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Phosphorus adsorption in soils under forest and savanna from Northern Amazon, Brazil

Adsorção de fósforo em solos sob floresta e savana do Norte Amazônico, Brasil

Carlos Henrique de Lima Matos^{1*}; Valdinar Ferreira Melo²; Sandra Cátia Pereira Uchôa²; Pedro Paulo Ramos Ribeiro Nascimento³; Raimundo Almeida Pereira¹

Abstract

Studies on maximum phosphorus adsorption capacity (MPAC) in soils from Roraima State and attributes that interfere with the magnitude of this characteristic are relevant and motivated this study. In this context, topsoil samples (0–0.20 m) from four soil classes (Oxisol–LA and Oxisol–LV [ITÂ, Caracarái]; Oxisol–LA [Serra da Prata, Mucajaí]; Oxisol–LA and Ultisol–PA [CCA, Boa Vista]; Oxisol–FT [Bonfim] and Alfisol –SN [Surumu, Pacaraima]) representative of Roraima State were used in this study in order to determine the influence of soil physical, chemical, and mineralogical attributes on MPAC. Air-dried soil samples of 2.5 g and 0.01 mol L⁻¹ CaCl₂ (25 mL) solution were stirred for 24 h, being added P in the form of KH₂PO₄ at concentrations of 0–60, 0–80, and 0–110 mg L⁻¹. P was analyzed in the supernatant for determining its adsorbed amount (P-rem). Adsorption values were fitted to the Langmuir isotherm in order to assess MPAC. Correlation tests were performed between MPAC and binding energy, pH, organic matter, clay, and CEC. MPAC values ranged from 14.50 to 527.93 mg kg⁻¹ in the soil. The soils FT–Bonfim and LV–ITÂ presented a higher MPAC. Considering the representative soil classes in the State, MPAC does not correlate with any of the assessed attributes. In the soil classes Oxisol and Ultisol, MPAC has a negative and significant correlation with binding energy.

Key words: Maximum phosphorus adsorption capacity. Correlation. Langmuir isotherm.

Resumo

Estudos sobre capacidade máxima de adsorção de fósforo (CMAP) em solos de Roraima e atributos que interferem na magnitude dessa característica são relevantes e motivaram esse trabalho. Nesse contexto, amostras da camada superficial (0-0,20 m) de quatro classes de solos: Latossolo Amarelo – LA e Latossolo Vermelho – LV (ITÂ, Caracarái); Latossolo Amarelo – LA (Serra da Prata, Mucajaí); Latossolo Amarelo – LA e Argissolo Amarelo – PA (CCA, Boa Vista-RR); Plintossolo Argilúvico – FT (Bonfim) e Planossolo Nátrico – SN (Surumu, Pacaraima) representativos do estado de Roraima, foram utilizadas no presente trabalho, com a finalidade de determinar a influência de atributos físicos, químicos e da mineralogia dos solos sobre a CMAP. Amostras de 2,5 g de TFSA (terra fina seca ao ar) foram mantidas em contato com soluções de CaCl₂ 0,01 mol L⁻¹ (25 mL), mediante agitação por 24 h, as quais foram adicionados fósforo (P), na forma de KH₂PO₄, nas concentrações de 0-60, 0-80 e 0-110 mg L⁻¹. O P foi analisado no sobrenadante para a determinação da quantidade adsorvida (P-rem). Para avaliar a capacidade máxima de adsorção de fósforo (CMAP), os valores de adsorção foram ajustados à isoterma de Langmuir. Foram realizados testes de correlação entre CMAP e energia de ligação, pH,

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matéria orgânica, argila e CTC. Os valores da CMAP situaram-se entre 14,50 e 527,93 mg kg⁻¹ de P no solo. Os solos FT (Bonfim) e LV (ITÃ) apresentaram maior CMAP. Considerando as classes de solos representativas do Estado, a CMAP não se correlaciona com nenhum dos atributos avaliados. Nas classes Latossolo e Argissolo, a CMAP tem correlação negativa e significativa com a energia de ligação.

Palavras-chave: Capacidade máxima de adsorção de fósforo. Correlação. Isotermas de Langmuir.

