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ORIGINAL ARTICLE

Spatial variability of soil fertility in areas cultivated with grains in the region of Paragominas, Pará state, Brazil

Variabilidade espacial da fertilidade do solo em áreas cultivadas com grãos na região de Paragominas-PA

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ABSTRACT: The application of precision agriculture techniques in the management of soil fertility has optimized the use of fertilizers, enabling more sustainable agricultural systems. In this study, we aimed to assess the spatial variability of soil fertility in areas cultivated with grains in the region of Paragominas, Pará state, Brazil. The study was conducted in 17 farms in 2009 and 2010. We measured 1945 soil samples collected at the 0-0.20 m depth. The following variables were analyzed: pH, V%, m%, sum of bases, K, Ca, Mg, Al, CEC, CEC t, P, and OM. The results were evaluated by means of descriptive statistics and frequency distribution. The soils cultivated with grains presented low acidity; base saturation below 50%; medium to high values of K, Ca and Mg. The levels of available P in the soil were considered low or very low in over 40% of the soil samples analyzed, constituting the most limiting factor to production.

KEYWORDS
Soil management
Chemical properties
Crop systems
Precision agriculture

RESUMO: *A aplicação de técnicas de agricultura de precisão no manejo da fertilidade do solo tem otimizado o uso de fertilizantes e corretivos, possibilitando maior sustentabilidade aos sistemas agrícolas. O objetivo deste trabalho foi avaliar a variabilidade espacial da fertilidade do solo em áreas cultivadas com grãos na região de Paragominas-PA. O estudo foi desenvolvido em 17 propriedades agrícolas, nos anos de 2009 e 2010, mensurando 1.945 amostras de solos, coletados na profundidade de 0-0,20 m, para as variáveis pH, V%, m%, soma de bases, K, Ca, Mg, Al, CTC, CTC t, P e MO. Os resultados foram avaliados por meio de estatística descritiva e de distribuição de frequência. Os solos cultivados com grãos apresentaram baixa acidez, saturação por bases abaixo de 50% e teores de K, Ca e Mg com valores de médio a alto. Os teores de P disponível apresentaram níveis considerados baixos e muito baixos em mais de 40% das amostras avaliadas, constituindo-se o fator mais limitante da produção.*

PALAVRAS-CHAVE
Manejo do solo
Atributos químicos
Sistemas de produção agrícola
Agricultura de precisão

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1 Introduction

The municipality of Paragominas, which occupies a land area of 1.93 million hectares (IBGE, 2007), is located in the northeast mesoregion of the state of Pará, 320 km from the state capital city - Belém. Important economic activities developed in the Amazon region are concentrated in this area, such as cattle raising, logging, forest management, reforestation, soybean and maize cultivation, and bauxite mining. Since 2000, Paragominas began to stand out in the agricultural scene, especially because of the cultivation of rice, maize and soybean. The territorial expansion in grain production was favored by areas that had been opened as a result of the anthropic action, flat topography, and defined rainfall regime of the region, placing the municipality among the largest grain producers in the state of Pará, with approximately 35,000 hectares of cropland (PINTO et al., 2009).

The soils of this region present large spatial variability of attributes with low natural fertility and predominance of Yellow Dystrophic Latosols. They show strong acid reaction with pH values, sum of exchangeable bases (SB), and contents of exchangeable aluminum (Al^{3+}) ranging from 3.5 to 5.3, 0.2 to 7.9, and 0 to 2.1 $cmol_c$ dm^{-3}, respectively (RODRIGUES et al., 2003). The contents of phosphorus (P) and potassium (K) are usually very low, varying from 1 to 7 mg dm^{-3} and 0.13 to 0.35 $cmol_c$ dm^{-3}.

For soils with low fertility and variability of attributes, precision agriculture constitutes a set of principles and technologies applied to the management of soil fertility based on the determination of the spatial and time variability associated with agricultural production, leading to increased crop yield, improved environmental quality (PIERCE; NOWAK, 1999), and hence, to greater profitability. In practical terms, it involves the collection and processing of detailed and georeferenced information about the areas of agricultural cultivation, allowing the definition of more efficient management strategies (USERY; POCKNEE; BOYDELL, 1995), especially the rational use of agricultural inputs (MOLIN; MASCARIN; VIEIRA JÚNIOR, 2006; MACHADO et al., 2007).

