Revista Brasileira de Fruticultura

Spatial correlation between soil and leaf macronutrients in semiarid Brazilian mango (*Mangifera indica* L.) fields

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Abstract - Understanding the relationship between the levels of nutrients in the soil and those found in the plant is of fundamental importance for site-specific fertility management in mango (*Mangifera indica* L.) crop fields. This study aimed to evaluate the spatial distribution of macronutrient contents both in the soil and in the leaf and their correlations in commercial mango orchards under semiarid region conditions and to delimit the management zones using soil and leaf data. The experiment was carried out in three commercial areas in San Francisco Valley, Brazil, cultivated with irrigated mango. Soil samples were collected in 0-0.2 and 0.2-0.4 m depths as well as leaf samples following sample grids. Ca, Mg, K, P, and N contents from soil and leaf samples were determined. Descriptive and geostatistics analyses were performed. Co-kriging was used for the delimitation of management zones. Positive spatial correlations were obtained between soil Ca^{2+} and leaf Ca contents ($R^2 = 0.80$-0.93), soil K^+ and leaf K contents ($R^2 = 0.35$-0.61), and soil Mg^{2+} and leaf P contents ($R^2 = 0.51$). Negative correlations were observed for soil Mg^{2+} and leaf Ca contents($R^2 = 0.79$-0.93) and soil Mg^{2+} and leaf K contents ($R^2 = 0.98$). The soil 0-0.2 m depth had the greatest influence on mango Ca and K uptake. The negative correlation between soil Mg^{2+} and leaf Ca shows the competition existing in the plant uptake process. It was possible to delimit specific management zones using co-kriging for the three areas using soil and leaf data.

Index Terms: Geostatistics. Mineral nutrition. Spatial analysis. Management zones.

Correlação espacial entre macronutrientes de solo e folha em pomares de mangueira (*Mangifera indica* L.) no semiárido brasileiro

Resumo - Compreender a relação entre os níveis de nutrientes no solo e aqueles encontrados na planta é de fundamental importância para o manejo específico da fertilidade em áreas de cultivo de mangueira (*Mangifera indica* L.). O objetivo deste estudo foi avaliar a distribuição espacial dos teores de macronutrientes no solo e na folha, e suas correlações em pomares comerciais de manga, em condições de região semiárida, e delimitar as zonas de manejo utilizando dados de solo e de folha. O experimento foi realizado em três áreas comerciais do Vale do São Francisco, Brasil, cultivadas com manga irrigada. Amostras de solo foram coletadas nas profundidades de 0-0,2 e 0,2-0,4 m, bem como amostras de folhas, seguindo malhas amostrais. Foram determinados os teores de Ca, Mg, K, P e N das amostras de solo e de folha. Foram realizadas análises descritivas e geoestatísticas. A co-krigagem foi usada para a delimitação de zonas de manejo. Correlações espaciais positivas foram obtidas entre Ca^{2+} no solo e Ca foliar ($R^2 = 0,80$-$0,93$), K^+ no solo e K foliar ($R^2 = 0,35$-$0,61$) e Mg^{2+} no solo e P foliar ($R^2 = 0,51$). Correlações negativas foram observadas para o Mg^{2+} no solo e Ca foliar ($R^2 = 0,79$-$0,93$) e Mg^{2+} no solo e K foliar ($R^2 = 0,98$). O solo de 0-0,2 m de profundidade teve a maior influência na absorção de Ca^{2+} e K^+ pelas plantas. A correlação negativa entre Mg^{2+} do solo e Ca foliar mostra a competição existente no processo de absorção das plantas. Foi possível delimitar zonas de manejo específicas utilizando cokrigagem para as três áreas, usando dados de solo e de folha.

Termos para indexação: Geoestatística. Nutrição mineral. Análise espacial. Zonas de manejo.

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Introduction

Mango crops are cultivated in the tropical and subtropical regions of the world. They stand out in the agribusiness because of their demand and export potential (CORDEIRO et al., 2014). In this context, Brazil produced 1,087,091 megagrams (Mg) of mango (IBGE, 2017) in 2017, with the semi-arid region of the Northeast being the main exporter of this fruit (KIST et al., 2018).

The correct recommendation regarding fertilization is essential to meet plant nutritional needs and, thereby, obtain profitable productivities in commercial mango orchards (COSTA et al., 2011). However, fertilizers and other crop inputs have been traditionally applied to mango orchards without considering the spatial variability of the field. Such agricultural management practices may be inefficient because of the under-application and over-application of the crop inputs in specific orchard areas. Consequently, the under-treated zones do not reach optimum levels of yield, whereas in the over-treated zones, there may be increased production costs and environmental pollution (AGGELOPOULOU et al., 2011; LÓPEZ-GRANADOS et al., 2004).

The most commonly-used approach to manage spatial variability within fields is homogeneous management zones (MZs), in which the field is subdivided into smaller areas that have relatively homogeneous attributes such as soil properties. This technique can be used to direct variable-rate fertilizer application (FAROOQUE et al., 2012).

The delimitation of MZs using soil maps is a viable and efficient tool for optimizing fertilization in crop fields, as reported in several studies (AGGELOPOULOU et al., 2013; FAROOQUE et al., 2012; OLDONI et al., 2019; SILVA et al., 2020). However, most of these studies did not consider leaf analysis. There are some studies on leaf nutrient spatial variability on apple fields (SHARMA, 2018) and oil palm fields in India (BEHERA et al., 2016), olive fields in Spain (LÓPEZ-GRANADOS et al., 2004), coffee fields in Brazil (SILVA et al., 2013), as well as citrus fields in both Brazil (ARMINDO et al., 2012) and the USA (QAMAR UZ; SCHUMANN, 2006). However, none of them had used the data of leaf and soil nutrients in the same map to define management zones.

It is necessary to map the nutrients in both soil and plant for a more accurate determination of the recommended amount of fertilization, as the existence of nutrients in the soil in adequate conditions does not necessarily guarantee that these elements will be taken up by plants (FARIA et al., 2016). This is because factors such as soil type, soil compaction, nutrient concentration, soil pH, competition among nutrient molecules for adsorption sites in the soil, uptake rate by roots, and nutrient equilibrium affect their availability, and can cause nutritional deficiency (NOVAIS et al., 2007).

Therefore, it is hypothesized that the use of both soil and leaf nutrient data will enable the determination of management zones more accurately than approaches that use only soil data for fertility management in mango crops.

Based on this hypothesis, the aim of this study was to evaluate the spatial distribution of macronutrient contents in the soil and in the leaves, and determine their correlations in commercial mango orchards under the conditions associated with semiarid region. Using the data from both soil and leaf, we also sought to delimit management zones.

Materials and Methods

- Site description

The experiment was carried out during 2017 and 2018, in three commercial mango orchards considered homogeneous by the farmers (same soil and crop management practices), in the Brazilian semiarid region of the San Francisco Valley. Cultivation was performed under irrigation with the cultivar "Tommy Atkins" in distinct soils which varied in texture and textural gradient. The main characteristics of these fields are described in Table 1. According to Köppen's classification, the local climate is BSh, which is semiarid with annual precipitation less than 500 mm that is concentrated in only three to four months of the year. Furthermore, annual average temperature varies between 18.7 °C and 33.6 °C (ALVARES et al., 2013).

