou-se a malha geoestatística para a coleta de dados do solo e da planta, com 120 pontos amostrais, num talhão de 14,6 ha com a cana-de-açúcar de segundo corte. A população de plantas e o teor de matéria orgânica do solo, por evidenciarem substanciais correlações, lineares e espaciais, com a produtividade de colmos foram indicadores de zonas de manejo fortemente associados à referida produtividade.

Palavras-chave: agricultura de precisão, geoestatística, manejo e conservação do solo, *Saccharum* spp., variabilidade espacial.

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INTRODUCTION

In Brazil, sugarcane (*Sacchharum officinarum* L.) is vitally important within a socioeconomic context. It is the main raw material to produce ethanol for motor fuel, and sugar. In the domestic crop of 2009/10, 604.5 million tons of sugarcane stalks (bagasse) were processed. The state of São Paulo contributed with 54% of this amount, in an area of 4.1 million hectares, and with an average productiction of 79.6 t ha^{-1} (Conab, 2010; Souza *et al.*, 2012).

Precision agriculture determines exact crop management based on site-specific soil management mapping. Its main benefits are the reduction of costs by spending less on supplies and the increase of agricultural productivity. The soil variability analysis using geostatistics enables the adjustment of the semivariogram for georeferenced data with spatial dependence. However, with the affinity between the spatial dependencies of any two attributes, modeled by crossed semivariogram, the kriging map for the main attribute can be obtained with difficulty, and it is of greater interest due to the secondary attribute, which is usually easy to obtain (Molin *et al.*, 2007; Montanari *et al.*, 2010; Siqueira *et al.*, 2010; Dalchiavon *et al.*, 2011a; Marin & Carvalho, 2012). Then, from the second attribute, more site-specific soil management for the primary attribute could be obtained.

Recently, some studies have been conducted in order to investigate the spatial relationship between the soil attributes (secondary) and crop productivity (main), observing geostatistical ranges from 13.9 to 169.0 m. Some of the referred studies were developed by Martins *et al.* (2009), Lima *et al.* (2010) and Dalchiavon *et al.* (2011b), respectively, for bean, eucalyptus and soybean crops.

The objective of this study was to characterize the site-specific soil management using Pearson's and spatial correlations between sugarcane productivity and physical-chemical attributes of the soil, in order to indicate the one that is the mostly effective related to the increase in the aforementioned productivity.

MATERIALS AND METHODS

The study was conducted in 2009, at the Power plant Vallew of the Paraná S/A Alcohol and Sugar, farm Caiçara, in Suzanápolis (São Paulo State, Brazil), latitude 20°28'10'' S, longitude 50°49'20'' W. The soil was a Typic Tropustalf (USA Soil Taxonomy) or Argissolo Vermelho Eutrófico típico, textura arenosa/média, A moderado (Brazilian Soil Classification – Embrapa, 2006). On 03/13/2009, sugarcane (variety SP79-1011) was planted in an area of 14.6 ha (418.46 x 349.00 m) spaced at 1.5 m, and was harvested on 06/20/2006 for data collection. The grid comprised nine parallel transects spaced at 43 m with 11 sampling points, spaced at 42 m. The seven smaller grids, randomly allocated in order to detect spatial dependence ranges for spacing's of less than 42 m, were apart at 5.7 m points, adding 21 more. Thus, the total number of sampling points was of 120, from which the attributes (soil and plant) were collected (Figure 1).

The soil attributes, collected at a depth of 0-0.20 m were: a) penetration resistance (PR in MPa), b) gravimetric moisture (GM in kg kg^{-1}), c) organic matter content (OM in g dm^{-3}), d) phosphorus content (P in mg dm^{-3}), e) pH content in $CaCl_2$, f) K, Ca, Mg, H+Al and Al contents (in $mmol_c$ dm^{-3}), g) sum of bases (S in $mmol_c$ dm^{-3}), h) cation exchange capacity (T in $mmol_c$ dm^{-3}), and i) base saturation (V%). Regarding the plant, the features assessed were stem productivity (PRO in t ha^{-1}), stem volume (VOL in m^3 ha^{-1}), population (POP in pl. m^{-2}) and total recoverable sugars (TRS in kg t^{-1}), with the cane in the second cut manually repeated and harvested after removing the dry straws (after the fire).