Introduction

Soils can work as a source or drain of P depending on its ability to meet the requirements of plants or compete with them, fixing part of P added to the soil (NOVAIS et al., 2007). With the increase in the weathering process, soils change from sources to drains due to their increased anion adsorption capacity through positive active sites formed mainly by iron and aluminum oxy-hydroxides (FARIAS et al., 2009).

The use of the Langmuir isotherm has been common in determining these factors since it contains a quantitative parameter related to the maximum phosphorus adsorption capacity (MPAC) and a qualitative parameter that expresses the binding energy between anions and adsorption sites (FARIAS et al., 2009). According to Corrêa et al. (2011), the use of isotherms has two advantages: the first is the ability to estimate P adsorption attributes and the second is the possibility of knowing the nature of its adsorption processes. This estimation depends on the parent material characteristics, content and mineralogy of clay fraction, the presence of Fe and Al oxides, pH, and organic matter (OM) (RANNO, 2007).

One of the factors influencing MPAC in soils is the mineralogy of clay fraction (BERA et al., 2006). According to Fox and Searle (1978), the adsorption process in this fraction can follow the following preferential order: 2: 1 clays < 1: 1 clays < crystalline Fe and Al oxides < amorphous Fe and Al oxides. Minerals that present superficial groupings of Fe-OH and Al-OH directly influence P adsorption by means of binder changes (chemisorption), and this adsorption is potentiated by the structural form and contact surface of each mineral (FONTES et al., 2001). Iron and aluminum oxides and kaolinite

are responsible for the phenomenon of specific P adsorption, thus establishing a direct relationship with MPAC (CORRÊA et al., 2011).

In acid soils, Fe and Al oxides increase phosphate adsorption through positive charges formed at acidic pH or through “bridges” created by the partial bond between oxides and cations such as Ca²⁺ and Al³⁺ (NOVAIS et al., 2007). The increase in Fe and Al oxides influences MPAC taking into account their concentration and soil acidity (RANNO et al., 2007; PINTO et al., 2013).

There is controversy about the role of OM in anion adsorption due to its ambivalence. At the same time as OM provides to the soil positive charges from carboxylic and phenolic radicals at acidic pH, it can also block the active sites of phosphate in the soil by the adsorption of Fe and Al oxides (CHAVES et al., 2007). The reduction of P adsorption in oxides has been attributed to the action of carbonic acid on the solubilization of P-containing minerals, formation of complexes with humus, increases in the competition between organic anions and phosphate by P adsorption sites, and formation of humus layers around Fe and Al oxides (MOREIRA et al., 2006; NOVAIS et al., 2007; PINTO et al., 2013).

In the Amazon, about 90% of the soils present high contents of kaolinite and low contents of Fe and Al oxides, resulting in a low P adsorption capacity (SMYTH, 1996). A high MPAC in this region is found in soils with higher contents of clay, free iron, and total iron (MELO et al., 2006). However, the role of kaolinite in P adsorption should be better investigated since the literature indicates that it may present low or high contents (ROLIM NETO et al., 2004; MOREIRA et al., 2006; BERA et al., 2006). According to Vilar et al. (2010), the importance of

kaolinite in P adsorption is related to its degree of crystallinity, in which the adsorption increases with a high crystallinity.

Thus, the aim of this study was to assess the maximum phosphorus adsorption capacity and identify its relationship with soil mineralogical, chemical, and physical attributes representative of Roraima State, Brazil.

Material and Methods

Sampling sites

Roraima State has a climate classified as Aw, a rainy tropical climate without a cold season, hot and humid, presenting a well-defined dry (December to March) and rainy (May to August) period according to the Koppen climate classification. According to Barbosa (1997), the average annual temperature is 25 °C and the average precipitation is 1100 mm in the northeast region, 1600 mm in the central region, and 2900 mm in the southwest region.