- Data Collection and Soil Analysis

Soil samples were collected under the canopy region after harvest (before the application of fertilizers), at depths of 0.0-0.2 m and 0.2-0.4 m, following regular grids containing 56 georeferenced points (56 × 30 m) in the Barreiro de Santa Fé area (Figure 1A), 50 points (32 × 25 m) in the Mandacaru area (Figure 1B), and 53 points (42 × 35 m) in the Sempre Verde area (Figure 1C). The number of samples was defined according to two criteria: 1) obtaining at least 30 pairs of points for calculation of the semivariance in the first lag (ARÉTOUYAP et al., 2016) following Yamamoto and Landim's (2013) recommendation of at least 30 to 40 points, and 2) the geometric shape of each area.

Table 1. Location, slope, soil type, area size, age and spacing of the crop, irrigation and fertilization of the Barreiro, Mandacaru and Sempre Verde crop areas cultivated with irrigated mango cv. Tommy Atkins in the San Francisco Valley region, Brazil

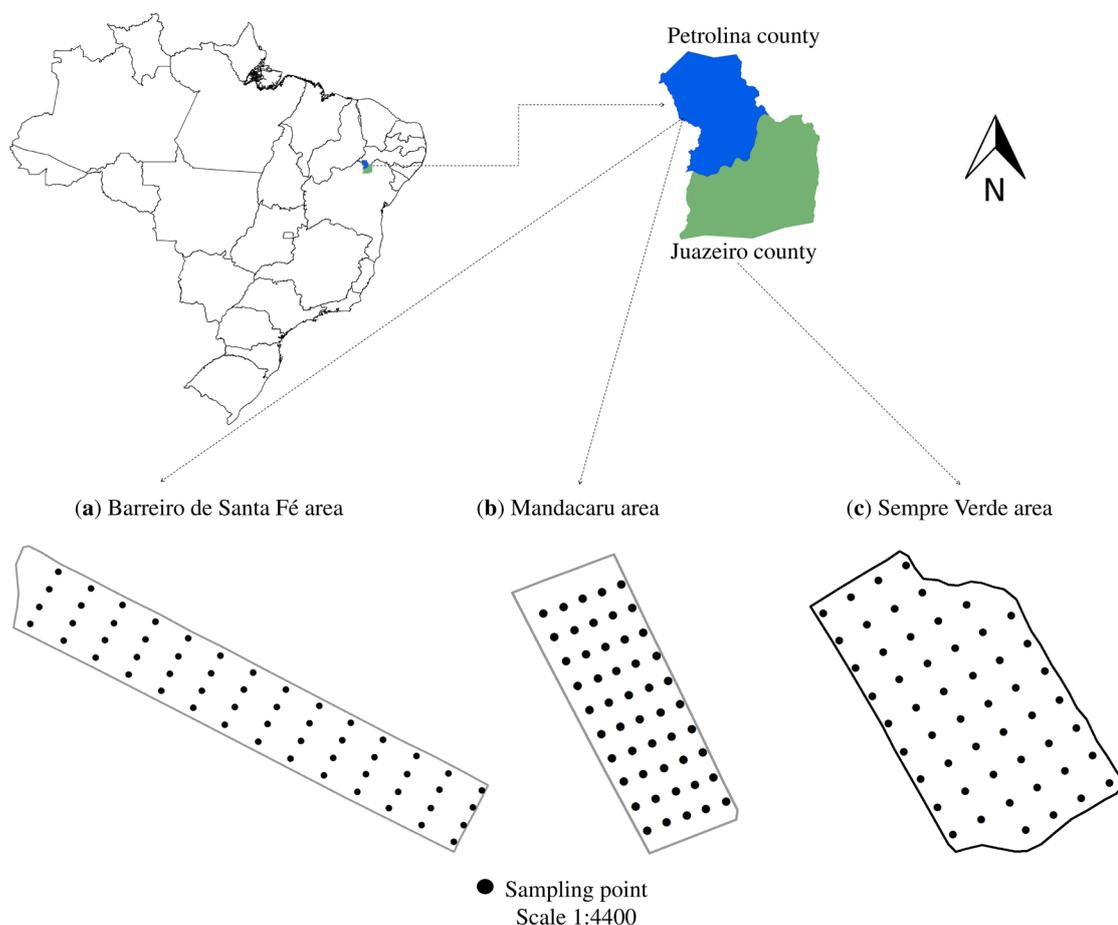|	**Barreiro de Santa Fé**	**Mandacaru**	**Sempre Verde**
Location	Petrolina, Pernambuco (9°23'39.37" S and 40°44'32.91" W)	Petrolina, Pernambuco (9°20'50.58" S and 40°33'04.51" W)	Juazeiro, Bahia (9°14'59.38" S and 40°16'58.40" W)
Slope	Very gentle	Very gentle	Very gentle
Soil type	Oxisol	Ultisol	Ultisol
Size	9 ha (797 x 114 m)	4.5 ha (353 x 125 m)	9.5 ha (411 x 232 m)
Crop age	25 years old	26 years old	25 years old
Crop spacing	8 x 5 m	8 x 5 m	7 x 6 m
Irrigation	sprinkler (two sprinkles /plant)	sprinkler (two sprinkles /plant)	sprinkler (two sprinkles /plant)
Fertilization	fertigation for N, P and K and manual application for Ca and Mg	fertigation for N, P and K and manual application for Ca and Mg	fertigation for N, P and K and manual application for Ca and Mg

Figure 1. Sampling design in the mango fields located in the San Francisco Valley region, semi-arid, Brazil. a) 56 georreferenced points in the Barreiro de Santa Fé area, b) 50 points in the Mandacaru area, and c) 53 points in the Sempre Verde area

The disturbed soil samples were obtained using a Dutch auger probe and each soil sample was analyzed for Ca^{2+}, Mg^{2+}, K^+, and P concentrations. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) were extracted using 1.0 mol L^{-1} KCl solution and the reading was carried out through atomic absorption spectrometry. The phosphorus content (P) was obtained using visible ultraviolet (UV) spectrometry. The potassium content (K^+) was extracted using the Mehlich-1 and the reading was performed using flame emission photometry. All soil analyses were performed following the procedures described by Teixeira et al. (2017).

The leaves were collected in the four quadrants and at the height of the middle third of the canopy of the plants, following the same sampling grids used in the soil collection. Two leaves from the last flushes of vegetation were collected per quadrant (GENÚ; PINTO, 2002). The leaves were then quickly washed with tap water and rinsed with distilled water. Thereafter, they were placed in paper bags and placed in an oven with forced air circulation at 60ºC until a constant weight was obtained, before being crushed in a mill to obtain particles that were 0.85 mm in diameter. The leaf samples were subjected to nitric-perchloric digestion to determine the levels of Ca and Mg (via atomic absorption spectrometry), and K (via flame photometry). Furthermore, sulfuric digestion was used to determine N by distillation, following the procedures described by Silva (2009).