The starting point has been the collection of georeferenced samples arranged in a sampling grid, so that the results of these analyses can be processed using geostatistics and, subsequently, interpolated maps representing the spatial variation on the values of each analyzed attribute can be elaborated (EARL; THOMAS; BLACKMORE, 2000; LAMPARELLI; ROCHA; BORGHI, 2001). Based on these maps, it is possible to diagnose specific factors that are limiting to crop yield, and thereby indicate management interventions (AMADO et al., 2007). With the results of the attributes of soil fertility, it is possible to generate accurate maps regarding the supply of fertilizers and correctives in specific amounts for particular parts of the field, according to the changes in the chemical quality of soil from one location to another within the area in question (BALASTREIRE; ELIAS; AMARAL, 1997).

The aim of this study was to evaluate the spatial variability of soil fertility in areas cultivated with grains in the region of Paragominas, Pará state.

2 Materials and Methods

The study was conducted in the central part of the northeast mesoregion of the state of Pará on 17 grain producing farms in the municipality of Paragominas, located at the geographic coordinates 39° 2' and 3° 40' latitude south and the meridians 46° 27' and 48° 50' longitude west of Greenwich.

The climate in the region is defined as Aw according to the Köppen classification, which corresponds to a rainy tropical climate with well-defined dry season; the average annual rainfall in the region is 1,802 mm, with average annual temperature of 26.5 °C and average air humidity of 82%. The natural vegetation of the area was classified as dense subperenial equatorial forest of low lands and characterized as dense alluvial forest (EMBRAPA, 1988).

The data used were obtained from a database of soil samples collected in 2009 and 2010 in different locations on 17 farms (Figure 1). Soil sampling was carried out in the periods preceding the sowing of soybean, more specifically from September to November, in a total area of approximately 9,725 ha, with 5 ha sampling grids, totaling 1,945 sampling points (composite samples). Each composite sample was formed from 10 single samples collected in a circle around each sampling grid, thus resulting in a total of 19,450 single samples collected. The study area has been cultivated with grains for approximately 12 years.

Soil sampling was carried out at a depth of 0-0.2 m with the aid of an automated stainless steel screw auger with electric motor, installed on a four-wheeled motorcycle equipped with a GPS device. The samples collected were properly stored and then sent to a specialized laboratory for chemical analysis. Soil pH was determined potentiometrically using the ratio 1:2.5 (soil:water); exchamgeable calcium (Ca), magnesium (Mg), and aluminum (Al) were extracted with a solution of potassium chloride (KCl) 1 mol L^{-1}; potassium (K) and phosphorus (P) were extracted by Mehlich 1; potential acidity (H + Al) was extracted with a solution of calcium acetate using the methodology proposed by Embrapa (1997); and organic matter (OM) was obtained by colorimetry according Raij et al. (2001). Based on the results of the sorption complex, the values of sum of bases (SB), total cation exchange capacity (CEC T), effective cation exchange capacity (CEC t), base saturation (V), and aluminum saturation (m) were calculated.

The results were submitted to descriptive statistical analysis using the SISVAR software (FERREIRA, 2011). The variability of attributes was classified as low (CV <12%), medium ($12 \leq CV \geq 62\%$), and high (CV> 62%) (WARRICK; NIELSEN, 1980), and interpreted based on the contents and critical limits reported by Raij et al. (1996) and CFSEMG (1999).

3 Results and Discussion

The chemical properties of the soils showed high variability (Table 1), which occurs owing to variation in the level of management practiced by farmers, such as the amount of fertilizer applied and the correction periods of soils. According to the information reported by Raij et al. (1996) and CFSEMG (1999), the results described indicated levels ranging from very low to high, in the cases of Al^{3+} and K^{+}, respectively. The