The PR and GM were obtained according to Dalchiavon *et al.* (2011b); the OM, P, pH, K, Ca, Mg, H+Al, Al, S, T and V%, according to Raij *et al.* (2001). The PRO was obtained by manually harvesting the canes in the two rows adjacent to the spot staked. The spacing between rows was of 1.50 m, comprising 3.00 m. Therefore, considering 3.00 m in the crop plantation, the sample area of each point was 9 m² (3.0 m x 3.0 m). The canes representing each point were weighed immediately after cutting, in the field, using an electronic-digital analytical balance (+/- 0.05 kg) of 300 kg capacity. The weight transformation, point by point, was given by:

$$PRO = 1{,}111.11 \cdot m \qquad (1)$$

where: PRO is the cane productivity (t ha^{-1}), 1,111.11 is the multiplication factor to extrapolate the productivity of 9 m^2 (useful area) for 10,000 m^2 (1 ha) and m is the stem weight in the sampling area of 9 m^2 (kg). The VOL was calculated from five stems, measuring the average lengths and diameters (base, middle and apex); the POP was given by counting the stems in the useful crop area (9 m^2), and TRS, according to Consecana (2006).

The statistical analysis was performed using the Statistical Analysis System (SAS) software and an Excel spreadsheet, following the procedures by Montanari *et al.* (2010) and Dalchiavon *et al.* (2011b). The descriptive analysis of the attributes was performed by calculating the mean, median, minimum and maximum, standard deviation, coefficient of variation, kurtosis, asymmetry, and the frequency distribution analysis by the Shapiro-Wilk test. The correlation matrix was assembled between all attributes studied, containing all possible paired combinations. The objective was to detect the existence of significant correlations between attributes (plant *x* plant and plant *x* soil) to perform simple and multiple linear regressions (*stepwise*) of PRO in relation to the other attributes, in order to trace the existence of one of them, which could work as a quality indicator, when the goal was to increase the sugarcane productivity (Dalchiavon, 2012).

The geostatistical analysis was performed using the *Gamma Design Software 7.0* (Gs+, 2004), following the procedures according to Dalchiavon *et al*. (2012) and Montanari *et al*. (2012). The spatial dependence was analyzed by calculating the semivariogram for each attribute separately. However, for those with spatial interdependence, their cross-semivariograms were also calculated, based on intrinsic stationarity hypothesis assumptions. Kriging was carried out, especially for the PRO and soil and/or plant attributes. The objective was to confirm the existence of an attribute (soil and/or plant) that could spatially function as quality indicator, when the goal is to increase the productivity. The simple and cross-semivariograms, depending on their models, were adapted according to: 1) lower residual squared sums (RSS); 2) highest coefficient of determination (r^2), and 3) highest spatial dependence evaluation (SDE). However,

