Spatial variability in fertigated coffee yields and plant nutrients in soil saturation extracts

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Abstract

The spatial distribution and levels of available plant nutrients (elements) in the soil can limit coffee yield and must be evaluated for effective crop management. Therefore, we analyzed spatial variability in yield and plant nutrients in the saturation extract of a clayey Oxisol cropped with fertigated coffee. The experiment was carried out on 14 hectares of coffee in Monte Carmelo, Minas Gerais, Brazil. Soil samples were collected (0 - 0.2m layer) at 61 regular grid points (spaced 50x50m) and used to determine plant *nutrients in the saturation extract. Coffee yield was also determined at these points. Descriptive statistics were calculated for each variable and geostatistics were used to build a spatial variability model representing the physical attributes of the soil. Variographic analysis was performed using semivariograms. These showed that yield and soil chemistry varied throughout the study site. Thus, the maps generated from geostatistics can be useful tools for soil management in fertigated coffee crops.*

Keywords: precision agriculture; *Coffea arabica* L.; geostatistics;

1. INTRODUCTION

Brazil is the global leader in coffee production, with 61.7 million processed bags in 2018 (CONAB, 2018). Thus, coffee is an important part of Brazilian agribusiness and the Brazilian economy. The Cerrado of Minas Gerais has the soil and climate conditions needed to produce (Ortega and Jesus, 2011), high quality coffee (Alves et al. 2011) that can achieve certification and compete in the market (Barra and Ladeira, 2016).

Various interrelationships among the physical, chemical and biological properties of the soil control processes and related aspects that vary by time and location. Thus, the fertility, structure and biological activity of the soil can be modified by any changes to the soil, which can in turn affect production processes (Stefanoski et al. 2013, Silva et al. 2015) and crop yields. Therefore, strong yields require the monitoring of soil fertility and nutrient availability and consequent soil corrections (Deus et al., 2015).

Soil solution analysis is an underutilized tool that is used to evaluate nutrient availability in the soil (Coscione et al., 2014) and show plant nutrition elements available in the soil saturation extract (Souza et al., 2015). Analysis of the soil saturation extract plays an important role in agriculture and is widely used in several countries (Riedi, 2013). In Brazil, this type of analysis has been carried out since 1973 to quantify heavy metal contamination and since 2002, the company Agrichem has employed this process to determine micronutrient availability for crops (Riedi, 2013).

In an interview, Riedi (2013) stated that, unlike normal chemical analysis, which gives a partial picture of nutrient levels, the saturation extract shows exactly what the plant can absorb from the soil. Understanding the levels of plant nutrient elements available in the soil can be useful for achieving an optimal nutritional balance for coffee. Thus, precision agriculture is important and increasingly complemented by an understanding of spatial variability in soil attributes (Zanao Junior et al., 2010, Zonta et al., 2014), which is essential for monitoring the distribution of plant nutrients.

Moreover, a better understanding of the dependence and spatial distribution of soil nutrients can be used to efficiently manage and optimize the coffee fertilization. Several studies have shown that the mapping of soil properties based on geospatial data can be used to manage spatial variability in soil nutrients. Xu et al. 2017 used remote sensing to show that the spatial resolution of orbital images directly affects the effectiveness of empirical models used to estimate potassium concentration in the soil.

Geostatistics can also be used to detect variability and spatial distribution of variables, which is useful for analyzing and describing variability in soil attributes. Recently, geostatistics has been used in several studies to evaluate soil variability but has been little used in the field of soil chemistry.

Given the spatial dependence of soil attributes, spatial interpolation (e.g. kriging) has also been widely used as a management tool for various crops. Studies on sugarcane (Li et al, 2019) and conilon coffee (Santos et al., 2015) have demonstrated that spatial interpolation via kriging can be used to estimate calcium (Ca) and magnesium (Mg) deficiencies in the soil, and may be a useful tool in the process of meeting crop nutritional requirements.

Given the importance of coffee and the lack of studies that examine the relationship between spatial variability in soil attributes and yield, studies involving soil nutritional variables are essential for precision agriculture. Thus, the objective of the present study was to analyze spatial variability in yield and available nutrients in the saturation extract of a clayey Oxisol cropped with fertigated coffee.

