Special Supplement: *Cerrado* **[Brazilian Savanna]**

Effect of Savanna windrow wood burning on the spatial variability of soil properties[1]

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ABSTRACT

Tropical Savannas cover an area of approximately 1.9 billion hectares around the word and are subject to regular fires every 1 to 4 years. This study aimed to evaluate the influence of burning windrow wood from Cerrado (Brazilian Savanna) deforestation on the spatial variability of soil chemical properties, in the field. The data were analysed by using geostatistical methods. The semivariograms for pH(H_2O), pH($CaCl_2$), Ca, Mg and K were calculated according to spherical models, whereas the phosphorus showed a nugget effect. The cross semi-variograms showed correlations between pH(H_2O) and pH($CaCl_2$) with other variables with spatial dependence (exchangeable Ca and Mg and available K). The spatial variability maps for the pH(H_2O), pH($CaCl_2$), Ca, Mg and K concentrations also showed similar patterns of spatial variability, indicating that burning the vegetation after deforestation caused a well-defined spatial arrangement. Even after 20 years of use with agriculture, the spatial distribution of pH(H_2O), pH($CaCl_2$), Ca, Mg and available K was affected by the wood windrow burning that took place during the initial deforestation.

KEY WORDS: Wildfire, soil digital mapping, soil fertility.

RESUMO

Efeito da queima de madeira proveniente de desmatamento do Cerrado na variabilidade espacial das propriedades do solo

As Savanas tropicais cobrem uma área de aproximadamente 1,9 bilhões de hectares ao redor do mundo e estão sujeitas a incêndios regulares a cada 1-4 anos. Objetivou-se avaliar a influência da queima de madeira proveniente do desmatamento do Cerrado na variabilidade espacial das propriedades químicas do solo, em campo. Os dados foram analisados utilizando-se métodos geoestatísticos. Os semivariogramas para pH(H_2O), pH($CaCl_2$), Ca, Mg e K foram calculados de acordo com modelos esféricos, enquanto o fósforo apresentou efeito pepita puro. Os semivariogramas cruzados mostraram correlações entre pH(H_2O) e pH($CaCl_2$) com outras variáveis com dependência espacial (Ca e Mg trocáveis e K disponível). Os mapas de variabilidade das concentrações de pH(H_2O), pH($CaCl_2$), Ca, Mg e K também apresentaram padrões semelhantes de variabilidade espacial, indicando que a queima da vegetação após o desmatamento causou arranjo espacial bem definido. Mesmo após 20 anos de uso com agricultura, a distribuição espacial de pH(H_2O), pH($CaCl_2$), Ca, Mg e K disponível foi afetada pela queima da madeira que ocorreu após enleiramento, durante o desmatamento inicial.

PALAVRAS-CHAVE: Incêndios florestais, mapeamento digital do solo, fertilidade do solo.

INTRODUCTION

Tropical Savannas cover an area of around 20 million km^2 around the world (Young & Solbrig 1993). Cerrado (Brazilian Savanna) is a tropical Savanna in Central Brazil, which encompasses around 23 % of the national territory, or approximately 2 million km^2 (Beuchle et al. 2015). Its native vegetation is composed by understory grass, with a variable cover of shrubs and trees. Ferralsols (FAO 2014) are the most common soils, covering about 45 % of the Cerrado area.

In the Cerrado biome, fire disturbance (lit by man or caused by lightning) are common, and

[1] Received: Dec. 01, 2020. Accepted: Apr. 22, 2021. Published: June 28, 2021. DOI: 10.1590/1983-40632021v5166853.
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have occurred for thousands of years (Nardoto & Bustamante 2003), every 1 to 4 years, during the dry season, with the highest frequency in the humid Savannas (Pivello et al. 2010). Fires triggered by lightning occur naturally in the dry season and are recognized for their ecological importance, influencing nutrient cycling and affecting the vegetation dynamics, particularly the grass/woody biomass ratio (Nardoto et al. 2006). However, the increased population pressures and land use changes have promoted both the deforestation intensity and the frequency and severity of anthropogenic fires (Lambin et al. 2003). The historic occupation of the Cerrado region began in the 1920s by the coffee industry and was later (1930-1945) perpetuated by government policies that stimulate grants for providing technical assistance to farmers (Goedert et al. 2008).