- Descriptive statistics

Descriptive analysis of the data (mean, maximum, and minimum values; standard deviation; and coefficient of variation) was performed. Data normality was verified by the Shapiro-Wilk test, at 5% probability, using R statistical software (version 3.2.2) (R Core Team, 2015). The coefficient of variation (CV) was classified according to Pimentel-Gomes and Garcia (2002), who defined CV ≤ 10% as low, 10% < CV ≤ 20% as medium, 20% < CV ≤ 30% as high, and CV > 30% as very high variability. Furthermore, Quaggio's (1996) classification was used to obtain the leaf nutrient reference values in mango trees, whereas Manica's (2001) classification was used to obtain soil nutrient reference values for mango production.

- Geostatistical analysis

Semivariogram models were used to estimate the spatial dependence between the samples and to identify whether the variations were systematic or random using GS+ software v. 10 (Free Trial License) (ROBERTSON, 2008). The trend surface method, proposed by Vieira et al. (2010), was performed for variables that showed a trend, meaning there was no stabilization of the sill values and thus the intrinsic hypothesis was not satisfied. This method involves fitting a trend surface by the least squares method and subtracting it from the original data, thereby generating a new variable called, residuals. The semivariogram was then fitted using the residuals. The spatial dependency index (SDI) proposed by Seidel and Oliveira (2016) was used to verify the degree of spatial dependence.

To verify the spatial correlation between the soil and leaf variables, a cross-semivariogram was used, which describes the spatial dependence that occurs between two variables simultaneously. It is important to highlight that the cross-semivariogram can only be fitted if the two variables present spatial dependence verified by the simple semivariogram (ROSEMARY et al., 2017; SCHAFFRATH et al., 2015; TEIXEIRA et al., 2013). The correlation will be positive if the model is presented in the first quadrant of the Cartesian plane and will be negative if the model is presented in the fourth quadrant. Moreover, the degree of spatial dependence can also be measured by the SDI.

Co-kriging was used to delimit the management zones, considering both leaf and soil data. This interpolation method is the multivariate extension of kriging, which is used between any two variables, soil and/or plant, in which spatial correlation occurs (YAMAMOTO; LANDIM, 2013).

Results and Discussion

- Description analysis results

Data variability, measured by the CV and based on the limits proposed by Pimentel-Gomez and Garcia (2002), generally indicates great variability of nutrients both in the soil and in the leaf, even in areas considered homogeneous by farmers (Table 2). Evidence of this can be found when Rodrigues et al. (2018) identified high variability in soil nutrients in a commercial mango orchard under Alfisol in Bahia state, Brazil. The CV values of leaf nutrient content were similar to those found by Sharma et al. (2018) in commercial apple-growing areas in the Himalayas.

Table 2. Soil and leaf nutrient content in three irrigated mango crop field cv. Tommy Atkins in the post-harvest stage in the San Francisco Valley region, Brazil

	K⁺	Ca²⁺	Mg²⁺	P	K⁺	Ca²⁺	Mg²⁺	P	K	Ca	Mg	P	N
	--- cmol$_c$ dm⁻³ --- 0-0.2 m			mg dm⁻³	--- cmol$_c$ dm⁻³ --- 0.2-0.4 m			mg dm⁻³	--------- g kg⁻¹ --------- Leaf				
Barreiro de Santa Fé													
Mean	0.29	4.51	1.84	60.02	0.53	3.46	1.56	49.33	8.58	39.80	2.16	1.12	8.00
Maximum	0.44	6.25	2.3	249.14	0.92	4.63	2.10	224.73	22.21	38.06	3.31	1.50	10.68
Minimum	0.15	3.15	1.47	10.45	0.26	2.36	1.08	11.59	3.24	23.06	1.55	0.78	5.74
Standard deviation	0.07	0.73	0.2	63.72	0.16	0.59	0.20	47.53	4.78	15.86	0.40	0.19	1.10
CV (%)	25	16	11	76	31	17	13	96	56	40	19	17	14
CV Classification	H	M	M	VH	VH	M	M	VH	VH	VH	M	M	M
W	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.19ns	0.00*
Mandacaru													
Mean	0.43	2.38	0.82	14.81	0.33	1.19	0.65	37.55	7.75	445.56	2.63	1.24	13.42
Maximum	0.92	3.78	1.43	68.75	0.62	1.93	0.87	49.09	21.24	501.88	3.54	1.59	16.56
Minimum	0.21	1.54	0.50	3.27	0.13	0.60	0.42	26.86	2.00	343.60	1.81	0.86	10.36
Standard deviation	0.18	0.52	0.22	12.77	0.13	0.32	0.12	12.77	5.25	38.13	0.49	0.16	1.56
CV (%)	42	22	27	86	38	27	19	14	68	9	19	13	12
CV Classification	VH	H	H	VH	VH	H	M	M	VH	L	M	M	M
W	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.01*	0.00*	0.61ns
Sempre Verde													
Mean	0.61	6.00	2.09	69.84	0.72	5.98	1.89	38.59	6.02	93.54	2.50	3.24	12.43
Maximum	1.21	10.22	2.56	159.75	1.56	10.61	2.73	91.98	13.74	122.91	3.78	4.95	14.70
Minimum	0.38	3.00	1.50	22.22	0.26	3.00	0.73	2.71	2.20	57.13	1.54	2.21	9.38
Standard deviation	0.21	1.85	0.30	32.02	0.33	1.96	0.51	24.05	3.00	22.14	0.59	0.65	1.22
CV (%)	31	31	14	46	45	33	27	62	50	24	24	20	10
CV Classification	VH	VH	M	VH	VH	VH	H	VH	VH	H	H	M	L
W	0.00*	0.45ns	0.30ns	0.00*	0.00*	0.43ns	0.13ns	0.00*	0.00*	0.00*	0.33ns	0.02*	0.00*

CV: coeficiente of variation; W: Shapiro-Wilk's test (p<0,05); CV classification: L (CV ≤10%) - low, M (10% < CV ≤ 20%) - medium, H (20% < CV ≤ 30%) - high, VH (CV > 30%) - very high.

Data normality was observed for the following values: leaf P content in the Barreiro de Santa Fé area; leaf N content in the Mandacaru area; and soil Ca^{2+} and Mg^{2+} contents in the two soil layers, and leaf Mg content in the Sempre Verde area (Table 2). The other variables had a non-normal distribution according to the Shapiro-Wilk test ($p<0.05$). Notably, the normality of the data is not a requirement of geostatistics; it is only convenient that the distribution does not have very elongated tails, which can compromise the estimation of the data when performing the interpolation using kriging (YAMAMOTO; LANDIM, 2013).

The soil P content, and leaf Ca and K contents in the areas studied showed the highest amplitudes (maximum-minimum values), demonstrating that these attributes showed less uniformity in the area. Similarly, Kongor et al. (2019) found the highest amplitudes for soil P content in cocoa fields in Ghana. The P in the soil can be lost or fixed within the soil particles. Therefore, this loss can occur both in the solid phase, by the adsorption of the P to the oxide particles of Fe and Al, and via the precipitation of P with Fe, Al, or Ca (NOVAIS et al., 2007). As a result, this can increase the P content variability. Qamar Uz and Schumann (2006) also found high amplitude for leaf Ca in a citrus field in Florida, USA; however, medium amplitude was found for leaf K content in the same field. The oscillation of leaf Ca and K contents in mango crops may be the result of foliar applications of calcium nitrate and potassium nitrate during the floral induction process of the mango tree, which is common practice on this crop in the Brazilian semiarid region (SILVA; NEVES, 2011).