2. MATERIAL AND METHODS

The evaluations were carried out on fertigated coffee crops in a region of the Brazilian Cerrado (Monte Carmelo MG, 18° 42' 28,9" S and 47° 33' 27,0" W) with a clayey Oxisol (SANTOS et al., 2013). This coffee crop was replanted with Coffea arabica L. (spaced 3.8 x 0.7 m) in January 2012. In March 2015, approximately 14 ha of this plantation was mapped with a 61-point sampling (soil and plants) grid (50 x 50m) (Figure 1).

The coordinates of the grid points were determined using an L1 / L2 dual frequency Hipper Global Navigation Satellite System (GNSS) receiver. One receiver was used as a static relative positioning device and provided the basis for GNSS tracking. The resulting data were processed with Topcon Tools 8.2.3 software and using the Uberlândia MG and Rio Paranaíba MG stations of the Brazilian Continuous Monitoring Network (RBMC - Rede Brasileira de Monitoramento Contínuo).

Soil samples were collected (0 – 0.2m) at each of the grid points, which covered the varying topography of the landscape. These soil samples were used to create a paste (35% humidity) from which the saturation extract was obtained (Teixeira et al., 2017), which was then used to determine plant nutrition content via ICP-OES. In May 2015, coffee plants were harvested from each grid point to determine yield per plant (average of 5 plants per grid point). Data analysis was divided into two stages: exploratory analysis and geostatistical analysis. The exploratory analysis consisted of statistical analysis (non-spatial) and determination of spatial dependencies through experimental semivariograms (spatial). The geostatistical analysis involved fitting data to theoretical models and mapping.

Statistical analysis was performed to determine central tendencies and dispersion and histogram measurements to confirm data normality. Descriptive statistics were used to determine principal moments for each variable. These were then used to create probability distributions and examine data variability. The statistical moments included the mean, variance, coefficient of variation, asymmetry coefficient and kurtosis coefficient. Data minimums, maximums and amplitudes were also identified.

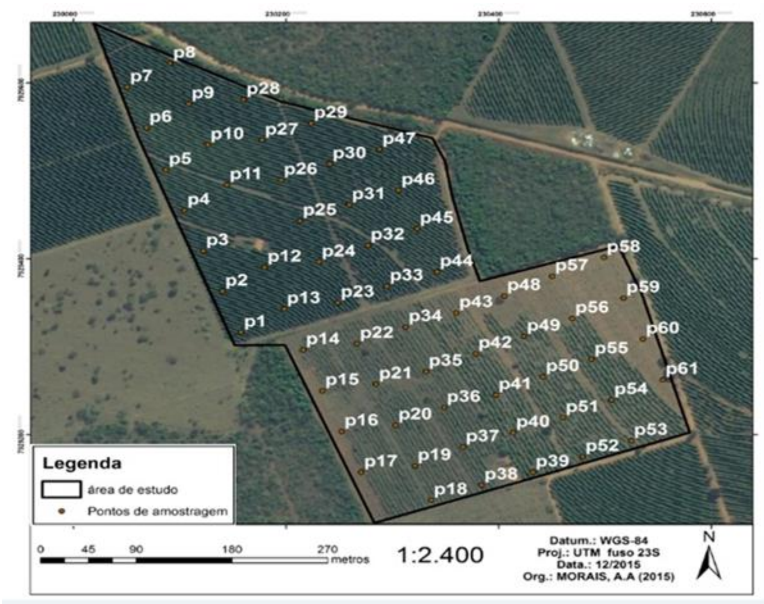


Figure 1. Layout of the study area at Fazenda Juliana, Monte Carmelo, MG, Brazil.

Geostatistics were used to build spatial variability models of soil physical attributes. Variographic analysis was performed using semivariograms. Semivariance was then graphed (γ (h) versus distance (h)) and used to build semivariogram models that fit the experimental data. The GS+ geostatistical software package (Robertson, 1998) was used to calculate semivariance and to select semivariogram models. After defining the models, interpolation was performed using the ordinary kriging method. Cross- semivariogram calculations were also used to determine spatial correlations between attributes.

The models were fit to the semivariograms using the Jack-knifing validation method, which analyzes the mean and variance values of the reduced errors (Souza et al., 1997), of spherical, exponential, Gausian and linear models.

3. RESULTS AND DISCUSSION

The descriptive statistics and classification of the coefficient of variation (Warrick and Nielsen, 1980) as low (CV < 12%), medium (12% < CV < 60%) or high (CV > 60%), showed that the pH and copper variables were low and homogenous (Table 1). However, all other CVs were classified as median. The heterogeneity of these variables may be affected by agricultural practices and soil attributes. This conclusion corroborates the results of Almeida et al. (2018) regarding the physical attributes of soil cropped with coffee.