In the State's south-central region, particularly in the Itã region, there are developed soils of acidic volcanic rocks (granites/gneisses) that form part of the crystalline basement. From this parent material, yellow hue soils are formed, predominating acid and low-fertility Ultisols and Oxisols (MELO et al., 2010). The reddish soils of the region originate from the Serra da Prata Intrusive Suite, composed of hyperstenius, granites, and gneisses, and Rio Urubu Metamorphic Suite, composed of biotite-gnaiss and metagranitoids; due to the richness of minerals such as biotite and plagioclase, an improvement in soil fertility can be observed (BRASIL, 1998).

The soils of the State's central region are formed from pre-weathered sediments of the Boa Vista Formation accumulated in a shallow basin, dating from the end of the Tertiary and beginning of the Quaternary periods, concomitantly to residual reliefs formed by the Sierras Murupu, Nova Olinda, Serra Grande, Serra da Lua, among others, with kaolinite mineralogy and poor iron

oxides associated to granites and gneisses from the Guianense Complex or Basalts of the Apoteri Formation (VALE JÚNIOR; SCHAEFER; COSTA, 2007). Therefore, these soils are acid, with a low fertility, low OM content, low CEC, and a high aluminum saturation (m %) (MELO et al., 2010; BENEDETTI et al., 2011). The main representative classes of this Formation are Oxisols and Ultisols. The occurrence of residual reliefs from granites and gneisses of the Guianense Complex or Basalts of the Apoteri Formation can also be observed, which are responsible for the red soils occasionally found in the region. The vegetation varies from grassland savanna to park savanna on soils from sediments to forest islands, in inclusions of soils originating from basalt (MELO et al., 2006; VALE JÚNIOR; SCHAEFER, 2010).

In the northern region, the domain of the depression of Surumu, Parimé, and low Cotingo, large patches of Planosols with a high sodium saturation, originating from acidic and intermediate volcanic rocks such as rhyolites, dacites, and riodacites can be found (VALE JÚNIOR et al., 2011). Vegetation presents intrinsic characteristics of the transition from savanna to Caatinga, being common species such as *Curatella americana*, *Byrsonima* sp., *Cereus*, and *Melocactus* (SCHAEFER et al., 1993).

Selection and collection of soil samples

Four reference soil classes were selected in the State for conducting the experiment (Table 1). The selection of soil classes was based on their agricultural importance for Roraima State. Profiles of each sampling point were opened and the soils were classified morphologically according to the Manual of Soil Description and Collection (SANTOS et al., 2013). Soil taxonomy was obtained following the criteria of the Brazilian System of Soil Classification (EMBRAPA, 2013). Samples of a depth of 0–0.20 m were collected from each soil class for the analyses and P adsorption study. At this

depth, the root system of annual crops presents a greater efficiency. Air-dried soil samples from the different soils were characterized physically and chemically according to Embrapa (1997) (Table 2).

Table 1. Classification and location of seven soils in Roraima State, Brazil.

Soil	Abbreviation	Municipality	Geographical coordinate
Oxisol (Petroplinthic Dystrophic Yellow Latosol)	LA-ITÃ	Caracarái	01°31'36.8" N, 60°45'0.4" W
Oxisol (Petroplinthic Dystrophic Red Latosol)	LV-ITÃ	Caracarái	01°30'7.1" N, 60°43'13.7" W
Oxisol (Typic Dystrophic Yellow Latosol)	LA-Serra da Prata	Mucajá	02°22'20.3" N, 60°59'54.0" W
Oxisol (Typic Dystrophic Yellow Latosol)	LA-CCA	Boa Vista	02°52'15.9" N, 60°42'40.2" W
Ultisol (Typic Dystrophic Yellow Argisol)	PA-CCA	Boa Vista	02°52'22.9" N, 60°42'41.8" W
Oxisol (Abruptic Dystrophic Argiluvic Plinthosol)	FT-Bonfim	Bonfim	03°32'14.0" N, 60°0'33.3" W
Alfisol (Orthic Natric Planosol)	SN-Surumu	Pacaraima	04°11'33.2" N, 60°46'19.5" W

Table 2. Amplitude of P doses required for determining the MPAC of seven soils in Roraima State, Brazil.