According to Quaggio's (1996) leaf-nutrient classification, the three studied areas showed adequate levels of K and Mg. Leaf N content was classified as deficient only in the Barreiro de Santa Fé area, while Mandacaru and Sempre Verde areas showed excessive levels of leaf Ca concentration (Table 2). Most of the soil nutrients in the three areas studied showed excessive levels according to Manica's (2001) soil nutrient classification. Exceptions to this trend were the soil K^+ and Mg^{2+} contents in the Mandacaru area, which showed adequate levels.

It is important to note that the excessive levels of leaf nutrients found in the present study did not reflect toxicity problems in the plants. As stated by Barbosa et al. (2016), despite the valuable information contained in the reference values of the literature for the interpretation of leaf nutrient levels, success in the interpretation of these analyses is conditioned to the collection of reference standards that can be obtained under specific conditions of climate, soil type, and orchard management. Therefore, mango production under the conditions of the San Francisco Valley is different from that found in the reference value tables. For example, the mean mango yield found in this region is higher than that found in other producing regions in Brazil; thus, the nutrient needs could also be higher.

In addition, the concentrations of soil and plant nutrients also vary according to the phenological crop stage, as found by Costa et al. (2011), who observed differences in leaf nutrient concentrations during the cultivation cycle in mango cv. "Tommy Atkins" in the state of Rio Grande do Norte, Brazil. In the present study, leaves were collected after harvest, while Quaggio's (1996) classification was obtained at the full flowering stage. According to Faria et al. (2016), the average values of nutrient content in mango leaves, as a function of different stages, indicate the occurrence of two distinct stages. The first of which is the period between the harvest and the beginning of the new flowering, during which there is an accumulation of nutrients. The second covers the period from the development of the fruit until its harvest, when there is a decrease in the levels of nutrients in the leaves. As a result, it is necessary to classify the leaf nutrient levels according to each stage.

- Geostatistics analysis

It was observed, using semivariograms analysis (Table 3), that soil K^+ and Mg^{2+} content in soil 0.2-0.4 m deep in the Barreiro de Santa Fé area, leaf Mg content in the Barreiro de Santa Fé and Sempre Verde areas, and leaf N content in the Barreiro de Santa Fé area, showed pure nugget effect (PNE). This means that they did not show spatial dependence. However, spatial dependence was found for leaf Mg content both by Behera et al. (2016) in an oil palm field in India and by Qamar Uz and Schumann (2006) in a citrus field in the USA. In addition, López-Granados et al. (2004) found spatial dependence of leaf N content in an olive field in Spain. The presence of spatial dependence of soil K^+ and Mg^{2+} contents, in soil at depths of 0.2-0.4 m, may be related to the type of soil. This is because in the areas under Ultisol, which has an increase of clay in the B horizon, spatial dependence was observed. Meanwhile, a pure nugget effect for these variables was observed in the area under Oxisol, a type of soil that has no textural gradient (SANTOS et al., 2018). The influence of soil type was not observed for the spatial dependence of leaf Mg content, probably because the concentration of Mg in the leaf may vary due to factors other than those associated with the soil.

Table 3. Variogram model parameters and interpolation method of the soil and leaf nutrient content in three irrigated mango crop field cv. Tommy Atkins in the San Francisco Valley region, Brazil

	K+	Ca2+	Mg2+	P	K+	Ca2+	Mg2+	P	K	Ca	Mg	P	N
	--- cmolc dm-3 --- 0-0.2 m			mg dm-3	--- cmolc dm-3 --- 0.2-0.4 m			mg dm-3	---------- cmolc dm-3 ----------			---------- g kg-1 ---------- Leaf	
Barreiro de Santa Fé													
Model	EXP	SPH	GAU	GAU	PNE	SPH	PNE	SPH	GAU	SPH	PNE	SPH	PNE
C0	0.0009	0.1190	0.0118	616.207	0.002	0.1089	0.0341	122.1602	3.2025	9.3011	0.2050	0.0201	1.2508
C0+C	0.008	0.491	0.035	6700.061	0.002	0.599	0.0341	1693.648	16.821	201.9	0.205	0.048	1.251
Range	57	103	79	53	-	138	-	62	43.8111	192.1	-	108.6	-
IM	Krig	Krig	Krig	Krig	IDW	Krig	IDW	Krig	Krig	Krig	IDW	Krig	IDW
SDI	W	W	W	W	-	M	-	W	W	S	-	W	-
Mandacaru													
Model	GAU	SPH	SPH	SPH	GAU	GAU	SPH	GAU	GAU	EXP	SPH	SPH	GAU
C0	0.0019	0.0054	0.0024	20.8943	0.0013	0.0038	0.0006	98.6928	1.0588	67.0188	0.0289	0.0023	0.347
C0+C	0.033	0.245	0.050	291.900	0.037	0.113	0.017	2710	20.731	2108	0.226	0.064	1.972
Range	43	45	42	43	57	50	42	46	39.664	111.87	34.9	44.6	91.11
IM	Krig	Krig	Krig	Krig	Krig	Krig	Krig	Krig	Krig	Krig	Krig	Krig	Krig
SDI	M	M	M	M	S	M	M	M	M	S	W	M	S
Sempre Verde													
Model	SPH	SPH	EXP	SPH	EXP	SPH	EXP	GAU	SPH	SPH*	PNE	SPH	EXP
C0	0.0150	1.4090	0.0214	783.8224	0.0161	2.0637	0.0174	93.0680	0.35	7.9546	0.3772	0.1193	0.583697
C0+C	0.030	3.658	0.102	1910.592	0.121	4.043	0.212	645.843	11.03	139.4	0.3772	0.3546	3.978
Range	122	126	92	120	127	113	138	82	83.5	135.4	-	184.3	99.3
IM	Krig	Krig	Krig	Krig	Krig	Krig	Krig	Krig	Krig	Krig	IDW	Krig	Krig
SDI	M	M	M	M	S	M	S	M	M	S	-	S	S

C0: nugget effect; C0+C: sill; IM: interpolation method; SDI: spatial dependency index proposed by Seidel and Oliveira (2016); EXP: exponential model; SPH: spherical model; GAU: gaussian model; PNE: pure nugget effect; Krig: Kriging; IDW: inverse distance weighting; W: weak spatial dependency; M: moderate spatial dependency; S: strong spatial dependency; *The semivariogram was estimated with the residues.