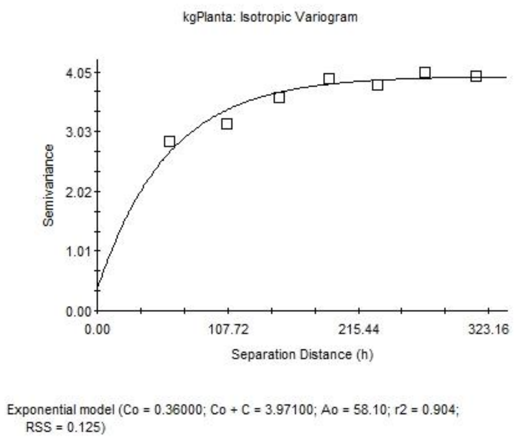
Table 1. Descriptive statistics for: coffee yield (kg plant $^{-1}$), pH, plant nutrients in the soil saturation extract (mg L^{-1} of P: phosphorus, S: sulfur, K: potassium, Ca: calcium, Mg: magnesium, B: boron, Cu: copper, Fe: iron, Mn: manganese and Zn: zinc)

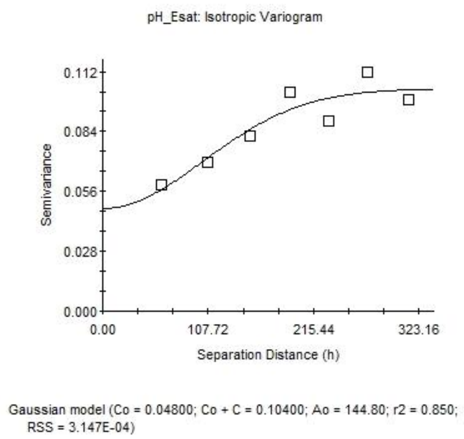
Variable	Descriptive statistics						
	Mean	Mín	Max	SD	CV	As	Kurt
yield	4.75	0.36	8.94	1.95	13.73	-0.02	-0.02
pH	7.31	5.96	7.70	0.29	3.91	-0.59	7.23
P	0.22	0.10	0.55	0.09	39.46	0.16	1.79

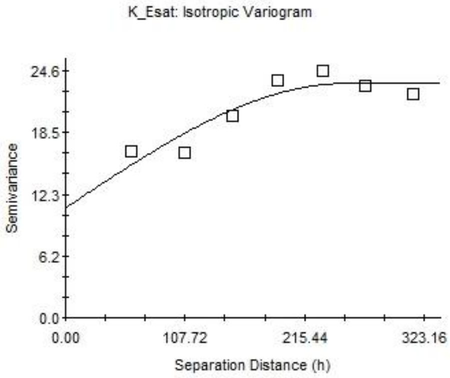
S	10.38	5.55	34.60	5.45	52.49	0.94	6.15
K	17.55	9.21	27.34	4.52	25.76	0.45	-0.51
Ca	18.24	5.37	42.62	6.57	36.03	0.91	2.11
Mg	5.79	1.01	13.73	2.63	45.39	0.69	2.18
B	0.15	0.09	0.19	0.02	14.28	-0.35	0.39
Cu	0.17	0.16	0.18	0.01	3.50	0.50	-0.11
Fe	2.23	0.14	4.39	1.25	55.97	-0.83	-0.95
Mn	0.16	0.13	0.24	0.02	14.34	0.75	1.59
Zn	0.15	0.11	0.27	0.03	19.01	0.70	8.48

* Min: Minimum; Max: Maximum; SD: standard deviation; CV: Coefficient of variation; As: Asymmetry; Kurt: Kurtosis.