Between 1970 and 1985, the intensification of deforestation in the Cerrado region culminated with the incorporation of the Cerrado area into the Brazilian agricultural production plan, due to the arrival of new technologies, such as phosphate fertilizer and lime to correct both nutrient deficiency and acidity; rhizobium-based nitrogen fixation; development of crop varieties; heavy use of herbicides and pesticides; and modern machinery (Camargo et al. 2017). Studies on the effects of fire on Cerrado soil properties are scarce (Silva & Batalha 2008, Pivello et al. 2010, Resende et al. 2011) and more studies are needed, because this biome is nowadays the most important area for grain production in Brazil, as well as one of the most endangered ecosystems in South America, with high levels of plant endemism (Klink & Machado 2005).

Biomass and plant functional traits affect the biogeochemical cycles of tropical ecosystems (Carvalho et al. 2014). The transformation of elements during combustion may affect the cycling and availability of nutrients for several years following the disturbance. The combustion of organic matter releases significant quantities of nutrients to the atmosphere as gaseous compounds. Other nutrients are deposited on the soil as ash and may prove valuable for plant regrowth (Nardoto et al. 2006). The mineral ash may also increase the soil pH due to the release of basic ions (Noble et al. 1996), and consequently change the microbial activity, which is intimately connected with decomposition and nutrient turnover, owing to the accumulation of P, Ca, Mg and K with the first rain after fires (Nardoto & Bustamante 2003, Pivello et al. 2010).

In the Cerrado, deforestation to clear the land for agriculture activities was traditionally done by tracked tractors pulling a clearing chain, and the vegetation was concentrated in windrows along the field before being burned. As a result, in much of the deforested area, the machinery and burning considerably altered the soil surface layer (Chazdon 2003, Lintemani et al. 2019).

While many studies on the effect of Savanna fires have been conducted, especially in connection with the ecology of these areas, few studies have examined the effects of fire on agricultural soils, especially on soil nutrients (Lal & Ghuman 1989, Fraser & Scott 2011, Tavares Filho et al. 2011). Although the effects of spatial variability of soil properties on crop production are a long-standing problem, this is still the case, especially for the practice of precision agriculture (Frogbrook et al. 2002, Negreiros Neto et al. 2014). Geostatistics (e.g., semi-variograms and spatial interpolation) has been used as an important and efficient tool to characterize spatial variability of soil properties. It is also a promising way to study the heterogeneity of soil properties after burning and land clearing.

This study aimed to assess the biased effect related to another pattern of soil nutrient distribution related to Savanna windrow wood burning on the spatial variability of soil chemical properties.

MATERIAL AND METHODS

A field experiment was carried out in the Cerrado (Brazilian Savanna) biome, as part of a research project on the impact of conservation agricultural practices on soil fertility and crop yields, in Unaí (16º32'26"S, 46º50'44" W and altitude of 600 m), north-western of the Minas Gerais state, Brazil (Figure 1).

The region is characterized by a typical sub-humid tropical climate of the Cerrado [tropical wet and dry "Aw" (or Savanna climate), according to the Köppen classification]. The average annual rainfall is 1,200-1,400 mm and occurs between October and April, while the dry season, lasting from five to six months, coincides with the coolest months. The average annual temperature is 24.4 ºC. The soils in the area are classified as Latossolo Vermelho (Santos et al. 2013) and Oxisols (USA 2014) or Ferralsols