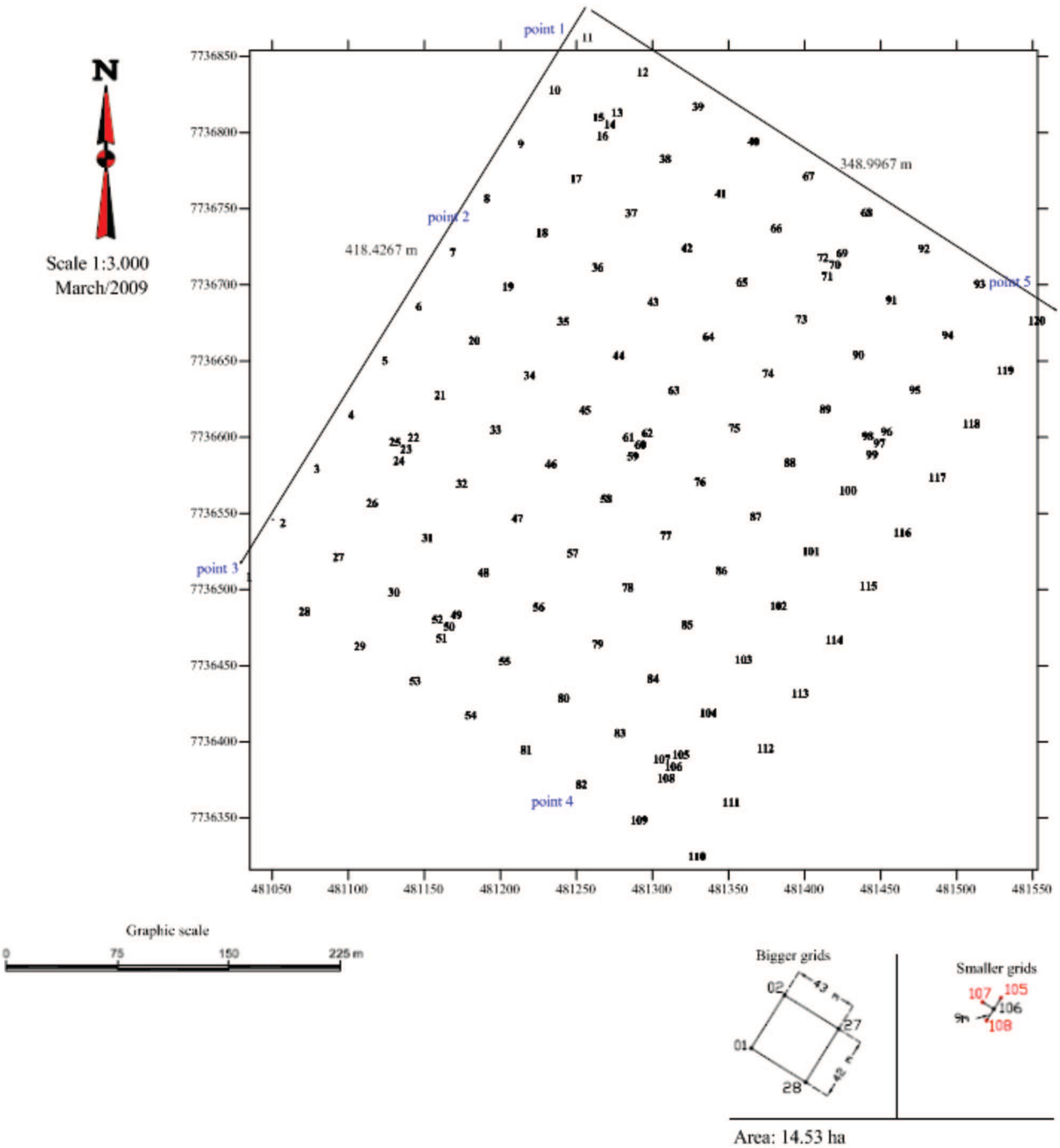

Figure 1. Outline of the experimental mesh of sampling.

for the attributes (ATR) with no spatial dependence, that is, in the absence of stationarity, the data trend was removed by the polynomial multiple regression technique. Thus, they were preceded by the symbol # when referred in the semivariographic analysis and cross-validation (#ATR). However when referred in the kriging and/or co-kriging map, they were preceded by £ (£ATR).

The model's final decision, which represented the adaptation, was performed by cross-validation, and to define the size of the neighborhood that provided the best kriging or co-kriging mesh, block kriging was performed. For each attribute, the nugget effect (C_o), the range (A_o) and sill (C_o + C) were related. The classification of the spatial dependency evaluation (SDE) were: a) SDE < 20% = very low dependence spatial variable (VLD); b) 20% ≤ SDE < 40% = low dependence (LOD); c) 40% ≤ SDE < 60% = average dependence (AVD); d) 60% ≤ SDE < 80% = high dependence (HID), and e) 80% ≤ SDE < 100% = very high dependence (VHD), according to the proposition of Dalchiavon & Carvalho (2012).

RESULTS AND DISCUSSION

In the case of a two-cycle sugarcane crop (24 month cycle), a higher PRO than that shown in Table 1 (89.2 t ha^{-1}) was expected. However, the PRO data are consistent with the low POP verified (10.5 pl m^{-2}), when optimal spacing should be at least 14.0 pl. m^{-2} (Braga, 2011). However, the PRO was 13.5% higher than that obtained by Souza *et al*. (2008), variety SP80-1816, in a RED-YELLOW LATOSOL, and lower than 100 t ha^{-1} obtained by Watanabe *et al*. (2004), for sugarcane at the third cut, variety RB85-5536, cultivated in a Dystrophic RED LATOSOL (Oxisol) (Table 1).