Based on the spatial dependence index (SDI) in the Barreiro de Santa Fé area, all soil properties within depths of 0.0-0.2 m, and soil P content within depths of 0.2-0.4 m, as well as leaf K and P contents, were classified as having weak spatial dependence. Meanwhile, leaf Ca content in this area was classified as having strong spatial dependence (Table 3). In the Mandacaru area, leaf Mg content was classified as having weak spatial dependence; while all soil properties in both soil layers, as well as the leaf K and P contents, showed moderate spatial dependence. Furthermore, leaf Ca and N contents in this area showed strong spatial dependence (Table 3). In the Sempre Verde area, all soil properties at 0.0-0.2 m depths, as well as soil Ca^{2+} and P contents at 0.2-0.4 m depths, and leaf K and N contents had moderate spatial dependence. Meanwhile, soil K^+ and Mg^{2+} contents at depths of 0.2-0.4 m, as well as leaf Ca and P contents, showed strong spatial dependence (Table 3). The stronger the spatial dependence of the variables, the better the estimate in the interpolation. These results reinforce the theory that the spatial structure and degree of spatial dependence of a variable can vary considerably in different fields, even those with similar characteristics (climate, soil type, slope, crop type, etc.). It also demonstrates that the spatial variability can be related to anthropomorphic factors such as fertilization and irrigation. Therefore, as stated by Silva et al. (2020), a geostatistical analysis is required for each crop field to understand and quantify the spatial variability of its variables.

In the cross-semivariograms performed between soil nutrients and leaf nutrients (Figures 2, 3, and 4), a positive correlation for soil K^+ content at depths of 0.0-0.2 m and leaf K content (Figures 2B and 3A) was observed. This result was also seen for soil Ca^{2+} content at 0.0-0.2 m depths and leaf Ca content (Figures 2A and 4A). For these two relationships (soil potassium & leaf potassium and soil calcium & leaf calcium), the SDI was classified as strong, confirming the high spatial dependence between these variables in the fields studied. Santos et al. (2014) have verified that in the mango cv. "Tommy Atkins" that was irrigated with micro-sprinklers and cultivated in the semiarid region of Brazil, the highest root density was between 0.20 m and 0.90 m depths. However, the results of the present study showed that the soil layer that contributes the most to the uptake of K^+ and Ca^{2+} by plants is the topsoil (0.0-0.2 m). This is because the areas are fertigated; meaning, nutrients are provided by the irrigation system, making absorption via the roots more superficial in the soil and around the micro-sprinkler. Another possible explanation for why the 0.2-0.4 m depth contributes less towards nutrient uptake is the high evapotranspiration rate present in the study region. This hinders the permanence of the nutrients in the soil solution of the subsoil because water and nutrients rise because of the capillarity motion as soon as fertigation ceases. In addition, due to the low solubility of limestone and the slow downward movement of Ca^{2+} (PAULETTI et al., 2014), the liming effects are limited to the superficial layers of the soil. This occurs without any incorporation, mainly because of the application of limestone in mango orchards of the semiarid region. These hypothesis can be confirmed by the negative correlation between Ca^{2+} content at 0.2-0.4 m depths and leaf Ca content (Figure 4B).

Based on the coefficient of determination (R^2), which indicates the goodness of the model fit to the data, the relationship between soil Ca^{2+} content at 0.0-0.2 m depths and leaf Ca content (Figures 2A and 4A) was stronger than the relationship between soil K^+ content at depths of 0.0-0.2 m and leaf K content (Figures 2B and 3A) . This can be explained because K does not form organic compounds in the plant tissue and is easily transported from leaves to soil after a rain (RODRIGUES et al., 2012), therefore, this may increase the spatial variability and decrease the spatial correlation between the soil K^+ content and the leaf K content.

A positive correlation between soil Mg^{2+} content at depths of 0.0-0.2 m and leaf P content, was found in the Barreiro de Santa Fé area (Figure 2C) with a R^2 equal to 0.51, and the SDI was classified as moderate. Faquin (2005) affirmed the existence of synergism between the nutrients Mg^{2+} and P, in which Mg^{2+} increases P uptake. This is probably due to the large amount of Mg^{2+} that is linked to polyphosphates, such as Mg-ATP (adenosine triphosphate). The abundance of this nutrient suggests a multiplicity of functions, mainly as an activator of enzymatic reactions. Thus, it can be proposed that Mg^{2+} influences the movement of carbohydrates from the leaves to other parts of the plant and stimulates the uptake and transport of P in the plant (NOVAIS et al., 2007).
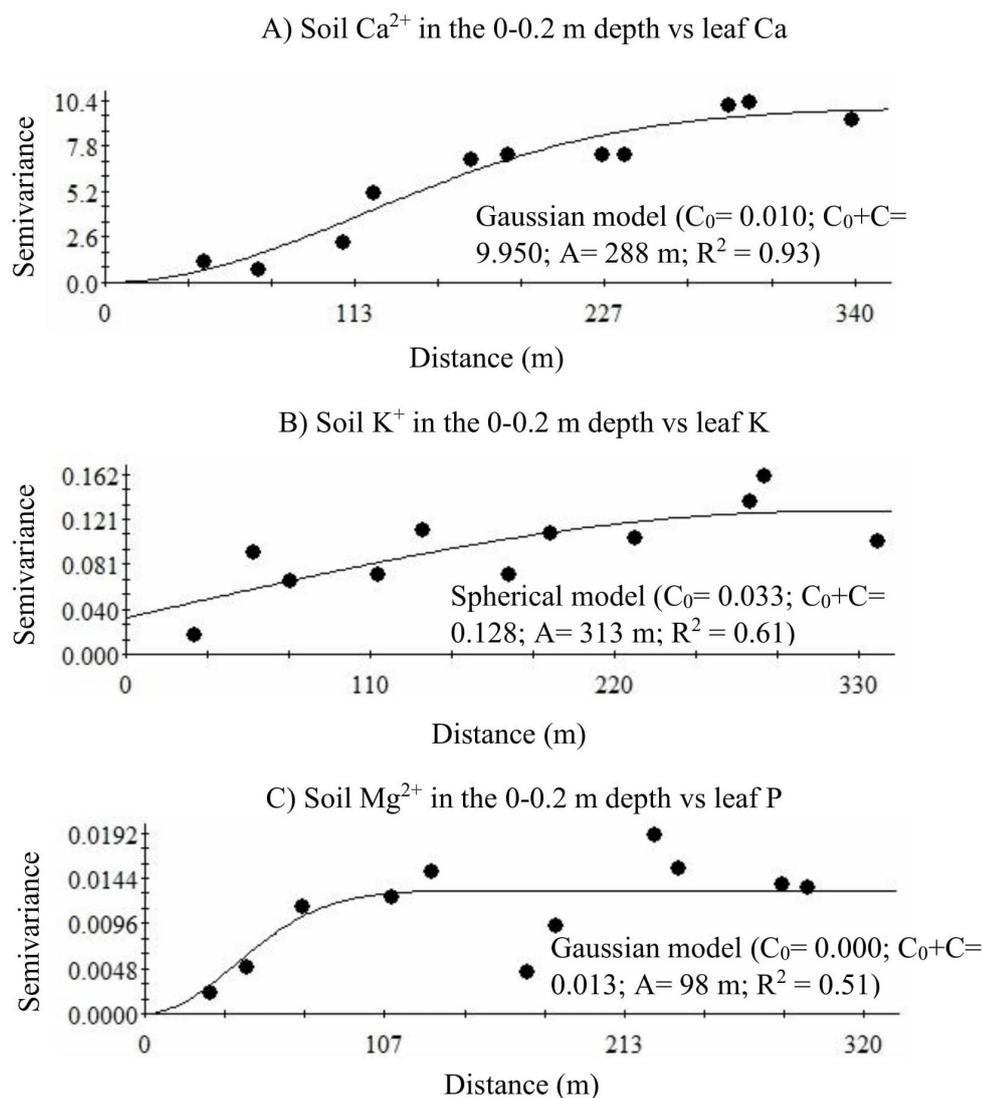
A) Soil Ca^{2+} in the 0-0.2 m depth vs leaf Ca