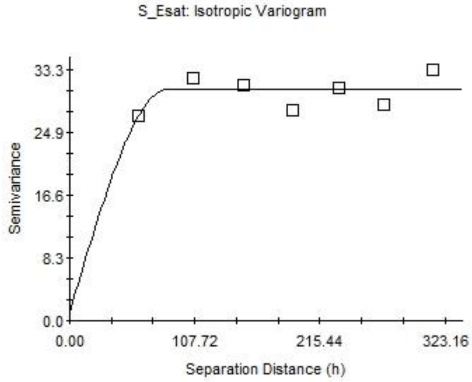
There was little variation among the mean values for most variables, as indicated by asymmetry values close to zero, except for sulfur, calcium, magnesium, iron, manganese and zinc, which had asymmetry values approaching 0.5, indicating normally distributed data (Webster, 2001).
The semivariograms show that the nugget effect was greater than zero for all variables (Figure 2). This suggests that variability was not explained or that the distance between grid points and/or small variations were not detected by sampling (Lundgren et al., 2017, Pelissari et al., 2018).
The model fit to coffee yield and plant nutrients in the soil saturation extract was exponential for phosphorus and copper; however, the coefficient of determination was low for phosphorus, copper, sulfur and manganese. The spherical model was fit to potassium, sulfur, magnesium, boron, iron and manganese in the soil saturation extract. The Gaussian model was fit to pH and calcium, while only zinc was fit to the linear model. Carmo et al. (2016) and Santos et al. (2015) fit the same models to coffee yield and plant nutrients in the soil. Nevertheless, few studies have fit models to the relationship between plant nutrients in the soil saturation extract and coffee yield.



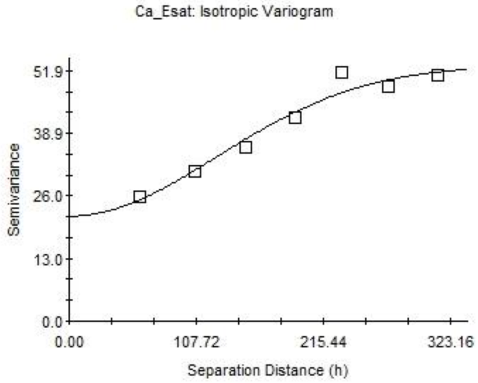




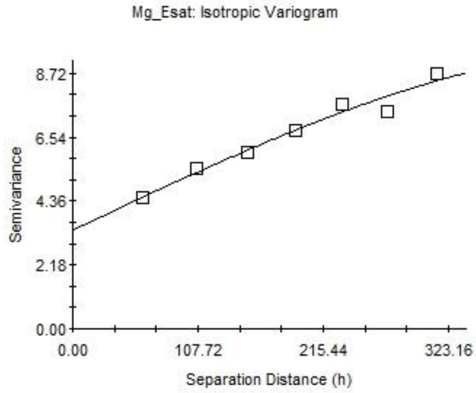
Spherical model (Co = 10.96000; Co + C = 23.39000; Ao = 252.60; r2 = 0.842; RSS = 10.7)



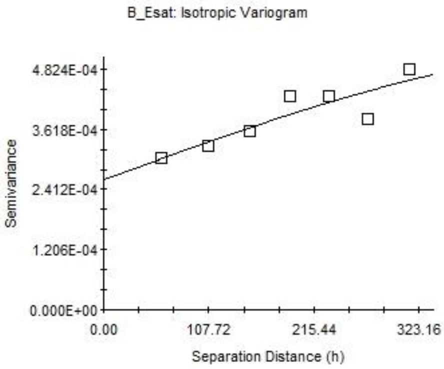
Spherical model (Co = 1.03000; Co + C = 30.67000; Ao = 84.50; r2 = 0.334; RSS = 21.1)



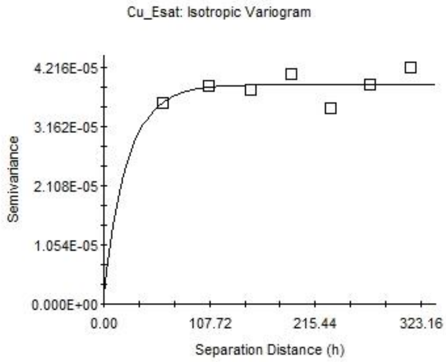
Gaussian model (Co = 21.79000; Co + C = 53.06000; Ao = 177.30; r2 = 0.958; RSS = 26.1)



Spherical model (Co = 3.37000; Co + C = 9.62100; Ao = 500.20; r2 = 0.967; RSS = 0.415)



Spherical model (Co = 0.00026; Co + C = 0.00052; Ao = 550.50; r2 = 0.777; RSS = 5.279E-09)



Exponential model (Co = 0.00000; Co + C = 0.00004; Ao = 24.40; r2 = 0.214; RSS = 3.160E-11)