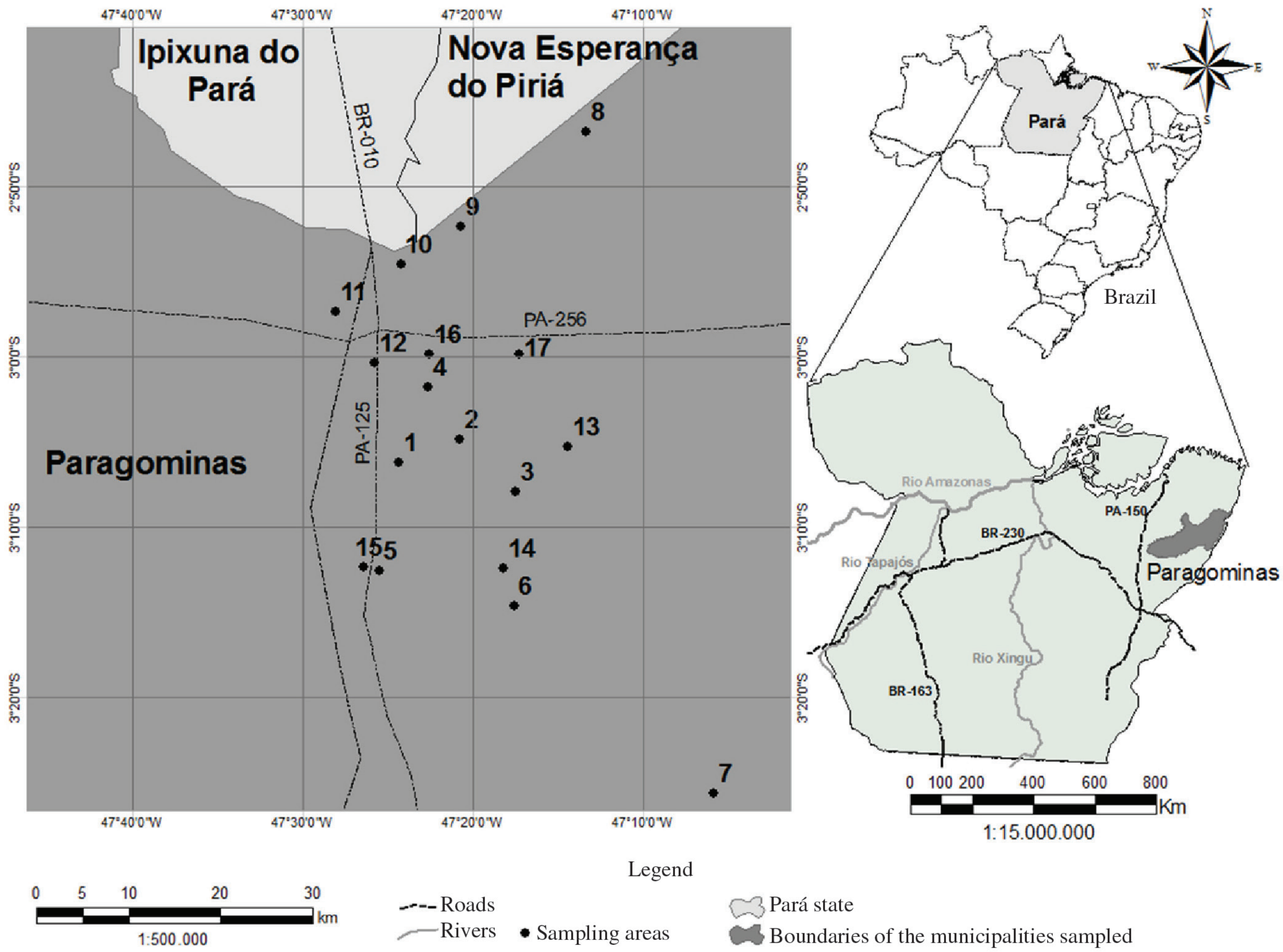

Figure 1. Location map of the agricultural areas sampled in the study.

Table 1. Descriptive statistics of chemical properties of 1,945 samples during 2009 and 2010 in cultivated soils in the region of Paragominas, Pará state-PA.