Interval	Concentration of P standards											
	----- mg L ⁻¹ -----											
	PA-CCA; SN-Surumu											
0-60	0.0	3.0	6.0	9.0	15.0	21.0	27.0	33.0	42.0	51.0	60.0	
	LA-ITÃ; LV-ITÃ; LA-Serra da Prata; LA-CCA											
0-80	0.0	4.0	8.0	12.0	20.0	28.0	36.0	44.0	56.0	68.0	80.0	
	FT-Bonfim											
0-110	0.0	5.5	11.0	16.5	27.5	38.5	49.5	60.5	77.0	93.5	110.0	

LA (ITÃ): Oxisol (Petroplinthic Dystrophic Yellow Latosol); LV (ITÃ): Oxisol (Petroplinthic Dystrophic Red Latosol); LA (Serra da Prata): Oxisol (Typic Dystrophic Yellow Latosol); LA (CCA): Oxisol (Typic Dystrophic Yellow Latosol); PA (CCA): Ultisol (Typic Dystrophic Yellow Argisol); FT (Bonfim): Oxisol (Abruptic Dystrophic Argiluvic Plinthosol); SN (Surumu): Alfisol (Orthic Natric Planosol).

Chemical analyses included pH in water, calcium, magnesium, exchangeable aluminum by means of 1 mol L⁻¹ KCl, potassium by means of Mehlich-1; potential acidity by means of 0.5 mol L⁻¹ calcium acetate, and OM determined by oxidation with 0.2 mol L⁻¹ potassium dichromate (EMBRAPA, 2009). In addition, particle size distribution was performed by the pipette method (EMBRAPA, 1997) and the textural class of samples was identified by means of a textural triangle proposed by Santos et al. (2013).

Mineralogical analysis of sand, silt, and clay fractions (oriented samples) was performed by X-ray diffraction (XRD). In this process, 100 mL of water and 10 mL of 1 mol L⁻¹ NaOH solution were added to 100 g of the soil sample for dispersing the

fractions. After 24 h, samples were submitted to physical dispersion by using a disperser for 10 min. The sand fraction was retained in a 0.053-mm mesh sieve and clay and silt fractions were separated by sedimentation, being washed constantly aiming at removing sodium residues to avoid halite crystal formation, which could interfere with the diffractograms. After sample drying at ambient temperature, soil fractions were macerated and fixed in glass slides with mineral oil for sand and water for silt and clay. Diffractograms were obtained in a Shimadzu diffractometer with a cobalt tube, operating in an interval of 4 to 70° and a speed of 0.02° per second. Diffractograms were interpreted according to Chen (1977).

Maximum phosphorus adsorption capacity (MPAC)

Before quantifying MPAC of each soil, P-rem was determined in solution after 5 cm³ of soil be stirred for 1 h with 50 mL of 0.01 mol L⁻¹ CaCl₂ solution containing 60 mg L⁻¹ P, as Alvarez V. et al. (2000). P-rem values were used to identify adsorption intervals for each soil, reducing the test amplitude and ensuring a greater reliability to the results. Table 2 shows the intervals and P doses used to determine MPAC of the studied soils.

With these intervals, MPAC was determined by using 2.5 g of soil and 25 mL of 0.01 mol L⁻¹ CaCl₂ containing different P concentrations, as listed in Table 3. These samples were stirred in a horizontal stirrer for 24 h, centrifuged at 3000 rpm

for 5 minutes, and filtered (ALVAREZ V. et al., 2000). The equilibrium concentration was used to determine the constants of Langmuir equation, as follows:

$$\frac{C}{\frac{x}{m}} = \left(\frac{1}{b} \right) \times C + \frac{1}{a \times b}$$

where C is the P concentration in the equilibrium solution (mg L⁻¹), x/m is the amount of P adsorbed to the soil (mg g⁻¹), a is a constant related to the binding energy of the element to soil (L mg⁻¹), and b is the MPAC of soil. Using this equation, both MPAC and binding energy of P to soil were estimated.

Table 3. Chemical and mineralogical attributes of seven soils in Roraima State, Brazil.