Gaussian model (C_0= 0.010; C_0+C= 9.950; A= 288 m; R^2 = 0.93)

B) Soil K$^+$ in the 0-0.2 m depth vs leaf K

Spherical model (C_0= 0.033; C_0+C= 0.128; A= 313 m; R^2 = 0.61)

C) Soil Mg^{2+} in the 0-0.2 m depth vs leaf P

Gaussian model (C_0= 0.000; C_0+C= 0.013; A= 98 m; R^2 = 0.51)

Figure 2. Cross-variograms between soil and mango cv. Tommy Atkins leaf nutrients in Barreira de Santa Fé farm, San Francisco Valley region, Brazil (C_o: nugget effect; C_o+C: sill; A: range)
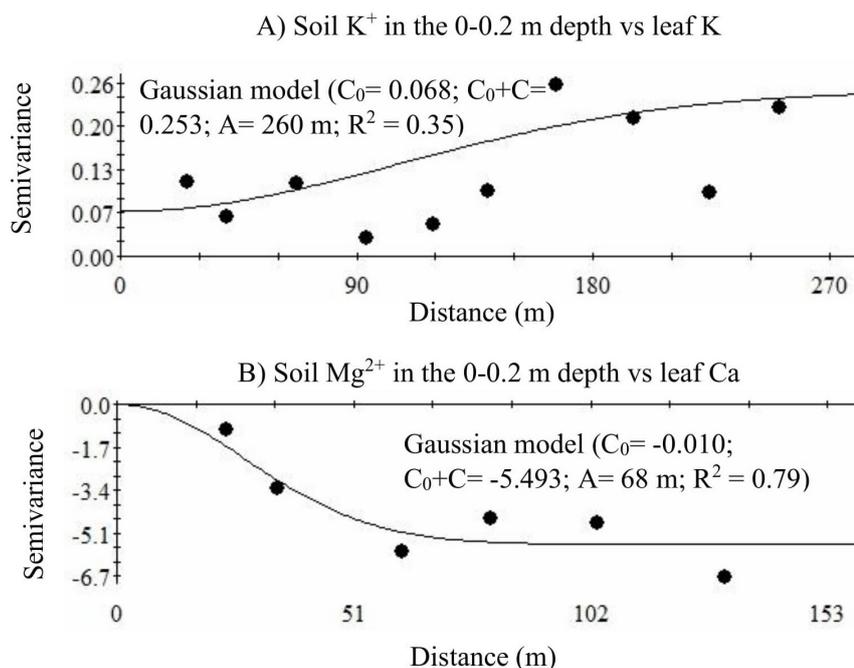
Figure 3. Cross-variograms between soil and mango cv. Tommy Atkins leaf nutrients in Mandacaru farm, San Francisco Valley region, Brazil (Co: nugget effect; Co+C: sill; A: range)

In the Mandacaru and Sempre Verde areas, soil Mg^{2+} content at 0.0-0.2 m depths, and leaf Ca content, showed a high negative correlation (Figures 3B and 4C) and the R^2 varied from 0.79 to 0.90. One of the most important relationships can be found between Ca^{2+} and Mg^{2+}. In plant nutrition, this relationship is related to their very similar chemical properties, such as the degree of valence and mobility in the soil. This causes competition for adsorption sites in the soil and uptake by the plant roots (SALVADOR et al., 2011). Therefore, the negative correlation between soil Mg^{2+} content at depths of 0.0-0.2 m and leaf Ca content can be explained by the three times greater amount of calcium in the soil in relation to magnesium. This ratio can affect the availability of Ca^{+2} for the plant, as Mg^{2+} is taken up in less quantity than Ca^{2+}. Furthermore, the competition between these cations is specifically important for Mg^{2+} and may lead to deficiencies in the crop field (BENITES et al., 2010).

The negative correlation between soil Mg^{2+} content at depths of 0.0-0.2 m and leaf Ca content shows that competitive inhibition occurs in the uptake process, as there is a decrease in the uptake of one due to the presence of the other. In this case, the effect of the inhibiting nutrients can be canceled out by increasing the concentration of the element being inhibited in the soil (FAQUIN, 2005). Thus, several authors propose that, instead of searching for adequate levels of Ca^{2+}, Mg^{2+}, or other elements in the soil, the relationships between nutrients should be monitored (AULAR; NATALE, 2013;

SALVADOR et al., 2011). In addition, to determine the $Ca^{2+}:Mg^{2+}$ ratio that is suitable for the adequate supply of the two nutrients, and to ensure that there is no interference in the absorption of other elements, it is necessary to study combinations of different concentrations of Ca^{2+} and Mg^{2+} in the cultivated species. It is also important to evaluate the plant's response as a result.