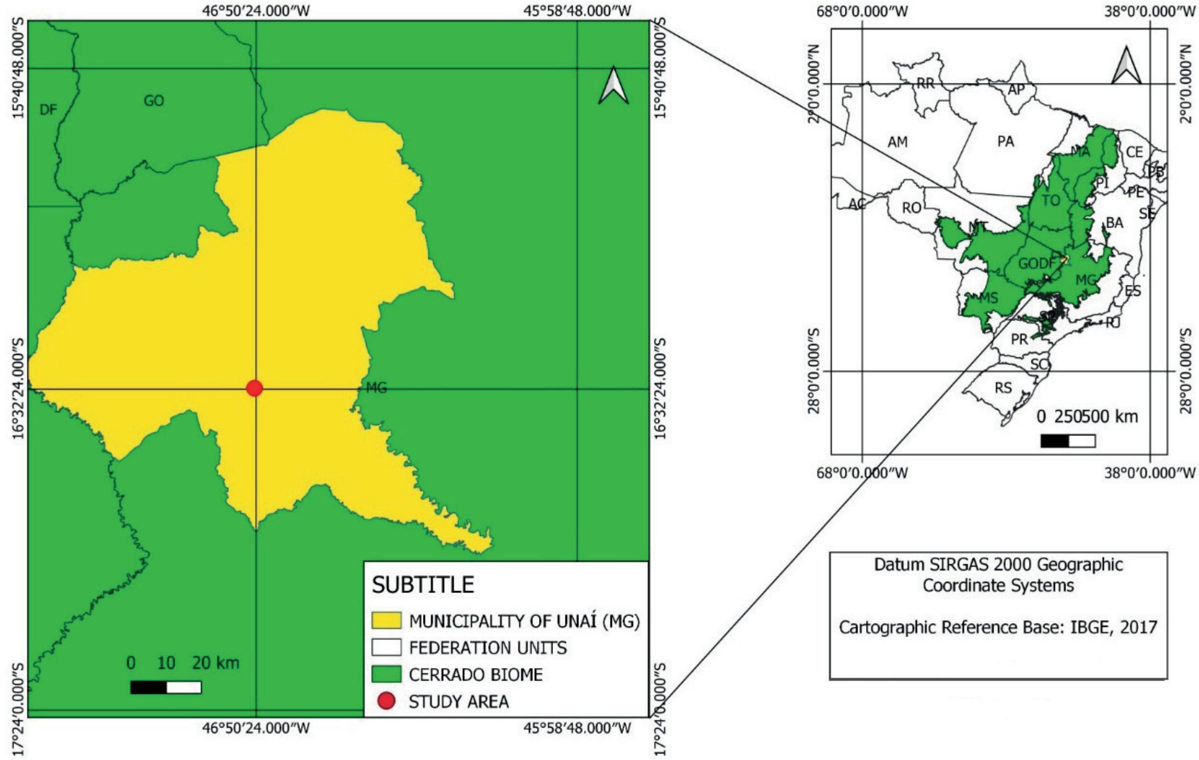

Figure 1. Cerrado region in Central Brazil (in green) and the location of Unaí, Minas Gerais state.

(FAO 2014). The general soil chemical and physical properties are present in Table 1.

The area was deforested 14 years before the establishment of the experiment, in 1991. The vegetation, classified as "Cerradão", was cleared by caterpillar tractors pulling a chain, and the vegetation was concentrated in windrows before being burned. The subsequent crops were upland rice for three years, bean for one year, soybean for two years, sorghum for one year, and maize for 11 years (Figure 2).

During the last five years before the soil sampling, maize was cultivated in association with cover crops [*Urochloa ruziziensis* (ruzigrass) - a grass species - or *Cajanus cajan* - a leguminous species] and tillage systems (conventional or no-tillage).

Table 1. Soil chemical and physical properties in the experimental area (0-0.2 m).

pH	MO	Ca	Mg	Al	H + Al	K	S	P	Clay	Silt	Sand
$CaCl_2$	%	$cmol_c\ dm^{-3}$					$mg\ dm^{-3}$		$g\ kg^{1}$		
4.5	2.5	1.3	1.3	0.05	5.4	0.56	1.2	0.7	730	160	110

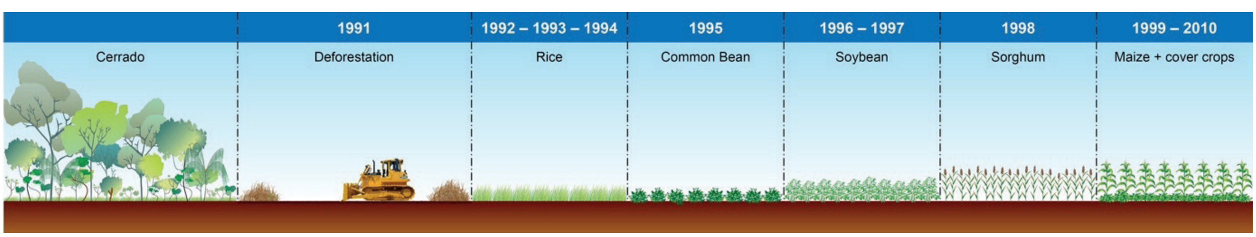

Figure 2. Schematic representation of the experimental area after deforestation until the soil sampling in 2010.