Soil	pH	Ca	Mg	K	Al	H+Al	SB	CEC	OM	Mineral
					cmol _c dm ⁻³				g kg ⁻¹	
LA-ITÃ	5.10	1.80	1.70	—	0.20	6.40	3.50	9.90	18.40	Kt, Gt
LV-ITÃ	5.40	5.40	1.90	0.50	0.20	3.00	7.80	10.80	26.30	Kt, Gb, Gt, Hm
LA-Serra da Prata	5.60	1.80	1.00	—	0.00	3.30	2.80	6.10	11.60	Kt, Gt
LA-CCA	5.10	0.10	0.10	0.10	0.10	2.90	0.30	3.20	9.20	Kt, Gt
PA-CCA	5.00	—	—	—	0.40	2.70	0.00	2.70	8.30	Kt
FT-Bonfim	5.50	2.50	0.90	0.20	0.10	1.50	3.60	5.10	15.40	Kt, Gt, Hm, Mt, Mi
SN-Surumu	5.50	0.20	0.50	0.10	0.10	1.80	0.90	2.60	19.00	Kt, It

Kt – Kaolinite; Ep – Expandable minerals; Gb – Gibbsite; Gt – Goethite; Hm – Hematite; It – Illite; Mi – Mica.

Statistical analysis

Linear correlation studies were performed between MPAC and binding energy, pH, OM, clay, and CEC for the depth of 0–0.20 m. All parameters were compared by t-test at 5% probability level and classified according to Larson and Farber (2010).

Results and Discussion

According to the data showed in Table 3, soils are very acid (pH 5–5.6), with values of the sum of bases varying from not detected by the method (PA-CCA) to 7.8 cmol_c dm⁻³ (LV-ITÃ), which is considered very high. In general, soils presented a low exchangeable acidity, except for PA-CCA,

which presented a medium value (0.4–1.0 cmol_c dm⁻³). Regarding potential acidity, soils were classified as high (LA-ITÃ), medium (LV-ITÃ, LA-Serra da Prata, LA-CCA, and PA-CCA), and low (FT-Bonfim and SN-Surumu) (CFSEMG, 1999). OM contents varied from 8.30 to 26.30 g kg⁻¹ (Table 3). In environments under Cerrado, increments in soil OM is lower than in soils under forest, where the bio cycling of plant material is high and constant (MENDONÇA et al., 2013). For this reason, the highest CEC values occurred in soils under forest (LA-ITÃ and LV-ITÃ).

The clay content of samples varied from 110 to 419 g kg⁻¹, with textural classes between sandy and clayey (Table 4). This characteristic influences CEC

of soils when considering the negative charges from the fraction, in addition to being responsible for

generating active sites for P adsorption via cation bridges (NOVAIS et al., 2007).

Table 4. Physical attributes of seven soils in Roraima State, Brazil.

Abbreviation	Particle size			Texture
	Sand	Silt	Clay	
	----- g kg ⁻¹ -----			
LA (ITÃ)	598.50	98.80	302.70	Sandy clay loam
LV (ITÃ)	402.20	178.40	419.40	Clay
LA (Serra da Prata)	581.30	163.60	255.10	Sandy clay loam
LA (CCA)	640.00	97.70	262.30	Sandy clay loam
PA (CCA)	869.00	21.00	110.00	Loamy sand
FT (Bonfim)	588.00	290.00	122.00	Sandy loam
SN (Surumu)	760.00	120.00	120.00	Sandy loam

Clay fraction of LA–ITÃ is predominantly kaolinite with a smaller amount of goethite whereas the clay fraction of LV–ITÃ is composed of kaolinite, gibbsite, goethite, and hematite. The predominance of oxy-hydroxides in LV–ITÃ, together with its more clayey texture, resulted in soils with a higher fertility and CEC when compared to LA–ITÃ (Table 3).

PA–CCA, LA–CCA, and LA–Serra da Prata soils have kaolinite in their clay fractions, occurring goethite in a smaller amount (Table 3). Because of this mineralogy, these soils have a low CEC (MELO et al., 2006; VALE JÚNIOR; SCHAEFER, 2010; BENEDETTI et al., 2011).