In the Sempre Verde area, soil Mg^{2+} content in 0.0-0.2 m depths, and leaf K content, showed a negative correlation (Figure 4D) preseting the highest R^2 among all relationships. It was, therefore, classified as having strong spatial dependence. According to Benites et al. (2010), despite its lower participation in the soil exchange complex and, consequently, lower level of activity in the solution, K is found in greater concentrations in the plant, compared to Ca and Mg. This shows that it has a preference for plant uptake. Moreover, Mg^{2+} uptake can be inhibited by high levels of K^+, which can occur because in the competitive inhibition process that occurs among the elements Ca^{2+}, Mg^{2+}, and K^+, there is no change in the maximum uptake speed (V_{max}). However, there is a change in the affinity constant (K_m), more often called the "Michaelis-Menten constant". Thus, the speed at which the plant takes up nutrients is not affected by its concentration in the solution, but rather its preference. Therefore, the element that is in a higher concentration in the soil solution, in relation to the others, is what will be preferably taken up (FAQUIN, 2005).
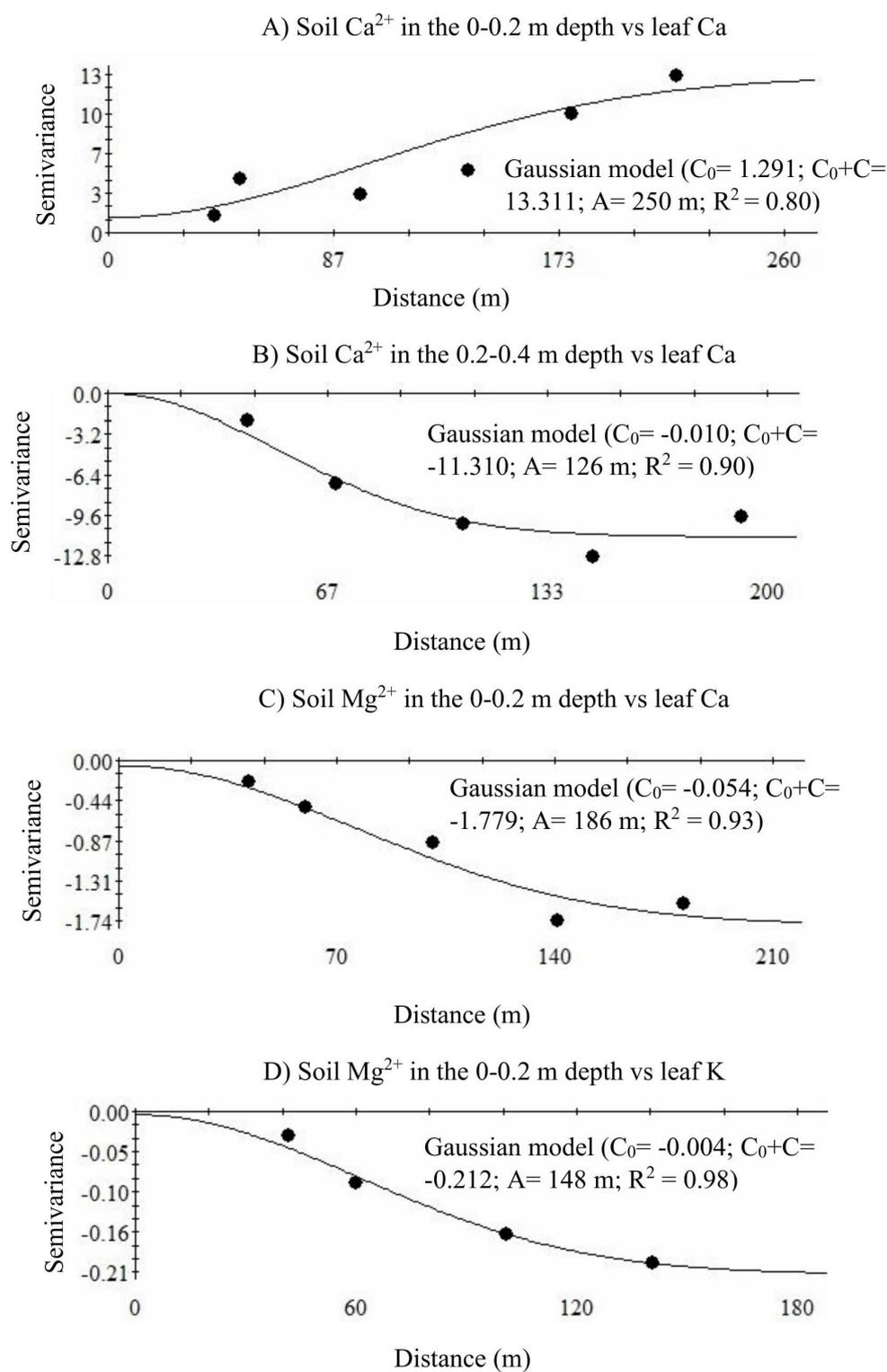
A) Soil Ca^{2+} in the 0-0.2 m depth vs leaf Ca

Gaussian model (C_0= 1.291; C_0+C= 13.311; A= 250 m; R^2 = 0.80)

B) Soil Ca^{2+} in the 0.2-0.4 m depth vs leaf Ca

Gaussian model (C_0= -0.010; C_0+C= -11.310; A= 126 m; R^2 = 0.90)

C) Soil Mg^{2+} in the 0-0.2 m depth vs leaf Ca

Gaussian model (C_0= -0.054; C_0+C= -1.779; A= 186 m; R^2 = 0.93)

D) Soil Mg^{2+} in the 0-0.2 m depth vs leaf K

Gaussian model (C_0= -0.004; C_0+C= -0.212; A= 148 m; R^2 = 0.98)

Figure 4. Cross-variograms between soil and mango cv. Tommy Atkins leaf nutrients in Sempre Verde farm, San Francisco Valley region, Brazil (C_o: nugget effect; C_o+C: sill; A: range)

Due to the positive correlations between soil K$^+$ content at 0.0-0.2 m depths and leaf K content, as well as between the soil Ca^{2+} content at 0.0-0.2 m depths and leaf Ca content in the Barreiro de Santa Fé, Mandacaru, and Sempre Verde areas (Figures 2, 3, and 4), it was possible to obtain maps using the co-kriging technique, so that specific soil management zones can be delineated (Figures 5, 6, and 7). The specific management zone is the sub-region of the crop field that presents a combination of the limiting factors of productivity and quality for which, uniform doses of input (e.g., fertilizers) can be applied. This facilitates the application of precision farming techniques (RODRIGUES JÚNIOR et al., 2011). Furthermore, it leads to the optimization of the use of these inputs, as their application at a variable rate allows a reduction in their costs (GAZOLA et al., 2017).

López-Granados et al. (2004) and Behera et al. (2016) verified the necessity of determining spatial variability in nutrient status before planning a differential fertilizer program. López-Granados et al. (2004) used contour maps of leaf nutrients, achieved by kriging, to estimate the percentage of an olive orchard in Spain that needed fertilization, where the concentration of the respective nutrients did not exceed the fertilization threshold. Similarly, Behera et al. (2016) used leaf nutrient maps from an oil palm field in India and verified that nutrient savings could be achieved by adopting site-specific nutrient management strategies. However, the maps obtained in the present study used data from both soil and leaf nutrients simultaneously, using co-kriging. Using the data in this manner can provide information that is even more accurate for the fertilization management plan, which is a novelty for mango crop production. Similar results were obtained by Liao et al. (2011), who estimated the cation exchange capacity in an area in Shandong Province, China, and verified that co-kriging was more reliable than kriging for spatial interpolation. Furthermore, Yang et al. (2016) studied interpolation methods for estimating soil bulk density in Yunnan Province, Southwest China, and verified that when there is a high spatial correlation between the variables, co-kriging improved the accuracy of estimation compared to kriging.

Therefore, co-kriging can be a useful tool to delimit management zones in mango fields in the semiarid region, assisting farmers in making decisions about both soil and foliar fertilization, and optimizing fertilizer application. This can result in economic and environmental benefits. However, the biggest limitation of this methodology is the cost of analyses, as many samples are required to obtain high-quality maps. To overcome this limitation, some studies have recommended the use of sensors, such as Vis-NIR spectroscopy, to estimate both soil properties (KODAIRA; SHIBUSAWA, 2013; NOCITA et al., 2013) and leaf nutrient content (SANTOSO et al., 2019; OSCO et al., 2020), which reduces the cost of soil and leaf mapping. Another important question lies in the temporal stability of management zones. Thus, further studies should be carried out to investigate the temporal variability of management zones in mango fields under semiarid conditions.
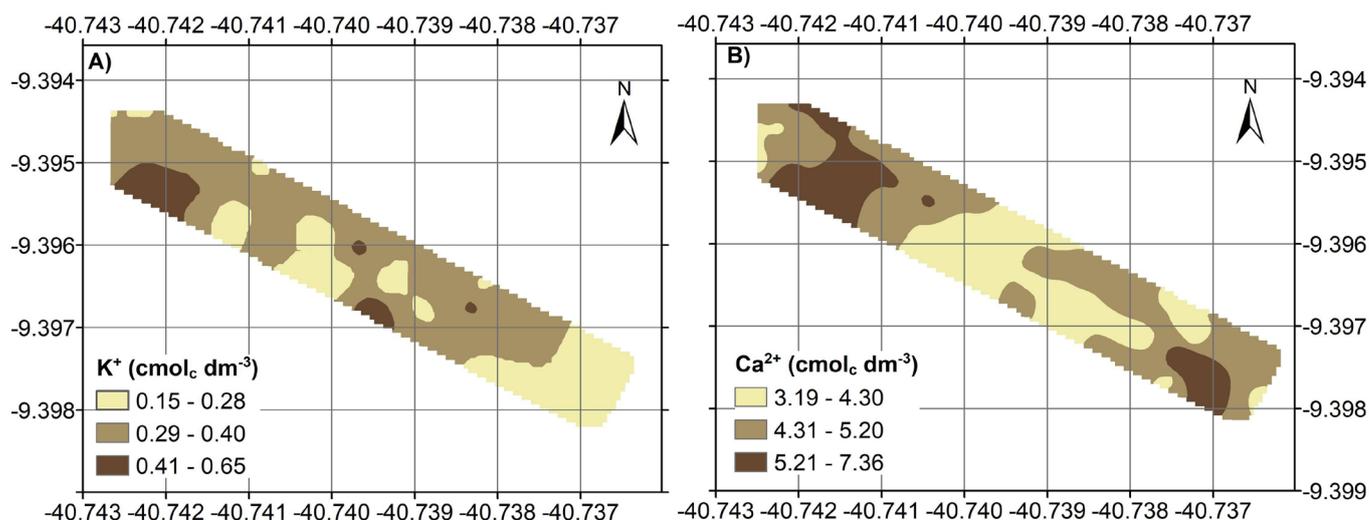