During this period, the experiment received the same amount of fertilizers distributed in the rows of cash crops, i.e., 230, 118 and 104 kg ha^{-1} of N, P and K, respectively.

The entire experimental area measured 80 x 75 m. Soil samples were collected in March 2010, on a 5 x 5 m grid, from the 0-0.2 m depth, resulting in a total of 240 samples (Figure 3). A 0-0.2 m sampling was chosen to avoid an effect related to soil stratification close to the surface in the no-tillage system (Crozier et al. 1999). The soil analysis was carried out with air-dried < 2 mm sieved material (Claessen 1997). The soil pH was measured in distilled water pH(H_2O) and 0.01 M $CaCl_2$ [pH($CaCl_2$)], using a 1:2.5 (w:v) soil:solution ratio. Exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) were extracted with 1 M KCl. Available potassium (K^+) and phosphorus (P) were extracted with a Mehlich-1 solution (0.0125 M H_2SO_4 and 0.050 M HCl).

A descriptive analysis was done using the BioEstat 5.0 software. Skewness and kurtosis indices were calculated to check the data dispersion and central tendency. The assumption of data normality was tested using the Kolmogorov-Smirnov test at 5 % of significance. The coefficient of variation (CV) was classified based on Warrick & Nielsen (1980) (low CV: < 12 %; average: 12 % < CV < 60 %; high: > 60 %). The data were analysed by geostatistical methods using the Geostat software, and the semi-variogram calculation was based on hypothetical intrinsic stationary assumptions, to study the spatial variability of soil properties (Vieira et al. 2002). The spatial correlation of samples was analysed by the experimental semi-variograms, to which the mathematical models were fitted. This is necessary for determining the structure of the spatial variation of the variables studied and to obtain input parameters for ordinary kriging interpolation. The spherical mathematical model was applied to spatially dependent semi-variograms. It generates values that increase for the distances (h) until reaching a maximum, after which it stabilizes at a level that corresponds to the distance limit of spatial dependence, the range (R). Measurements over longer distances than the range are randomly distributed and are thus independent from each other. The degree of spatial dependence (DSD), which measures the degree of the nugget variance (C_0)

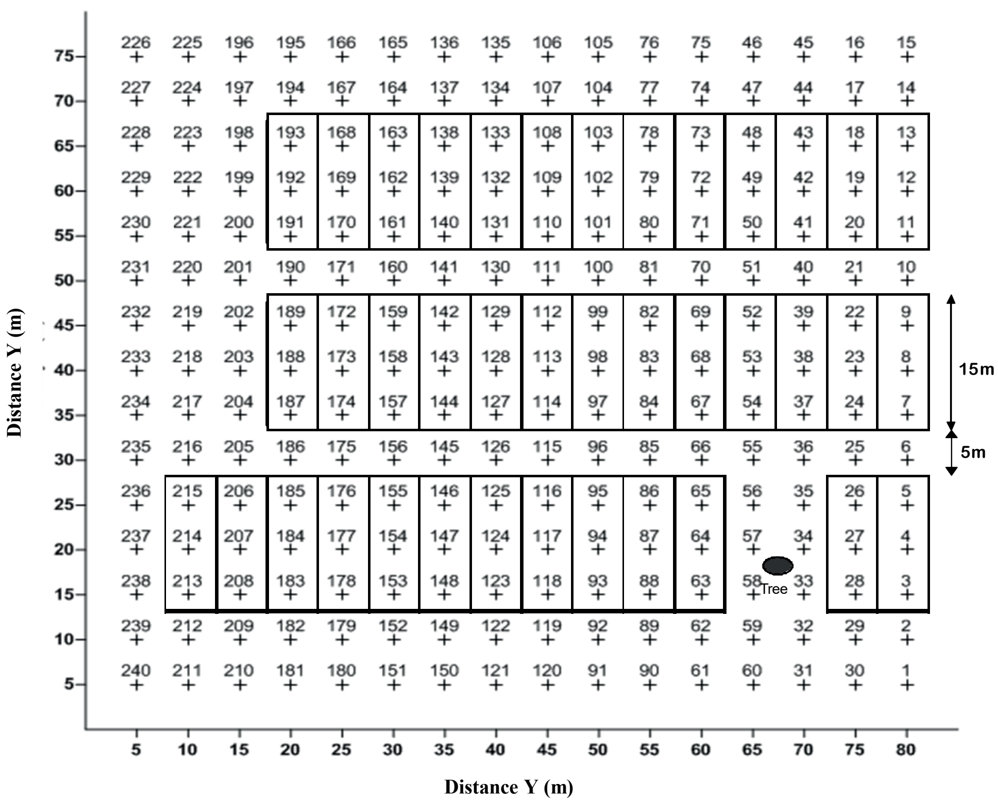

Figure 3. Site map with the location of the sampling grid and experimental area.