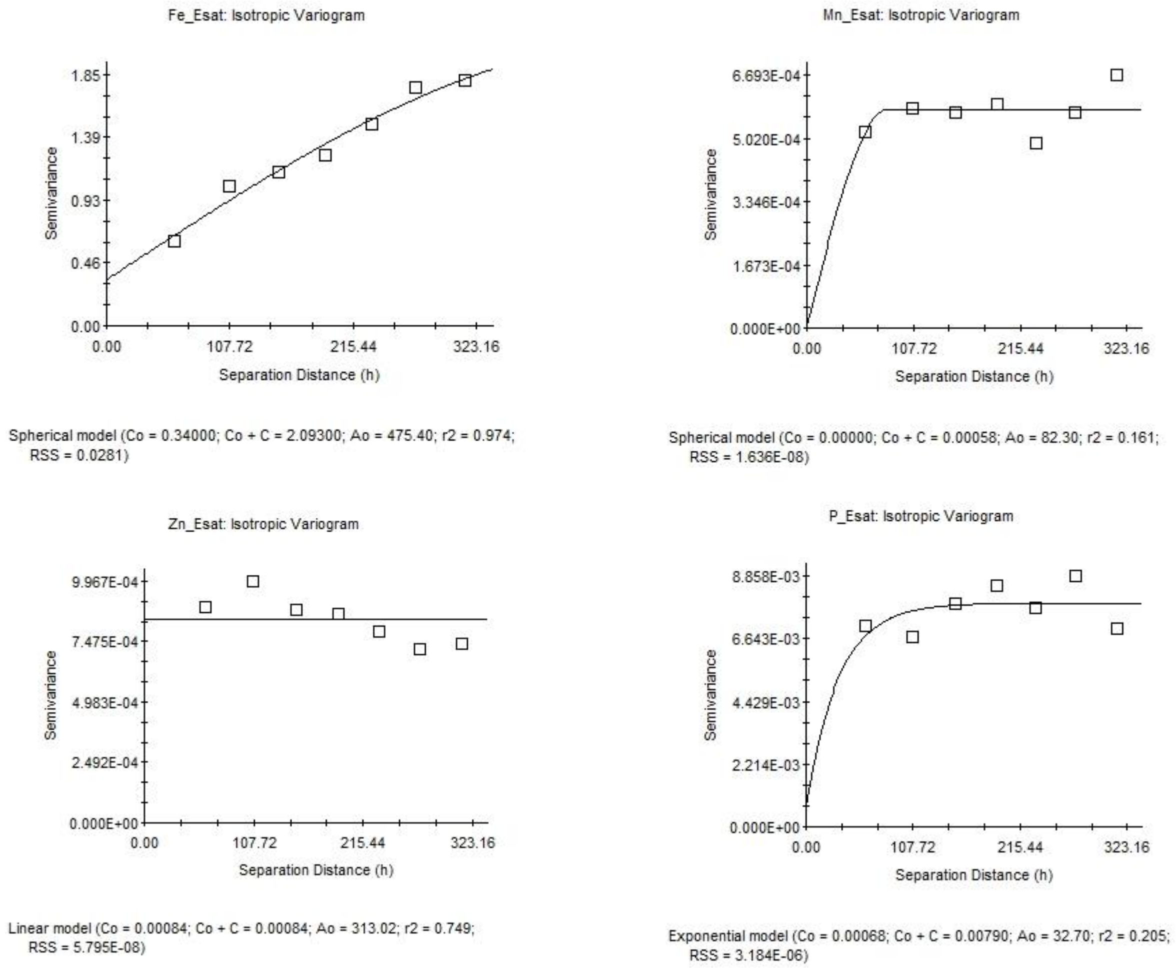


Figure 2. Semivariograms of coffee yield (kg plant^{-1}), hydrogen potential (pH-pH_Esat) and plant nutrients in the soil saturation extract (mg L^{-1} of: S: sulfur (S_Esat), K: potassium (K_Esat), Ca: calcium (Ca_Esat), Mg: magnesium (Mg_Esat), B: boron (B_Esat), Cu: copper (Cu_Esat), Fe: iron (Fe_Esat), Mn: manganese (Mn_Esat), P: phosphorus (P_Esat) and Zn: zinc (Zn_Esat)).

Analyzing variations in plant nutrients in the soil saturation extract and coffee yield is possible with maps and semivariograms, but not via an isolated analysis of minimums, maximums and means. Therefore, geostatistics were used to show that spatial dependence existed for all variables (i.e. none of the variables were randomly distributed) (Table 2).