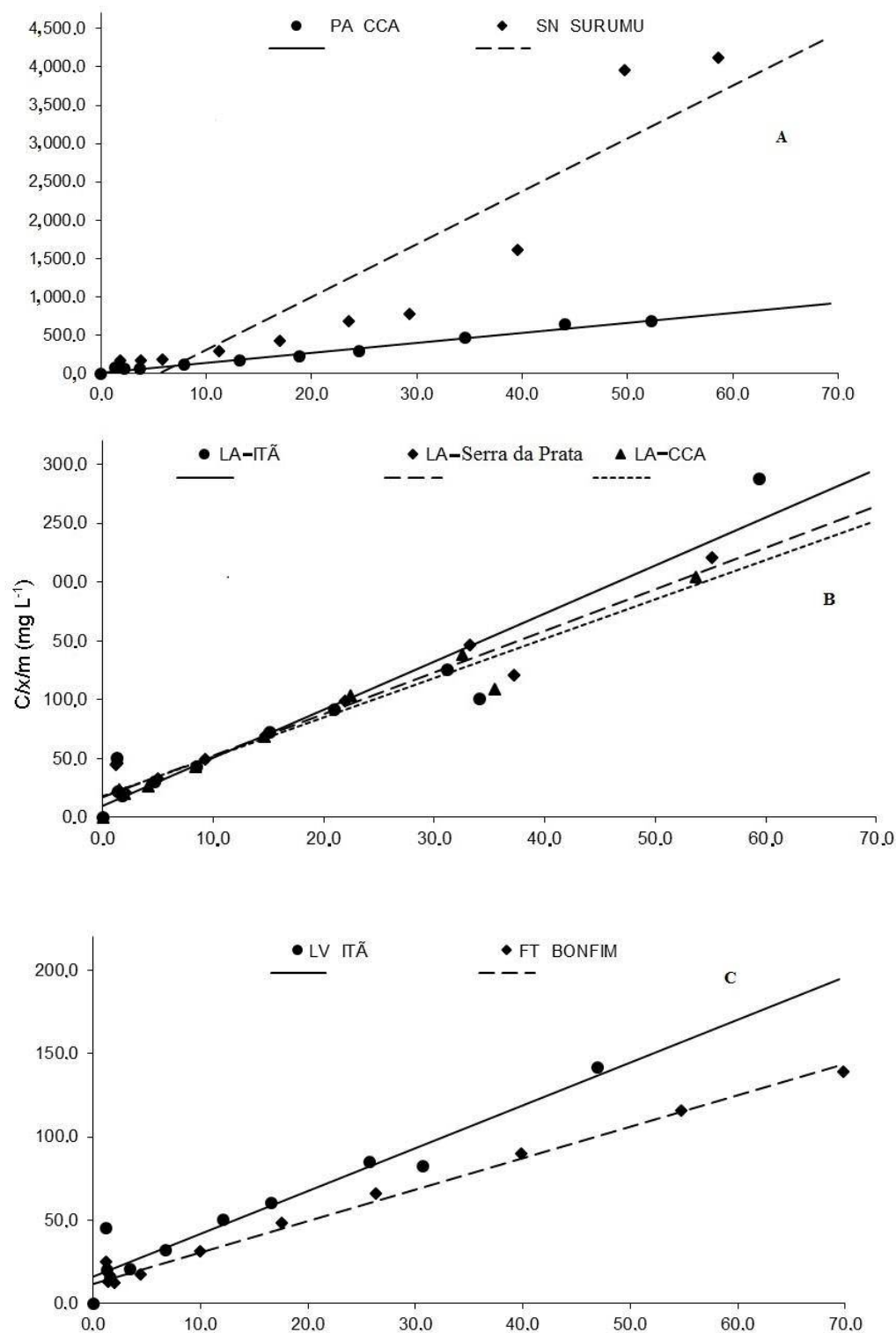
Clay fraction of FT–Bonfim is composed of kaolinite, Fe oxides, and traces of 2: 1 minerals (Table 3). Mica present in this fraction is represented in its totality by muscovite, the most resistant mineral to weathering among those in the mica classes, according to the Bowen series. Therefore, the higher CEC observed for FT–Bonfim among the studied savanna soils might be influenced by the expandable minerals in the clay fraction due to their higher specific adsorption surface when compared to the kaolinite (10–30 m² g⁻¹).