relative to the level (C_0 + C_1) (Cambardella et al. 1994), was calculated using the equation DSD = (C_0/ C_0 + C_1) x 100, to express the spatial dependence of a variable. According to Cambardella et al. (1994), the DSD can be classified as strong (DSD ≤ 25 %), moderate (25 % < DSD ≤ 75 %) and weak (DSD > 75 %) spatial dependence.

After the spatial autocorrelation among the samples demonstrated by the semi-variogram analysis, maps were generated using ordinary kriging as interpolator (Vieira 2000). Contour maps were drawn using the Surfer 7.0 software, visualizing the spatial distribution of the soil properties. Cross semi-variograms were used to determine whether two properties had a common variance (Goovaerts & Chiang 1993).

RESULTS AND DISCUSSION

The descriptive analysis of the chemical properties is shown in Table 2. The measures of central tendency (mean and median) are relatively similar for most the variables. It was found to be low for the variables pH(H_2O) and pH($CaCl_2$), average for exchangeable Ca, Mg and available K, and high for available P. The available P and K were not normally distributed, as shown by the skewness and kurtosis coefficient values and the Kolmogorov-Smirnov test (Table 2).

Table 3 shows the best fitted theoretical models and the estimated parameters of the experimental semi-variograms for the soil chemical properties. Of the models tested, the spherical model was the best for predicting the spatial variability, except for available P, which exhibited a nugget effect. The semi-variograms were calculated according to the spherical model for pH(H_2O), pH($CaCl_2$), K, LogK, Ca and Mg. Phosphorus and LogP showed a nugget effect. Except for P and LogP, all the theoretical models gave a good fit to the experimental semi-variograms, and the values for the coefficients of determination (R^2) were above 0.75 and, sometimes, close to 1 [pH($CaCl_2$), Ca and Mg]. The logarithm transformation did not improve the coefficients of determination of the models for K and P. The available P showed a nugget effect. Thus, it can be assumed that the distribution is completely random, with no spatial dependence between samples. This means that the methods of classical statistics may be applied with an arithmetic mean value that represents well the data set. However, it does not necessarily mean that there is a structure variance. The spatial

Table 2. Descriptive statistics of the soil chemical properties (number of samples for the grid = 240).

Variables	Minimum	Maximum	Median	Mean	SD	CV (%)	Skewness	Kurtosis	Probability level[a]
pH(H_2O)	4.15	6.03	5.07	5.06	0.30	6.01	0.07	0.47	ns
pH($CaCl_2$)	3.91	5.04	4.34	4.37	0.19	4.47	0.64	0.65	ns
P (mg kg^{-1})	1.41	38.17	4.42	6.41	5.68	88.73	2.71	9.41	< 0.05
K ($mmol_c$ kg^{-1})	3.59	18.72	6.41	7.05	2.41	34.13	1.73	3.91	< 0.05
Ca ($mmol_c$ kg^{-1})	5.70	38.70	16.75	16.89	5.57	33.00	0.49	0.55	ns
Mg ($mmol_c$ kg^{-1})	4.20	28.30	11.70	11.89	4.11	34.62	0.70	1.19	ns

[a] Probability level obtained from the Kolmogorov-Smirnov test; ns: not significant.

Table 3. Theoretical models and estimated parameters of the experimental semi-variograms of the soil chemical properties.