Table 2. Semivariogram parameters fit to coffee yield (kg plant^{-1}), hydrogen potential (pH), plant nutrients in the soil saturation extract (mg L^{-1} of P: phosphorus, S: sulfur, K: potassium, Ca: calcium, Mg: magnesium, B: boron, Cu: copper, Fe: iron, Mn: manganese and Zn: zinc)

Attribute	Parameters[1]					
	Model	Co	Co+C1	Co/(Co+C1)[2]	a	r^2
kg Plant^{-1}	Exponential	0.36	3.971	9.1	58.1	0.904
pH	Gaussian	0.048	0.104	46.2	144.8	0.850
P	Exponential	0.00068	0.00791	8.6	32.7	0.205
S	Spherical	1.03	30.67	3.4	84.5	0.334

K	Spherical	10.96	23.39	46.9	252.6	0.842
Ca	Gaussian	21.79	53.06	41.1	177.3	0.958
Mg	Spherical	3.37	9.621	35.0	500.2	0.967
B	Spherical	0.00026	0.00052	50.0	550.5	0.777
Cu	Exponential	0.00001	0.00004	25.0	24.4	0.214
Fe	Spherical	0.34	2.093	16.2	475.4	0.974
Mn	Spherical	0.00001	0.00058	1.7	82.3	0.161
Zn	Linear	0.00084	0.00085	98.8	313.02	0.749

[1] Co: nugget effect, Co + C1: threshold, [2]Degree of spatial dependence (percentage) such that: <25% = strong; between 25 and 75% = moderate and > 75% = weak (Cambardella et al, 1994); a: range.

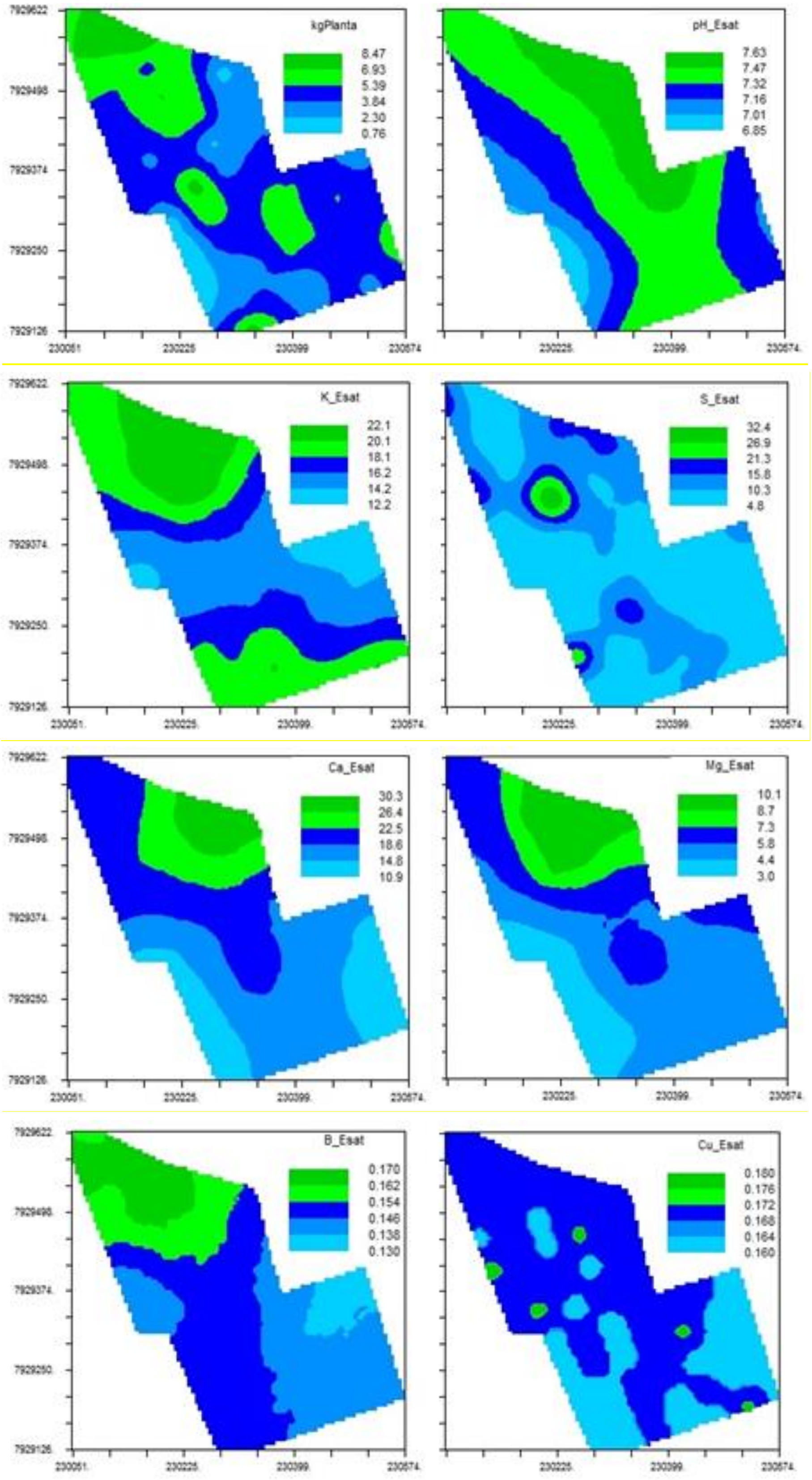
The lowest coffee yields (<2.3 kg plant^{-1}) were found at the longitudinal extremities of the study site while the highest values were found at higher and more central longitudinal bands. Other studies have found similarly wide spatial variations in coffee yields (Ferraz et al., 2018, Ferraz et al., 2012, Jacintho et al., 2017, and Silva et al., 2008).