Variable	Mean	Median	Min	Max	sd	CV	s^2	Kurt	Asym
pH (H_2O)	5.7	5.7	4.5	8.0	0.4	7.7	0.2	1.6	0.3
V (%)	47	46.7	10	94.8	13.6	28.9	185	0.1	0.3
m (%)	5.2	0.0	0.0	60.9	9.6	174	91	4.0	2.0
SB ($cmol_c dm^{-3}$)	3.81	3.58	0.67	14.14	1.63	42.8	2.68	1.07	2.68
K ($cmol_c dm^{-3}$)	0.25	0.23	0.04	0.74	0.12	48	0.01	–0.1	0.61
Ca ($cmol_c dm^{-3}$)	2.7	2.6	0.4	11.5	1.2	44.5	1.6	1.6	0.9
Mg ($cmol_c dm^{-3}$)	0.77	0.7	0.2	3.5	0.34	44.16	0.11	2.58	1.03
Al ($cmol_c dm^{-3}$)	0.11	0.0	0.0	1.2	0.19	172.7	0.04	2.86	1.71
CEC ($cmol_c dm^{-3}$)	7.89	7.9	2.6	15.2	1.64	20.78	2.71	1.06	0.05
CEC t ($cmol_c dm^{-3}$)	3.92	3.59	1.14	14.14	1.52	38.77	2.32	1.66	1.03
P ($mg dm^{-3}$)	10.3	8.1	1.2	59.9	8.1	78.64	2.32	1.66	0.99
OM ($g kg^{-1}$)	32.8	33	5	59.2	8.5	25.91	72	0.7	–0.3

Values for pH, soil base saturation (V), aluminum saturation (m), sum of bases (SB), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), cation exchange capacity (CEC), effective cation exchange capacity(CEC t), phosphorus (P), and organic matter (OM). Mean values (Mean), median values (Median), minimum values (Min), maximum values (Max), standard deviation (sd), coefficient of variation (CV), variance (s^2), kurtosis coefficient (Kurt), asymmetry coefficient (Asym).

adequate levels of pH and indicators of soil acidity found were probably resulting from the application of lime and fertilizers on the croplands for approximately 12 years.

The high values of coefficient of variation (CV) are shown in Table 1, in which the smallest amplitude was verified for pH, with 7.7%; and the highest values were found for Al, m, and P, with 172, 184 and 78%, respectively, which was classified as high CV according to Warrick and Nielsen (1980), corroborating the results found by Carvalho, Silveira and Vieira (2002), Silva et al. (2003), and Amado et al. (2009). In the other properties assessed, CV ranged from 20 to 48%.

Contents of P varied from 1.2 to 59.9 mg dm^{-3}, similar to that observed by Amado et al. (2009). Thus, the use of an average P concentration of 10.3 mg dm^{-3} as a criterion for the fertility of this nutrient can lead to errors, because according to Bongiovanni and Lowenberg-Deboer (2004), and Corá et al. (2004), the use of a fixed rate for the interpretation of results, based on average nutrient content in areas with high spatial variability, can cause inefficiencies in the assessment.

It is possible to observe that 52% of the soil samples collected presented medium acidity (Figure 2a) based on the classification by Raij et al. (1996) and CFSEMG (1999), which varies between 5.5 and 6.0, that is, most sampled soils presented pH variation within the range considered agronomically ideal for the growing of soybean (SOUZA; LOBATO; MIRANDA, 1993), corroborating the data reported by El-Husny et al. (2006), who recommended the cultivation of soybean in the microregions of Paragominas and Santarém. The adequate pH values for soybean cultivation occurred owing to soil correction through liming, which increased the values of pH and base saturation, and reduced the concentration of exchangeable Al^{3+} in the soils (LEMOS; MORAIS, 2004). Morais and Albuquerque (2006) observed significant increases in pH values in the arable layer of 0-0.20 m soil depth in Latosols of the Paragominas region, Pará state, as a function of quicklime application.

Most of the soil samples showed pH values above those reported by Tedesco et al. (1984) and Pires et al. (2003) for the states of Rio Grande do Sul and Espírito Santo in areas cultivated with soybeans. The pH values found in this study suggest that, before starting the production process, farmers adopted the practice of liming, mainly in order to inhibit limitation in the root system development of crops (PAVAN; BINGHAM; PRATT, 1982), as a result of the toxicity caused by Al (COLEMAN; THOMAS, 1967).

The majority of soil samples (95%) were classified as very low or low with respect to the contents of exchangeable Al^{3+} (RAIJ et al., 1996; CFSEMG, 1999). Such values seem insufficient in promoting toxicity to the root system. According to Caires et al. (2002) and Tissi, Caires and Pauletti (2004), values of 0.8 $cmol_c$ dm^{-3} of exchangeable Al in the soil are not able to cause restriction to the root growth of maize cultivated in no tillage system.