Variable	Model	Parameters					Spatial class
		C_0	C_1	R (m)	R^2	DSD (%)	
pH(H_2O)	Spherical	0.0467	0.0491	35.91	0.768	51.25	Moderate
pH($CaCl_2$)	Spherical	0.0154	0.0247	35.15	0.995	38.37	Moderate
P	Nugget effect	27.6100	29,719.0000	556,942.00	0.461	-	-
LogP	Nugget effect	0.0640	0.0260	41.00	0.414	-	-
K	Spherical	1,948.4000	7,481.0000	23.46	0.852	20.66	Strong
LogK	Spherical	0.0050	0.0130	25.00	0.837	27.78	Moderate
Ca	Spherical	0.0662	0.2342	20.99	0.996	22.02	Strong
Mg	Spherical	0.0731	0.0896	28.74	0.996	44.95	Moderate

C_0: nugget variance; C_1: baseline; R: range; R^2: coefficient of determination; DSD: degree of spatial dependence.

dependence may occur at a shorter distance than the distance between the sampling points.

The C_0 values reflect a variability not explained by the semi-variograms for distances smaller than the separation distance between the samples (Vieira 2000). It is indicative of the amount of random variation from one point to another, and the lower the values, the more similar are the neighbours. The C_0 values are 0.05, 0.02, 0.07 and 0.07, respectively for pH(H_2O), pH($CaCl_2$), Ca and Mg. Lower C_0 values were found for pH(H_2O), pH($CaCl_2$), Ca and Mg, indicating a higher continuity of spatial variability, when compared to available K.

The analysis of the $C_0/(C_0 + C_1)$ ratio makes it possible to quantify the random component (C_0) within the total variance ($C_0 + C_1$) and corresponds to the degree of spatial dependence (DSD). A moderate degree of spatial dependence (25 % < DSD < 75 %) was observed for pH(H_2O), pH($CaCl_2$) and Mg, whilst K and Ca presented a strong degree of spatial dependence (DSD < 25 %).

The range (R) is the distance at which the spatial autocorrelation between pairs of data points ceases. Its variation between 21 and 36 m implies that the distance of the spatial autocorrelation is longer than the average distance of 5 m between samples, indicating that the sample framework used was adequate to represent the spatial structure, so that geostatistical interpolation maps of good quality can be obtained (McGrath et al. 2004).

The cross semi-variogram estimates for pairs of variables using pH(H_2O), pH($CaCl_2$), Ca, Mg and K are shown in Table 4. All the cross semi-variograms were fitted to the spherical model. All the pairs of variables showed a strong or moderate degree of spatial dependence. Their ranges are similar, varying from 20 to 35 m, with a mean of 27 m.

The spatial distribution pattern of soil chemical properties was evaluated by the geostatistical maps of the kriged estimates (Figure 4). A visual map analysis showed that all properties tend to have the highest concentrations in the area which starts at the top centre and ends at the bottom left of the maps (west to east).

In the tropical Savanna, where the study was conducted, fire plays a critical role in the soil biogeochemistry (Pivello et al. 2010, Resende et al. 2011). The changes in the processes can be either harmful or beneficial to the agroecosystems, depending on the severity of the fire, and the effects may be short-lived or long-lasting (Neary et al. 1999, Thomaz 2018). In this region, the main change in the environmental characteristics is related to the soil nutrient concentrations (Lal & Ghuman 1989, Fraser & Scott 2011). In the present study, the atypical nutrient concentration after approximately 20 years of deforestation shown in the maps (Figure 4) is the first clue to changes in the nutrient distribution pattern due to Savanna windrow wood burning.

The variations of some of the soil properties analysed in this study are rather high (Table 2). The basic cations had CVs of 33-35 %, whereas the CV of P reached 89 %. However, a low CV was observed for soil pH (H_2O and $CaCl_2$), corroborating several studies that have reported that soil pH is among the most variable soil properties (Mulla & McBratney 2000, Vendrame et al. 2010, Vendrame et al. 2013).

The spatial variability analyses were conducted and soil properties for the whole area were predicted by ordinary kriging, showing spatial distribution patterns (Figure 4). The spatial correlation of samples was analysed by the experimental semi-variograms to which the mathematical models were fitted. A

Table 4. Theoretical models and estimated parameters of the experimental cross semi-variograms of the soil chemical properties.