All plant nutrient levels in the soil saturation extract, except Zinc, followed the same pattern as variations in yield. Zinc levels, on the other hand, were lowest in areas with the highest coffee yields. The agricultural and environmental significance of the current study is underlined by the lack of studies on precision agriculture or management zones that examine the relationship between plant nutrition levels and the soil solution under fertigated coffee, which is in contrast to the level of attention given to soil chemical attributes (Ferraz et al., 2018, Jacintho et al., 2017, Santos et al., 2015 and Silva et al., 2008).

Based on the classification system of Cambardella et al. (1994), coffee yield showed strong or moderate spatial dependence on plant nutrients in the soil saturation extract, except for zinc which was weakly dependent. Similarly, Almeida et al. (2018) found that physical soil attributes at georeferenced points had more in common with neighboring points than with the rest of the sample space. This shows the importance of spatial evaluations for the effective management of plant nutrients in the soil solution.

The yield figure shows that yields were highest in the extreme north and two central regions of the study area. Concomitantly, the levels of pH, K and B were also highest in these areas. Calcium, magnesium and iron also peaked within these same sites, but in a more limited area.

Significantly, the dispersion patterns of yield, pH, potassium, calcium, magnesium, boron and iron were zonal (i.e. higher concentrations covering larger areas). Conversely, the dispersion patterns of the remaining attributes were marked by smaller, more scattered areas within the study area.


kgPlanta
8.47
6.93
5.39
3.84
2.30
0.76
pH_Esat
7.63
7.47
7.32
7.16
7.01
6.85
K_Esat
22.1
20.1
18.1
16.2
14.2
12.2
S_Esat
32.4
26.9
21.3
15.8
10.3
4.8
Ca_Esat
30.3
26.4
22.5
18.6
14.8
10.9
Mg_Esat
10.1
8.7
7.3
5.8
4.4
3.0
B_Esat
0.170
0.162
0.154
0.146
0.138
0.130
Cu_Esat
0.180
0.176
0.172
0.168
0.164
0.160