Raij et al. (1996) and CFSEMG (1999) classify values of base saturation (V%) as follows: 20.1-40.0%, low; 40.1-60.0%, medium; and 60.1-80.0%, high. Therefore, the values of V% found in this study were considered medium in 52% of the soil samples collected, while 16% were characterized as high (Figure 2a), which favored plant development, taking into account that the base saturation recommended for grain crops is 45-50% for soybean and 60% for maize (SOUSA; LOBATO, 1996; QUAGGIO et al., 1998; FAGERIA, 2001). The combination between the high percentage of samples with high pH values and the low exchangeable Al values indicated efficiency in the practice of liming, highlighting the benefits of liming soils for agricultural use in the region (MORAIS; ALBUQUERQUE, 2006). According to Lemos and Morais (2004), increased V% reduced the availability of Al in the exchange complex in a Latossol in the Redençao region, Pará state, from 1.21 $cmol_c$ dm^{-3} to 0.09 cmolc dm^{-3}.

Medium to high values of base saturation are beneficial to maize and soybean crops, as they provide adequate supply of Ca, Mg, improve pH, and enable a proper balance between the basic cations (FAGERIA; STONE; SANTOS, 1999).

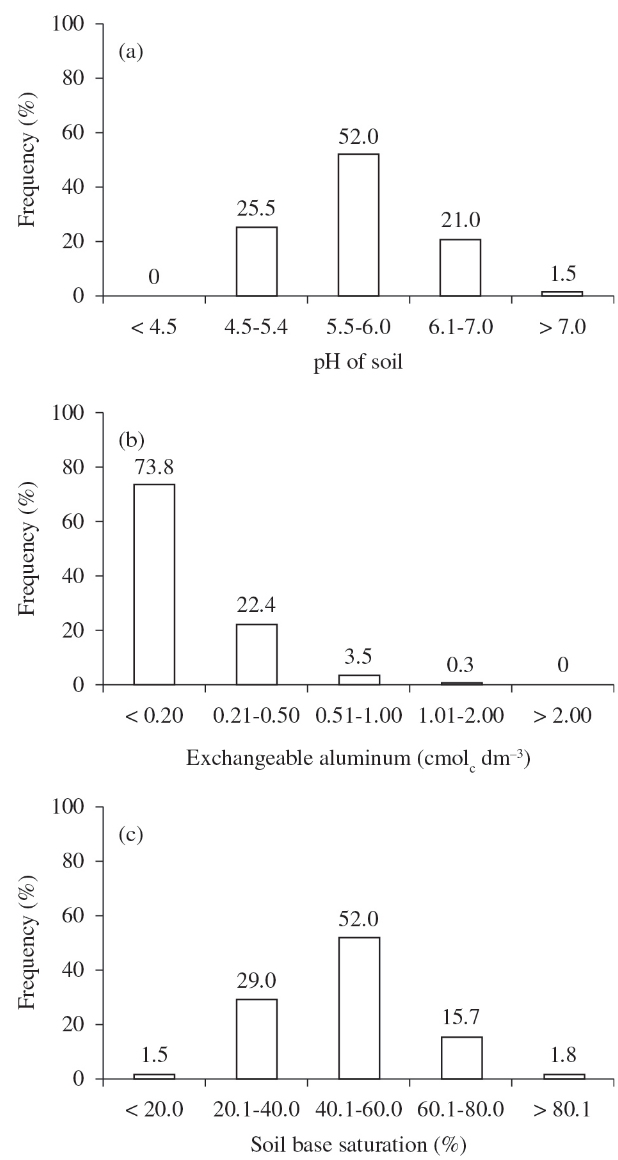

Figure 2. Frequency distribution of the evaluated attributes: soil pH (a), exchangeable aluminum (b), and base saturation (c) in soils under grain cultivation in the municipality of Paragominas during 2009 and 2010.