Figure 5. Management zone of (A) potassium (soil K$^+$ 0-0.2 m vs. leaf K) and (B) calcium (soil Ca2$^+$ 0-0.2 m vs. leaf Ca) obtained by co-kriging in Barreiro de Santa Fé area cultivated with mango cv. Tommy Atkins, San Francisco Valley region, Brazil
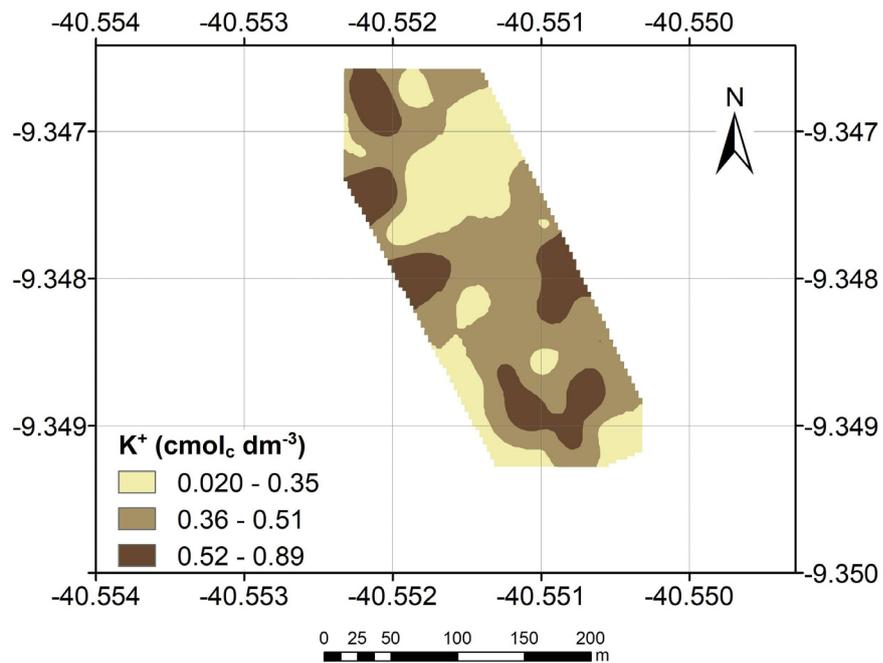
Figure 6. Management zone of potassium (soil K^+ 0-0.2 m vs. leaf K) obtained by co-kriging in Mandacaru area cultivated with mango cv. Tommy Atkins, San Francisco Valley region, Brazil
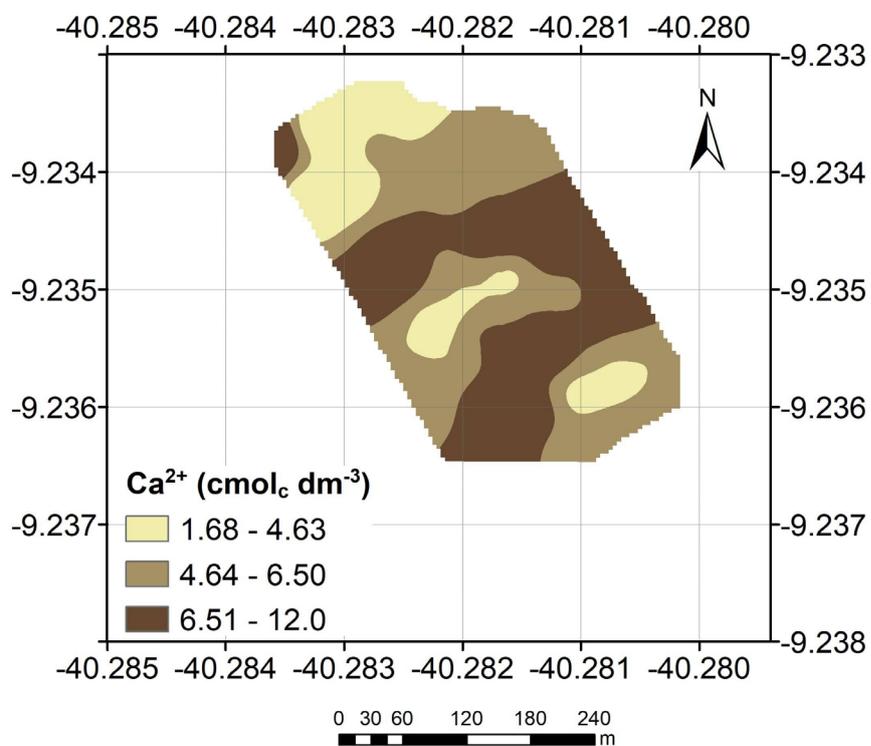

Figure 7. Management zone of calcium (soil Ca^{2+} 0-0.2 m vs. leaf Ca) obtained by co-kriging in Sempre Verde area cultivated with mango cv. Tommy Atkins, San Francisco Valley region, Brazil

Conclusions

Potassium and calcium nutrients showed a positive spatial correlation between their respective levels in the soil and leaves in two of the three studied areas.

The topsoil (0.0-0.2 m within the soil) was the factor that most influenced the uptake of potassium and calcium in areas of mango crops irrigated by micro-sprinkling in the San Francisco Valley of the semiarid region in Brazil.

The positive spatial correlation between soil magnesium and leaf phosphorus in the Barreira de Santa Fé area may indicate the existence of synergism between these nutrients.

The negative spatial correlation between soil magnesium and leaf calcium, in two of the three studied areas, showed competition in the process of plant nutrient uptake.

Furthermore, co-kriging can be a feasible tool for delimiting management zones in mango fields, in the semiarid region of Brazil, using soil and leaf macronutrients. In the present study, it was possible to apply this method for potassium and calcium.

Acknowledgments

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