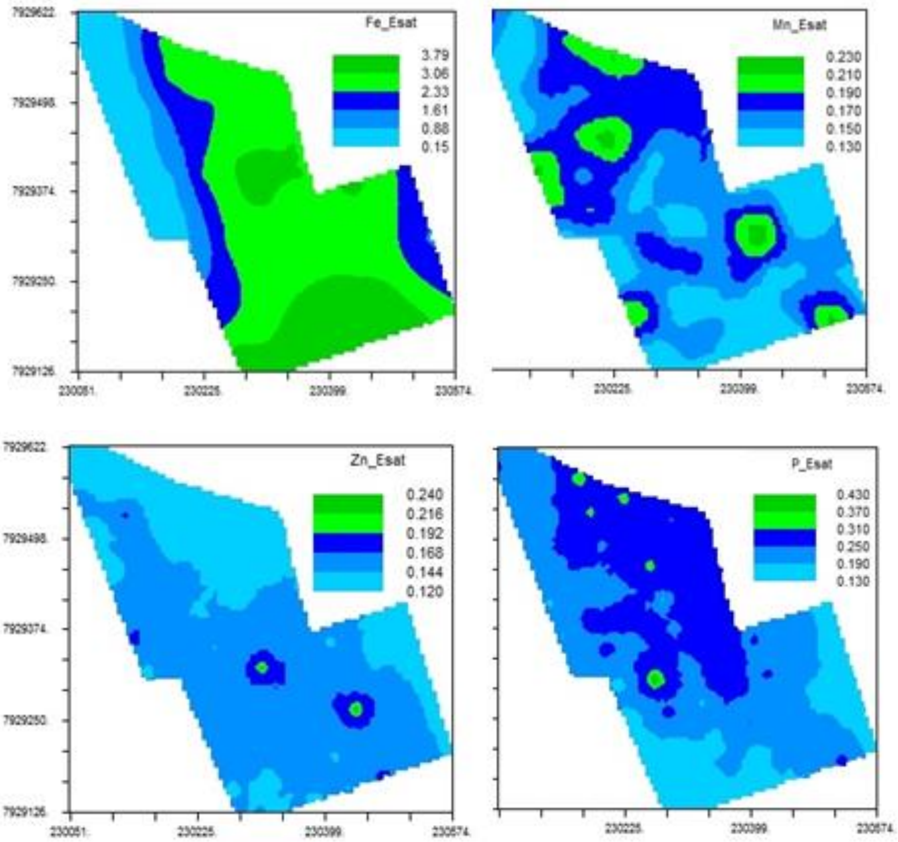


Figure 3. Spatial distribution of coffee yield (kg plant^{-1}), hydrogen potential (pH-pH_Esat) and mg L^{-1} of plant nutrients in the soil saturation extract (S: sulfur (S_Esat), K: potassium (K_Esat), Ca: calcium (Ca_Esat), Mg: magnesium (Mg_Esat), B: boron (B_Esat), Cu: copper (Cu_Esat), Fe: iron (Fe_Esat), Mn: manganese (Mn_Esat), P: phosphorus (P_Esat) and Zn: zinc (Zn_Esat)).

In Brazil, Silva and Lima (2012) used geostatistics to examine spatial variability in coffee yields and found that yields were limited by excess nitrogen and copper. Almeida and Guimarães (2012) used geostatistics to study sustainable soil fertility management in a drip fertigated coffee crop (Araguari, Minas Gerais, Brazil), grown in a Red-Yellow Latosol, and found that pH was strongly spatially dependent and was fit to a Gaussian model. The study found similar results for macronutrients, except the sulfur variogram data, which were fit to a spherical model. Cerri (2005), evaluated and correlated physical and chemical soil attributes to yields at the São João sugar and ethanol plant (Usina São João Açúcar e Álcool) in Araras, Sao Paulo Brazil, and found that these physical and chemical properties, including copper, showed isotropic characteristics and that a spherical model provided the best fit to the semivariogram data. Valladares et al. (2009), studied the spatial variability and availability of copper and zinc in vineyard soils in the city of Jundiaí, Sao Paulo, Brazil and found strong spatial dependence and spatial dependence ratios for copper, despite great distances between sampling points. The semivariograms from this study were fit to a Gaussian model and the nugget effect was lower and closer to zero for copper than for zinc.

The study of coffee yield and plant nutrients in the saturation extract is worthwhile and has been shown as a promising method for diagnosing soil fertility, especially in citrus fertigation systems (Souza et al., 2015). Nevertheless, studies and recommendations for coffee crops are lacking. Saturation extract analysis can be used to quantify the elements available in the soil solution and identify actual plant nutrient requirements, which in turn can be used to optimize fertilizer applications (Riedi, 2013). However, this process is currently employed by only a few companies. This underutilization may be due to a lack of information on how to make decisions based on the nutrient content of the soil solution. Appropriate fertilizer and corrective recommendations lead to better crop yields. A combination of these recommendations and precision farming techniques can make agricultural and environmental sustainability possible and result in gains for crops such as fertigated coffee.

4. CONCLUSIONS

We found a strong or moderate degree of spatial dependence between yield and plant nutrients in the soil saturation extract of a fertigated coffee crop. This shows that the behavior of these variables throughout the study area was not random and that geostatistics can be used to help make decisions to improve plant nutrition and soil sustainability in coffee plantations.

5. Acknowledgement

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