The normal frequency distribution, a typical representative of the plant data, that usually present mean and median values close among them, is ideal for statistical analysis (regression and/or geostatistical analysis). Otherwise, normality is sought by logarithmic transformation (Molin *et al.*, 2007). The PRO showed normal frequency distribution, with kurtosis and skewness of -0.401 and 0.677, respectively (Table 1). Similar to the VOL, the POP and PR also showed data normality, in full agreement with Dalchiavon *et al.* (2011b), who found normal frequency distribution for the PRO, POP and PR studying the soybean crop in a Dystrophic RED LATOSOL (Oxisol), indicating that the median tendency measures do not reflect atypical distribution values. On the other hand, OM and K showed frequency of distribution tending to normal and lognormal.

In the study using Pearson's linear correlation, there were significant correlations for pairs of attributes: 1) PRO x VOL (r = 0.31**), 2) PRO x POP (r = 0.43**), 3) PRO x OM (r = 0.24**), 4) VOL x POP (r = 0.73**), 5) VOL x TRS (r = -0.18**), 6) VOL x T (r = 0,18*), 7) POP x OM (r = 0.25**), 8) POP x P (r = 0.19**), 9) POP x K (r = 0.36**) and 10) POP x T (r = 0.20**).

For PRO, VOL and POP are dependent variables originating from the plant. However, the last two have no interdependence relationship with the former, showing high and positive correlation coefficients, showing a direct relationship between the attributes involved, in agreement with that reported by Lima *et al.* (2010) and Dalchiavon *et al.* (2011b). OM was the only significant soil attribute with the PRO (r = 0.24**), indicating a direct independence relationship between them, corroborating with Souza *et al.* (2008). Though highly significant, the correlation coefficients showed low magnitudes, mainly due to the large number of observations (n=120). Thus, the main adjusted equations were:

$$PRO = -0.002^{**}.VOL^2+0.723^{*}.VOL+21,5 \quad (r^2 = 0.134^{**}) \qquad (2)$$

$$PRO = -0.552^{**}.POP^2+16.13^{*}.POP-15.77 \quad (r^2 = 0.210^{**}) \qquad (3)$$

$$PRO = 1.864^{**}.OM+61.461 \quad (r^2 = 0.236^{**}) \qquad (4)$$

$$PRO = 7.637+18.583^{**}.PR+241.42^{*}.GM+2.282^{**}.OM \quad (r^2 = 0.144^{**}) \qquad (5)$$

Equations 2 and 3 show the quadratic influence of the VOL and POP over PRO. The maximum point for eq. 2 was 181 m^3 ha^{-1}, while for eq. 3 it was 14.6 pl m^{-2}. With these values, there was a reversal in their parables, showing that increments in the independent variable (VOL and POP) do not reflect a similar behavior in the dependent variable (PRO). It should be noted that the determination of optimal plant population is an extremely important phytotecnical factor as it has a close relationship with the production of sugarcane stalks. Eq. 4 shows a direct variation in the linear form with the PRO. Its independent variable (OM), as it does not have any interdependence relationship with the dependent variable (PRO), in addition to having the highest correlation (r = 0.236**), can be the quality indicator when the goal is to increase the productivity of sugarcane stalks (PRO). This equation is in full agreement with the equation of Vitti *et al.* (2008) and Aguilar *et al.* (2011), which also observed a positive linear relationship between the cane PRO and OM, confirming the importance of OM in the soil management and conservation by substantially influencing its chemical, physical and biological properties, with direct implications in plant productivity. The multiple linear regressions using stepwise increased the PRO due to the PR, GM and OM, given by Eq. 5.

Table 1. Descriptive productivity analysis of sugarcane, plant population and chemical attributes of a Typic Tropustalf