Most soil samples (68.5%) presented high to very high contents of K^+ (Figure 3a). According to Raij et al. (1996) and CFSEMG (1999), values of K in the soil above 0.31 $cmol_c$ dm^{-3} are considered high. The high values of K found in the soil samples occurred due to the residual effect of potassium fertilization, expressed as a function of retention of K in the CEC of soil, because the soils of the region present clayey texture and medium contents of K^+ in their natural fertility (MORAIS; ALBUQUERQUE, 2006). Furthermore, in acidic soils such as those of the present study, the concentration of potassium in the exchange complex of the soil may increase with liming, owing to the greater capacity of this element to exchange calcium and magnesium than aluminum (TISDALE; NELSON, 1970).

Regarding the levels of Ca^{2+}, it is possible to observe that over 90% of the soil samples presented equal and/or above average contents (RAIJ et al., 1996; CFSEMG, 1999), that is, values higher than 1.21 $cmol_c$ dm^{-3} (Figure 3b); while concerning the levels of magnesium, a frequency of more than 80% showed values from 0.46 to 1.50 $cmol_c$ dm^{-3} of Mg^{2+}, which according to Raij et al. (1996) and CFSEMG (1999) are classified as medium to high. The high contents of exchangeable Ca and Mg in the soil, combined with the medium contents of pH and base saturation, and with the low contents of exchangeable Al^{3+} (Figure 2), stressed the importance of liming to reduce Al toxicity (ERNANI; NASCIMENTO; OLIVEIRA, 1998) and increase the availability (TISSI; CAIRES; PAULETTI, 2004), mainly of macronutrients in the soil (PIRES et al., 2003). Significant effects in increasing the levels of Ca^{2+} and Mg^{2+} with the application of lime were also described by Veloso et al. (2001) for the municipality of Paragominas.

Regarding the variable organic matter (OM), the areas assessed presented values ranging from low to high; nevertheless, 75% of samples showed medium values (Figure 4a), considering the figures suggested by Raij et al. (1996) and CFSEMG (1999). The presence of adequate values of OM in the soils is of utmost importance in agriculture, with its numerous benefits and improvements in chemical and physical properties of agricultural soils being reported in the literature (MOREIRA; COSTA, 2004; RALISCH et al., 2008); therefore, OM is an effective indicator to discriminate soil quality (CONCEIÇÃO et al., 2005) and the one that best correlates with crop yield (AMADO et al., 2009).

According to Cerri, Feighl and Cerri (2008), OM is the result of historical balance between input (deposition of organic material) and output (mineralization) of carbon, so that the mismanagement of soil reduces the annual supply of material and implies the reduction of organic matter, and consequently, lower sustainability of agricultural soil (LUIZÃO, 2007; COSTA; FERREIRA; ARAÚJO, 2008). Despite the appropriate values found for this attribute, in the region of Paragominas, the adoption of conservation management practices such as crop rotation, green fertilization, incorporation of crop residues, organic fertilization, and no tillage (PIRES et al., 2003) are still incipient, and the adoption of these practices could greatly increase the contents of organic matter in the soil (CORRÊA; REICHARDT, 1995).

The assessment of phosphorus levels showed that 21 and 28% of the soil samples presented levels considered very low and low (RAIJ et al., 1996; CFSEMG, 1999), which can cause deficiency of P in plants, and the need for management to correct the levels of P through corrective phosphate fertilization in conjunction with maintenance fertilization.