For SN–Surumu, clay minerals presented kaolinite with traces of illite. These minerals are commonly found in Planosols of northeastern Roraima (SCHAEFER; DALRYMPLE, 1996), increasing their CEC. However, the predominantly sandy loam texture of this soil has a greater influence on the adsorption power of cations and anions, in addition to presenting the lowest CEC among the studied soils.

The Langmuir isotherms for the studied soils were classified according to MPAC (Figure 1). The linear equations of isotherms, binding energy, MPAC and their correlation with binding energy, pH, OM, clay, and CEC are shown in Table 5.

Adsorption isotherms presented a high and significant coefficient of determination (Figure 1 and Table 5), demonstrating that the linear equation of Langmuir is adequate in determining the constants of P adsorption. These isotherms reveal that P adsorption increases with the concentration of the element in equilibrium solution. Falcão and Silva (2004) and Chaves et al. (2007) obtained similar results in Oxisols and Ultisols in the States of Amazon and Paraíba, which are environments of tropical forest and Atlantic forest, respectively.

Figure 1. Langmuir adsorption isotherms classified according to MPAC. (A) 0–100 mg kg⁻¹; (B) 100–300 mg kg⁻¹; and (C) > 300 mg kg⁻¹.



A large amplitude was observed in MPAC, with values ranging from 14.50 and 527.93 g kg⁻¹ (Table 5). Soils with a higher adsorption followed the sequence FT–Bonfim > LV–ITÃ > LA–CCA > LA–Serra da Prata > LA–ITÃ > PA–CCA > SN–Surumu. The main factors that affected the adsorption were texture, mineralogy of clay fraction, OM, and the presence of iron oxides. In spite of the sandy loam texture and savanna environment, FT–Bonfim presented a higher MPAC (527.93 mg kg⁻¹) due to the diversity of Fe oxides in the clay fraction (Table 3). Clay fraction mineralogy is more important than texture in the availability of active sites for anion adsorption (CUI; WING, 2013; PALÁGYI et al., 2013). Chaves et al. (2007) concluded that, in soils of similar texture, MPAC is influenced mainly by clay mineralogy.

The highest MPAC was observed in LV–ITÃ (389.20 mg kg⁻¹) (Table 5) due to its clayey texture and presence of iron and aluminum oxides. The presence of these oxides generates pH dependent charges that may be positive. At an acid pH, H⁺ ions in solution tend to bind with the hydroxyls of these minerals, generating positive charges that act as active sites for anions (NOVAIS et al., 2007). At a high pH, cations with a higher valence in the soil, mainly Ca²⁺ and Al³⁺, can act as “bridges” between oxides and anions. This high adsorption

is common in weathered soils, standing out the Oxisols (FALCÃO; SILVA, 2004; CHAVES et al. 2007; FARIAS et al., 2009; CORRÊA et al., 2011).

Oxisols presented a low variation for MPAC values (Table 5), which is due to the texture and mineralogy. We expected that the higher OM and clay contents would determine a higher MPAC in LA–ITÃ, but it did not occur. This is possibly due to the effect of OM on blocking active sites of P adsorption, either by increasing the competition between organic anions and phosphate for sites of P adsorption or by the formation of humus layers around Fe and Al oxides (MOREIRA et al., 2006; NOVAIS et al., 2007; PINTO et al., 2013).

The lowest MPAC values were found in the soils PA–CCA and SN–Surumu (Table 5), which have specific conditions to explain the low anion adsorption such as a low clay and organic matter content and kaolinitic mineralogy. Although presenting a sandy loam texture, FT–Bonfim showed the highest MPAC (Table 5). The oxidic mineralogy, with the occurrence of goethite and hematite, favors a specific P adsorption and has a direct relation with MPAC (CORRÊA et al., 2011). Despite the low clay content, studies indicate that the ability of iron oxides to adsorb P is more a function of the specific surface area than of their abundance (BOORGARD, 1983).