Attribute[(a)]	Descriptive statistical measures									
	Mean	Median	Value		Standard Deviation	Coefficient			Test ofprobability[(b)]	
			Minimum	Maximum		Variation (%)	Kurtosis	Asymmetry	Pr<w	FD
PRO (t ha^{-1})	89.2	90.0	11.2	142.2	24.4	27.3	0.677	-0.401	0.108	NO
VOL (m^{3} ha^{-1})	159.5	155.6	41.5	269.7	41.94	26.3	0.170	0.193	0.403	NO
POP (pl. m^{-2})	10.5	10.5	5.0	15.9	2.10	19.9	0.486	-0.045	0.306	NO
TRS (kg t^{-1})	103.46	104.65	64.20	141.30	17.23	16.7	-0.691	-0.302	0.012	TN
PR (MPa)	1.066	1.092	0.349	1.907	0.324	30.4	-0.335	0.132	0.664	NO
GM (kg kg^{-1})	0.114	0.115	0.074	0.143	0.014	12.2	-0.031	-0.252	0.652	NO
OM (g dm^{-3})	15.5	15.0	10.0	23.0	2.87	18.5	0.003	0.212	0.012	TN
P (mg dm^{-3})	4.3	4.0	3.0	7.0	0.80	18.7	0.032	0.091	10^{-4}	ND
pH	5.1	5.1	4.3	6.3	0.40	7.9	0.221	0.345	0.015	TL
K (mmol$_c$ dm^{-3})	1.42	1.25	0.20	3.80	0.81	57.1	-0.065	-0.287	0.256	LN
Ca (mmol$_c$ dm^{-3})	13.9	13.0	6.0	33.0	5.32	38.4	-0.082	0.395	0.073	LN
Mg (mmol$_c$ dm^{-3})	7.3	7.0	1.0	18.0	3.26	44.4	0.651	0.815	$2x10^{-4}$	ND
H+Al (mmol$_c$ dm^{-3})	16.6	16.0	9.0	25.0	2.91	17.6	0.028	-0.127	0.036	TN
Al (mmol$_c$ dm^{-3})	0.7	0	0	5.0	1.05	161.6	3.244	1.807	10^{-4}	ND
S (mmol$_c$ dm^{-3})	22.62	21.00	10.00	51.00	8.37	37.0	-0.293	0.378	0.117	LN
T (mmol$_c$ dm^{-3})	39.20	37.85	27.70	62.80	7.15	18.2	0.243	0.581	0.012	TL
V (%)	56.2	55.0	33.0	84.0	10.93	19.5	-0.393	0.006	0.255	LN

[(a)] PRO, VOL, POP, TRS, PR, GM, OM, P, pH, K, Ca, Mg, H+Al, Al, S, T, V% are respectively the cane productivity per hectare, stalk volume per hectare, plant population per square meter, total recoverable sugars, penetration resistance, gravimetric moisture, organic matter content, phosphorus, hydrogenic potential, potassium, calcium, magnesium, potential acidity, exchangeable aluminum, sum of bases, cation exchange capacity and base saturation; [(b)] FD = frequency of distribution, and NO, TN, ND, TL and LN, respectively, are the normal type, tending to the normal, non-specific, tending to the lognormal and lognormal.

Table 2. Parameters of simple and crossed semivariograms of sugarcane productivity, plant population and chemical properties (0-0.20 m) of a Typic Tropustalf