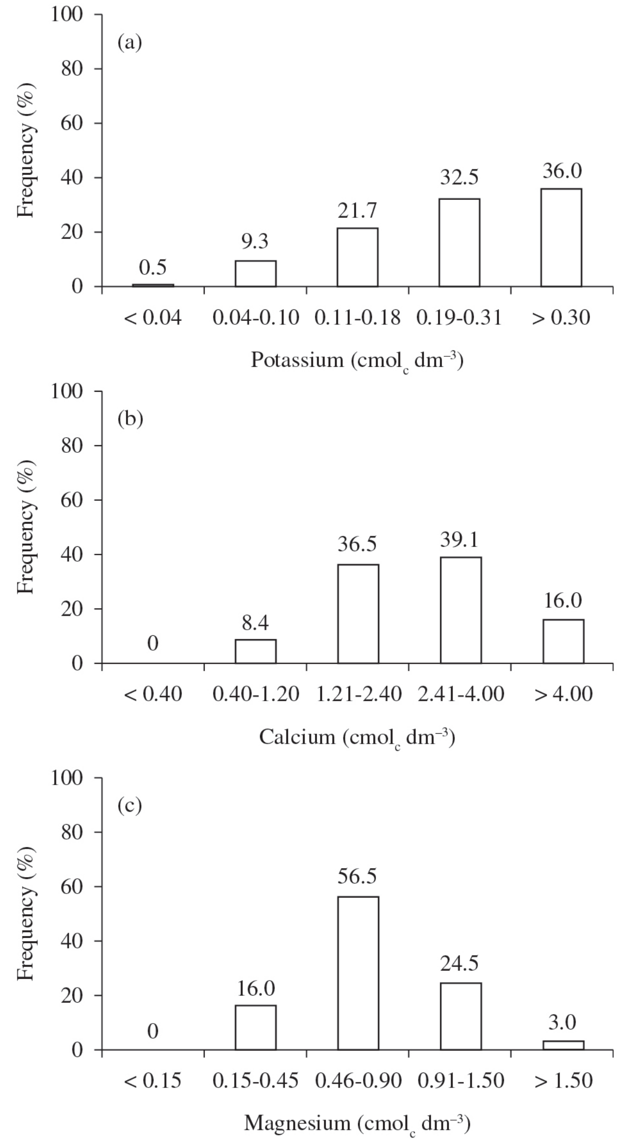

Figure 3. Frequency distribution of the evaluated attributes: potassium (a), calcium (b), and magnesium (c) in soils under grain cultivation in the municipality of Paragominas during 2009 and 2010.

The occurrence of low levels of P can be assigned to natural factors such as its low natural concentration in Latosols (COUTO et al., 1999; LONGO; ESPÍNDOLA, 2000), and to the clayey texture of soils, which according to Morais and Albuquerque (2006), present average P adsorption capacity, around 430 kg ha^{-1}. Another possible explanation is the lack of adoption of a direct sowing system, considering that Franchin et al. (2009), in a study of spatial variability of P, verified that 78% of the sites presented high or very high contents of this nutrient, attributed to the benefits of adopting no tillage in areas with more than 10 years of cultivation,

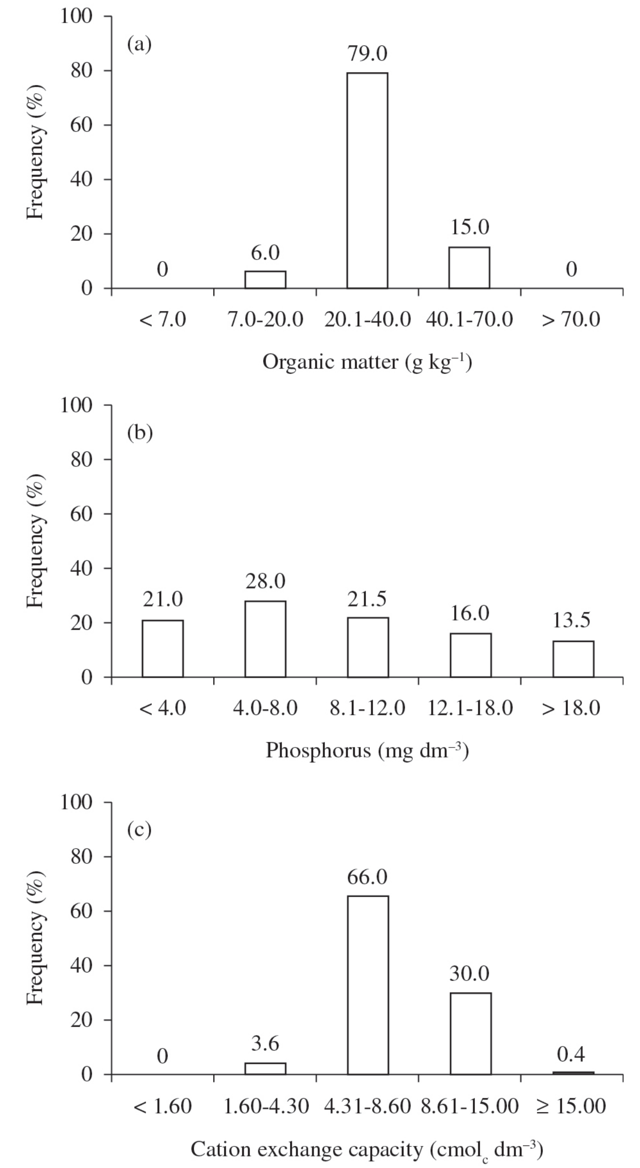

Figure 4. Frequency distribution of the evaluated attributes: organic matter (a), available phosphorus (b), and CEC (c) in soils under grain cultivation in the municipality of Paragominas.

with doses of P higher than those exported by the crops. Therefore, the supply of this nutrient is necessary for the adequate development of plants and grain yield (DADALTO; FULLIN, 2001).