Pairs of variables	Model	Parameters					Spatial class
		C_0	C_1	R (m)	R^2	DSD (%)	
Ca x Mg	Spherical	0.035	0.150	20	0.783	18.9	Strong
Ca x pH($CaCl_2$)	Spherical	0.015	0.060	25	0.787	20.0	Strong
Mg x pH($CaCl_2$)	Spherical	0.022	0.045	30	0.791	32.8	Moderate
K x pH($CaCl_2$)	Spherical	0.000	7.100	26	0.507	0.0	Strong
pH(H_2O) x pH($CaCl_2$)	Spherical	0.020	0.031	35	0.791	39.2	Moderate
pH(H_2O) x Ca	Spherical	0.021	0.068	25	0.686	23.6	Strong
pH(H_2O) x Mg	Spherical	0.021	0.060	30	0.756	25.9	Moderate
pH(H_2O) x K	Spherical	0.000	12.000	24	0.633	0.0	Strong

C_0: nugget variance; C_1: baseline; R: range; R^2: coefficient of determination; DSD: degree of spatial dependence.

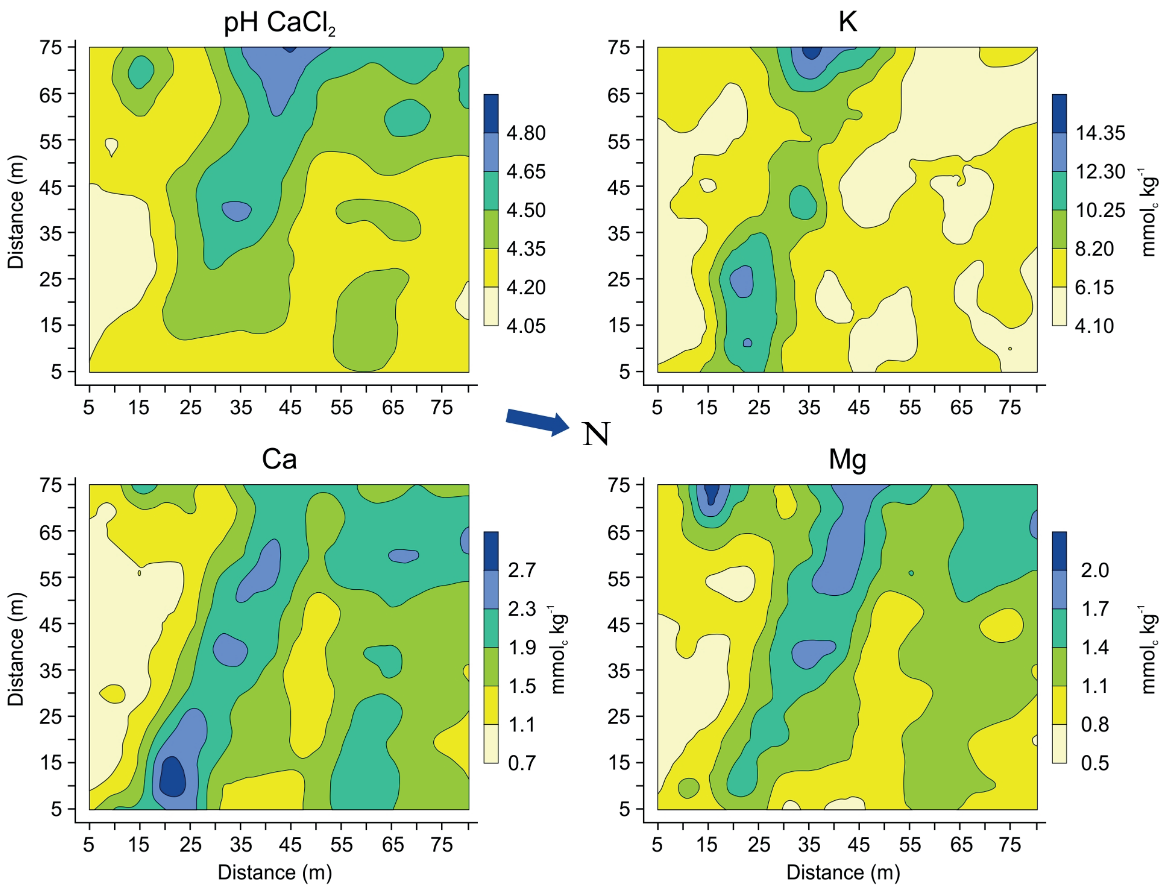

Figure 4. Maps of the kriged estimates for the soil chemical properties of the study site.