Table 5. Coefficients of Langmuir equation, MPAC, binding energy, and the correlation between MPAC and soil attributes (0–0.20 m).

Soil	Langmuir equation $C/(x/m) = A \times C + B$		R ²	MPAC	Binding energy
	A	B			
LA–ITÃ	4.09	10.16	0.92*	244.74	0.4023
LV–ITÃ	2.57	16.11	0.93*	389.20	0.1595
LA–Serra da Prata	3.54	16.91	0.96*	282.77	0.2091
LA–CCA	3.35	17.84	0.94*	298.72	0.1876
PA–CCA	12.95	15.40	0.98**	77.24	0.8405
FT–Bonfim	1.89	11.68	0.98**	527.93	0.1621
SN–Surumu	68.97	379.99	0.86*	14.50	0.1815

^{ns}, *, ** – not significant ($P > 0.05$), significant ($P \leq 0.05$), and significant ($P \leq 0.01$), respectively.

In spite of the variation in MPAC of the studied soils, P content is naturally low in most of the soils of Roraima State, as verified in Inceptisol Cambisols, Mollisol Chernosols, and Alfisol Nitisols from northeastern (MELO et al., 2010), Oxisols and Ultisols from the central region (VALE JÚNIOR; SCHAEFER, 2010; BENEDETTI et al., 2011), and Neosols and Spodosols from Southern State (MENDONÇA et al., 2013).

Binding energy varied among soils, following the diversity of attributes, being more expressive in PA-CCA and LA-ITÃ (Table 5). In general, negative charges from clay repel phosphate ions, reducing binding energy. In terms of OM and oxides, their influences vary according to OM quality, texture, the amount of oxy-hydroxides, pH, and base saturation. The set of these attributes defines the appearance of negative charges, which,

consequently, considerably reduce the binding energy of anions, particularly phosphates. Falcão and Silva (2004) observed the influence of clay and base saturation contents in the decrease of this energy.

No significant correlations were found between MPAC and binding energy, pH, OM, clay, and CEC (Table 6), disagreeing from the literature (CHAVES et al., 2007; RANNO et al., 2007; FARIAS et al., 2009). The pedological diversity of Roraima (VALE JÚNIOR et al., 2011), resulting from the weathering affected mainly by rainfall variability (2900 mm in the south and 1100 mm in the northern end) (BARBOSA, 1997) and different parent materials such as acidic (rhyolites and granites) and basic volcanic rocks (basalts), in addition to transported sandy sediments, may justify this absence of correlation.

Table 6. Results of statistical analysis obtained by simple Pearson correlation, where MPAC is the variable correlated with several attributes.

MPAC	Number of observations	Binding energy	pH	OM	Clay	CEC
All	7	-0.505 ^{ns}	0.293 ^{ns}	0.216 ^{ns}	0.370 ^{ns}	0.464 ^{ns}
LA and PA	5	-0.954 [*]	0.605 ^{ns}	0.673 ^{ns}	0.801 ^{ns}	0.623 ^{ns}

^{ns}, *, ** – not significant ($P > 0.05$), significant ($P \leq 0.05$), and significant ($P \leq 0.01$), respectively.

In Roraima State, Oxisols and Ultisols resemble their chemical, physical, and mineralogical characteristics, but differ their textural gradient required for class division. In this sense, when both soils were grouped, a significant and negative correlation between MPAC and binding energy was observed, showing that the binding energy between P and its active sites decreased due to the repulsion caused by negative charges from clays and oxides. This result is in accordance with Falcão and Silva (2004), Ranno et al. (2007), Farias et al. (2009), and Corrêa et al. (2011).

Conclusions

Maximum P adsorption capacity of soils follows the following sequence FT-Bonfim > LV-ITÃ > LA-CCA > LA-Serra da Prata > LA-ITÃ > PA-CCA > SN-Surumu.

Soils from forest environments present a higher MPAC, except for FT-Bonfim, due to the higher occurrence of iron oxides.

In Oxisols and Ultisols, a negative and significant correlation exists between MPAC and binding energy.

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