With respect to the variable CEC, it was possible to observe (Figure 4c) that 66% of the samples presented average contents and 30% showed contents considered high. This effect occurred possibly owing to the presence of high values of pH in the region, which contributes to the formation of negative electric charges with consequent increase in CEC, or else, because of the high levels of OM found in the present study, considering that it is responsible for 36 to 58% of the CEC and influences the overall balance of electric charges in soil (VERDADE, 1956).

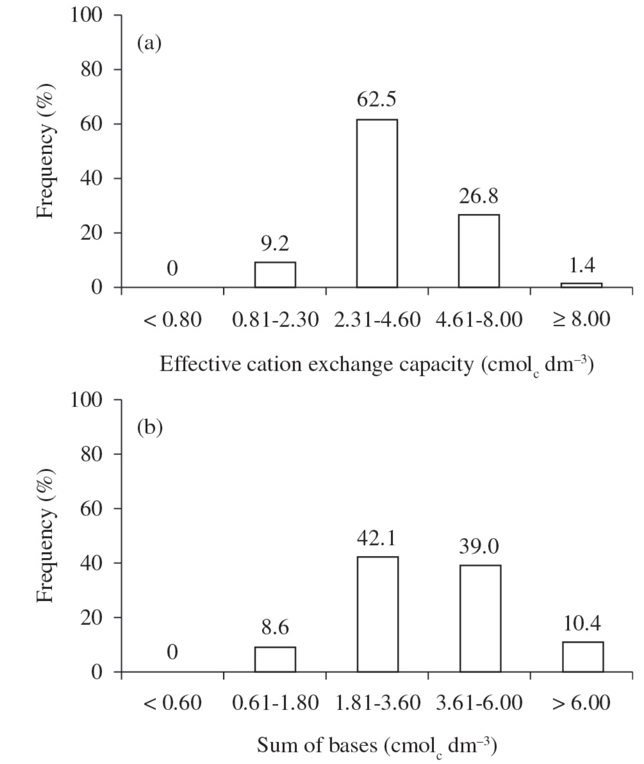

Figure 5. Frequency distribution of the evaluated attributes: effective cation exchange capacity (a), and sum of bases (b) in soils under grain cultivation in the municipality of Paragominas.

In 62.5% of the samples evaluated, it was possible to verify medium values of effective cation exchange capacity CECt, and 26.8% of sites with good CECt, according to Raij et al. (1996) and CFSEMG (1999) (Figure 5a), these values were close to those shown in Figure 4c for cation exchange capacity, demonstrating the similarity of these variables.

Regarding the sum of bases, it was possible to verify that 42.1 and 39.0% of the areas analyzed showed values considered medium or adequate, respectively (Figure 5b) (RAIJ et al., 1996; CFSEMG, 1999), reinforcing the results obtained in Figures 2 and 3, which demonstrated adequate soil correction in the region of Paragominas.

In general, the soils in the region of Paragominas, Pará state, presented chemical soil properties considered medium to high and low contents of exchangeable Al, which represents a significant improvement in soil fertility over time, allowing high yield in grain cultivation (CAIRES et al., 1998), as shown in the yield reports for maize (6.48 ha^{-1}) (SOUZA et al., 2002; FERNANDES et al., 2008) and soybean (3.51 ha^{-1}) (EL-HUSNY et al., 2003; SOUZA et al., 2011).

4 Conclusions

The soils cultivated with grains in the municipality of Paragominas, Pará state, present low acidity, base saturation below 50%, and contents of K, Ca, and Mg ranging from medium to high; however, the contents of available P show levels considered low and very low in over 40% of the samples assessed, constituting the most limiting factor to production.

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