Attribute[(a)]	Setting Parameters										
	Model[(b)]	C_o	C_o+C	A_o (m)	r^2	SSR[(c)]	SDE[(d)]		Cross Validation		
							%	Class	A	b	R
γ (h) simple – Plant											
PRO	gau (57)	$1.97x10^{-2}$	$4.86x10^{-2}$	72.0	0.854	$7.82x10^{3}$	59.4	AVD	6.51x10	0.281	0.122
VOL	exp (50)	$6.21x10^{2}$	$1.24x10^{3}$	158.1	0.858	$2.74x10^{4}$	50.0	AVD	3.09x10	0.808	0.322
#POP	exp (155)	1.73	3.46	258.3	0.710	$4.68x10^{-1}$	50.0	AVD	$2.00x10^{-2}$	0.897	0.338
#TRS	gau (51)	9.35x10	$2.05x10^{2}$	69.0	0.933	$5.77x10^{2}$	54.4	AVD	$9.00x10^{-2}$	0.599	0.239
γ (h) simple – Soil											
PR	exp (72)	$1.35x10^{-2}$	$6.16x10^{-2}$	144.0	0.947	$1.24x10^{-4}$	85.3	VHD	$4.80x10^{-1}$	0.555	0.318
GM	exp (64)	$1.03x10^{-4}$	$2.07x10^{-4}$	135.6	0.872	$6.13x10^{-40}$	50.2	AVD	$5x00x10^{-2}$	0.556	0.192
#OM	exp (236)	3.89	7.78	182.7	0.709	1.57	50.0	AVD	$-5.00x10^{-2}$	0.785	0.270
P	gau (226)	$3.6x10^{-1}$	$5.30x10^{-1}$	125.0	0.875	$2.41x10^{-3}$	32.1	LOD	1.99	0.527	0.205
#pH	gau (52)	$3.43x10^{-2}$	$1.20x10^{-1}$	69.5	0.972	$1.20x10^{-4}$	71.3	HID	0.00	1.000	0.428
#Ca	gau (42)	9.50	1.87x10	55.0	0.700	2.40x10	49.2	AVD	$-1.10x10^{-1}$	0.738	0.176
#Mg	gau (40)	3.90	6.50	70.5	0.824	$8.64x10^{-1}$	40.0	AVD	$-1.00x10^{-2}$	0.988	0.333
H+Al	gau (57)	6.95	8.80	240.0	0.885	$5.49x10^{-1}$	21.0	LOD	2.71	0.837	0.215
Al	exp (183)	$5.95x10^{-1}$	1.19	248.7	0.754	$4.47x10^{-2}$	50.0	AVD	$1.10x10^{-1}$	0.844	0.290
#S	gau (51)	1.35x10	5.30x10	60.5	0.890	9.36x10	74.5	HID	1.30x10	1.014	0.370
#T	gau (66)	2.38x10	3.90x10	61.5	0.777	2.99x10	38.9	LOD	$1.30x10^{-1}$	1.008	0.239
#V%	gau (64)	6.60x10	$1.08x10^{2}$	70.0	0.835	$2.01x10^{2}$	38.9	LOD	$-1.30x10^{-1}$	0.991	0.235
γ (h) crossed – Plant x Soil											
PRO=f(#POP)	exp (126)	1.26x10	2.51x10	357.3	0.781	2.34x10	50.0	AVD	6.70x10	0.263	0.173
PRO=f(GM)	gau (144)	$1.00x10^{-3}$	$3.99x10^{-2}$	110.0	0.616	$9.41x10^{-4}$	97.5	VHD	7.07x10	0.218	0.141
PRO=f(#OM)	exp (83)	$1.00x10^{-1}$	1.33x10	165.9	0.653	4.18x10	99.3	VHD	7.41x10	0.173	0.110

[(a)] See Table 1; # worked with the residue of the attribute; parentheses after the model means the number of pairs in the first *lag;* [(b)] gau = Gaussian, exp = exponential; [(c)] SSR = sum of squared residuals; [(d)] SDE = spatial dependence evaluator, where AVD = medium, VHD = very high, LOD = low and HID = high.

The geostatistical analysis (Table 2, Figure 2) showed that the plant attributes had spatial correlation coefficients (r^2) that ranged from high (0.710) to very high (0.933), medium spatial dependence (SDE - spatial dependence evaluator) (50.0-59.4%) and angular coefficients (b) of the cross-validation between 0.281 and 0.897. The soil attributes also showed r^2 ranging between high (0.700) and very high (0.972), SDE ranging between low (32.1%) and very high (85.3%) and angular coefficients between 0.555 and 1.014. These data were very similar to those obtained by Martins *et al.* (2009) and Lima *et al.* (2010), when studying bean and eucalyptus cultures, as well as soil physical and chemical attributes (Table 2 and Figure 2).

The semivariogram ranges were between 55.0 (#Ca) and 258.3 m (#POP), indicating that for site-specific management, the reference values should not be less than 55.0 m, as they represent the distance within which the values of a given attribute are equal.

The cross-semivariograms (Table 2, Figure 3) showed high r^2 (0.616 to 0.781) for the secondary variables #POP, GM and #OM, in accordance to Montanari *et al.* (2010). Thus, appreciable direct spatial correlations occurred, for #POP with PRO as well as for this one with #OM (Figure 2), thereby affording the definition of homogeneous management areas, which enables the use of precision agricultural system, since defining those management