high degree of spatial dependence was observed for Ca and K ($C_0/C_0 + C_1 < 25$ %) and a moderate one for Mg and pH (H_2O and $CaCl_2$) (25 % < $C_0/C_0 + C_1 < 75$ %). Only P showed a weak degree of spatial dependence. Except for P, the semi-variograms reached an upper limit, i.e., a sill. Such variograms suggest that the properties vary in a patchy way, resulting in some areas with lower and others with higher values (Frogbrook et al. 2002). The range of spatial dependence varied from 21 to 36 m for all the measured soil properties (Table 3). Moreover, the cross semi-variograms highlight the close relationship among these soil properties (Table 4): the coefficient of determination of pairs of variables varied from 0.51 to 0.79; and the ranges of the cross semi-variograms are much the same as those of the variograms. The kriged contour maps showed positional similarities, with a patchy zone crossing the study area, where all these properties were higher (Figure 4).

This patchy zone is supposed to be related to burning windrow wood from the Savanna (Cerrado) deforestation. During a fire, some of the plant nutrients are deposited on the soil as ash and some, mainly nitrogen, are released into the atmosphere as gaseous compounds (Pivello & Coutinho 1992). The total above-ground biomass of different types of Cerrado vegetation ranges 5-25 Mg ha^{-1} (Delitti et al. 2006). The nutrient concentration in the native vegetation biomass of the Cerrado varies 0.56-1.38 % for Ca, 0.08-0.10 % for Mg, 0.19-2.26 % for K and 0.11-0.6 % for P (Pivello & Coutinho 1992, Kauffman et al. 1994).

It is assumed that the changes in the soil properties (pH, exchangeable cations) mainly result from the amount of ash alkalinity added to the soils, i.e., the excess of cations over inorganic anions that is generally observed in plant material (Noble et al. 1996). Other studies have also shown large increases in Ca and Mg concentrations in the soil after fire or ash deposition (Strømmgaard 1992, Kauffman et al. 1994, Carvalho et al. 2014). The soil pH also tends to increase after a fire, due to the release of basic ions from the ash (Nardoto & Bustamante 2003). The only soil property that did not vary with the others was the available P content. The P semi-variogram (Table 3) showed a pure nugget effect, indicating a total lack of spatial dependence. This means that the range for the P data is smaller than the smallest spacing between samples (5 m). The high variability of the available P is probably related to the P fertilizer location. The band placement of P must increase the variability of the P availability, as this criterion has not been considered for soil sampling. Indeed, management practices could have great effects on P availability (Eberhardt et al. 2021).

Cerrado deforestation by piling up and burning wood has a major influence on the soil properties, even after several years (ca. 18) of agricultural land use. Other studies have shown that, after 20-40 years, i.e., nearly the time since deforestation of our study area, changes induced by fire in the soil chemical properties are still perceptible. Strømgaard (1992) reported, for an Orthic Oxisol, an increase in pH from 4.2 to 7.2, 5.2 and 5.1, respectively for 24 hours, 40 days and 9 years, after a fire. Fraser & Scott (2011) showed a persistent effect of fire (pH, Ca and Mg) after approximately 20 years. According to Fraser & Scott (2011), the burning effect could persist for up to 1,000 years before reverting to the pre-burn soil conditions.

The knowledge of the spatial variability of soil properties at the field scale is of great importance to crop management and soil quality assessment in precision agriculture (Negreiros Neto et al. 2014), and the models proposed are also relevant to digital soil mapping (Dalmolin & ten Caten 2015). Currently, identifying management areas within a field that represent subfield regions with uniform characteristics that can affect yield is essential for sustainable agroecosystem management. Then, these contour maps of soil properties, along with their spatial structures, can be used for better management decisions, as a fertilization strategy and mapping soil variability in management zones for precision agriculture.

CONCLUSIONS

1. The geostatistical analysis showed that burning windrow wood from Cerrado (Brazilian Savanna) deforestation has a great influence on the spatial variability of most soil chemical properties;
2. The spatial variability of pH(H_2O), pH($CaCl_2$), exchangeable Ca, Mg and available K contents showed similar patterns, i.e., a patchy zone crossing the study area, where all the soil properties were higher, indicating that burning piles of wood results in a well-defined spatial arrangement.

ACKNOWLEDGMENTS

The authors thank José Carlos Costa Gonçalves Rocha and Davi de Jesus Soaris da Silva, for field support; the Empresa Brasileira de Pesquisa Agropecuária (Embrapa), Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD) and Institut de Recherche pour le Développement (IRD), for the financial support; and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for the scholarships granted.

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