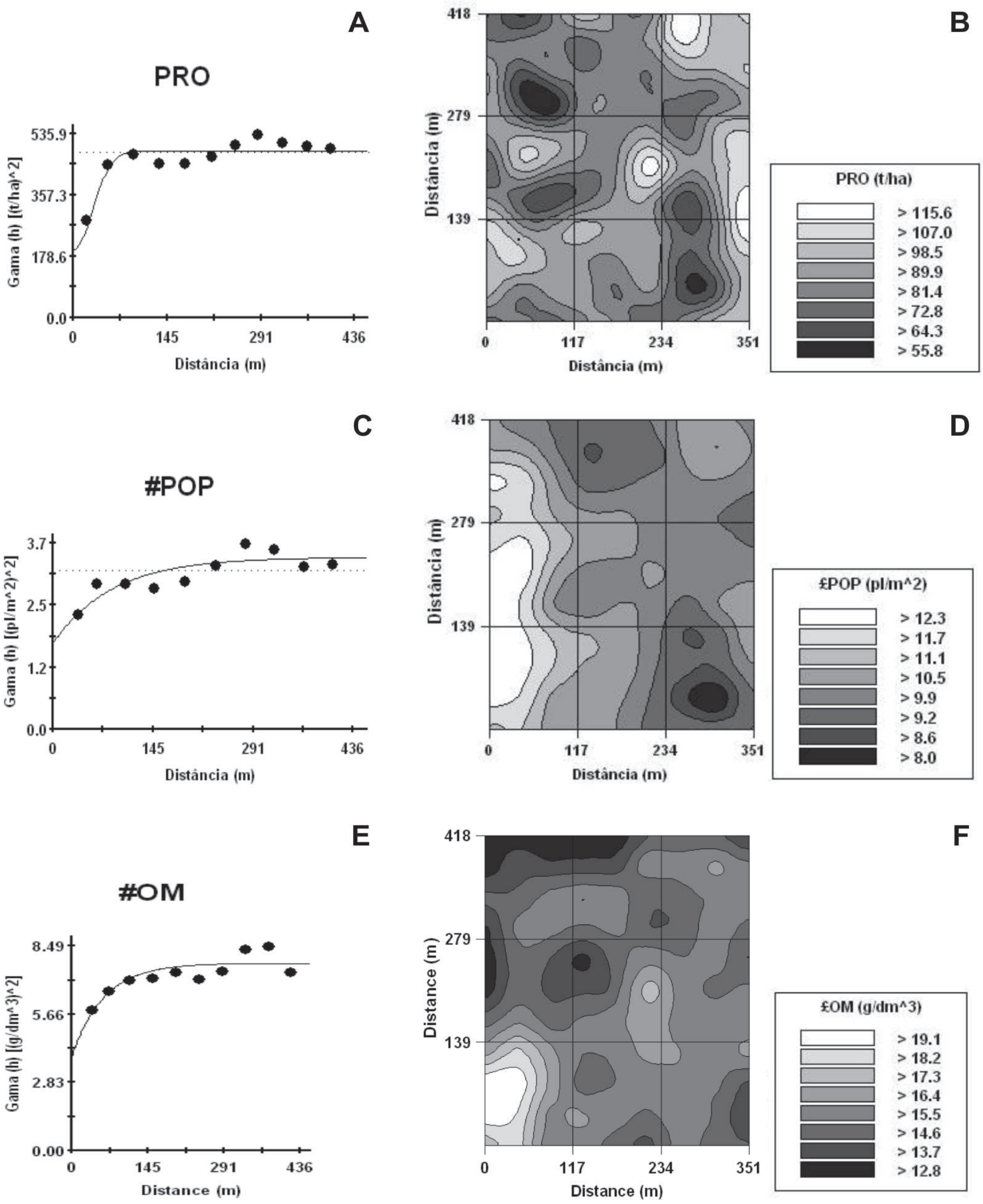

Figure 2. Simple semivariograms and kriging maps of sugarcane productivity, £POP and £OM of a Typic Tropustalf.

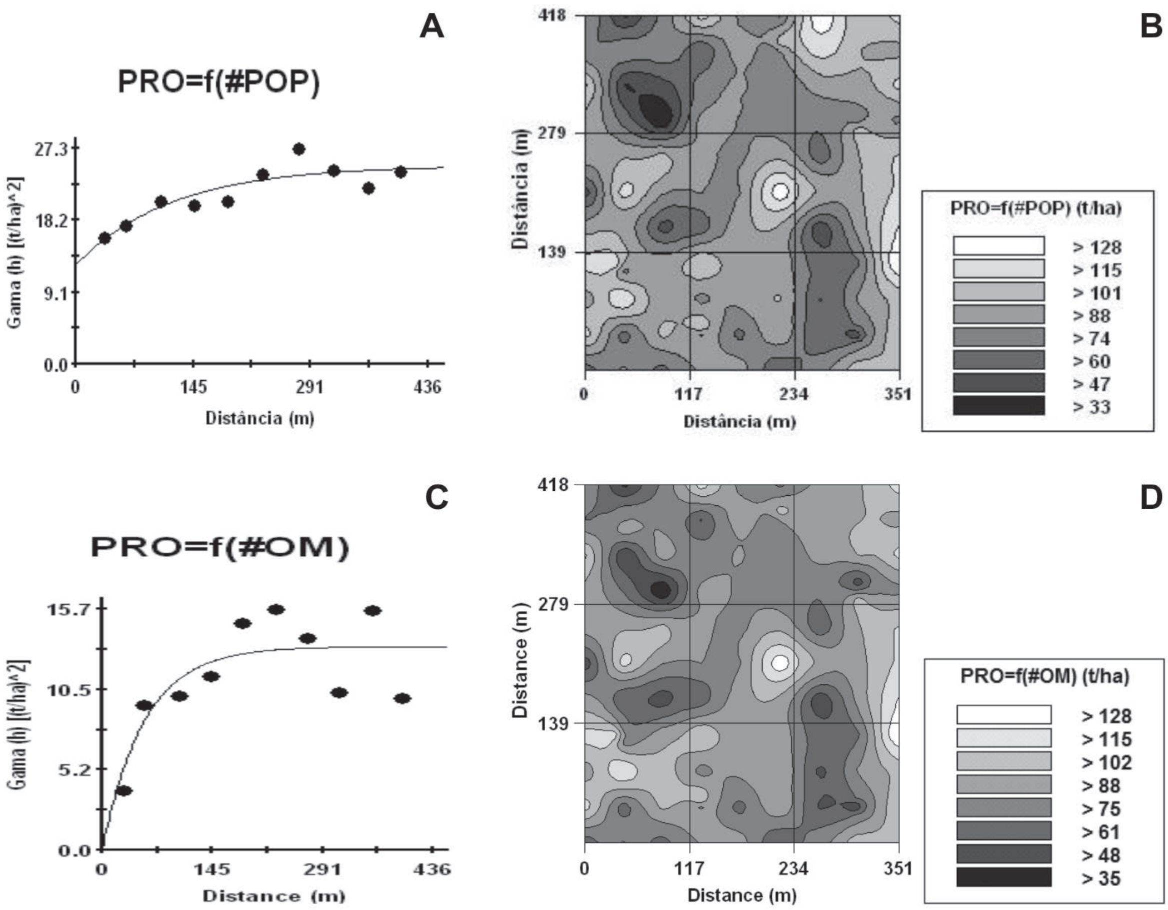

Figure 3. Cross-semivariograms and kriging maps of PRO according to £POP and £OM in a Typic Tropustalf.

areas by the interaction between crop productivity and plant populations is a promising tool, which should be complemented by analyzing the levels of soil organic matter to better define the intensity of soil sampling, already approached by Molin *et al.* (2007) (Figure 3).

In Figures 2 and 3, the direct krigings PRO=f(#POP) and PRO=f(#OM) showed at the lower #POP site (8.0-9.9 pl. m^{-2}), which coincided with the lowest #OM (12.8 to 15.5 g dm^{-3}), the lowest PRO (55.8 - 81.4 t ha^{-1}). In contrast, at the sites with higher #POP (10.5 - 12.3 pl. m^{-2}), coincided with the highest #OM (16.4 - 19.0 g dm^{-3}), the highest PRO (89.9 - 115.6 t ha^{-1}). Therefore, both attributes (#POP and #OM), as they showed appreciable direct spatial relationship with PRO, can be used as PRO indicators, when the goal is to increase the productivity of sugarcane stalks. These results are similar to those observed by Lima *et al*. (2007), which related direct spatial correlation in the productivity of corn forage as a function of soil density, by Cavallini *et al*. (2010), which reported an inverse spatial correlation of dry matter of *Brachiaria brizantha* according to soil porosity, and by Montanari *et al*. (2010), which described the direct spatial correlation of bean productivity with gravimetric soil moisture.

CONCLUSION

The plant population and soil organic matter content, as they evidenced substantial linear and spatial correlations with sugarcane stalks productivity, are indicators of site-specific management that are strongly associated with sugarcane production.

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