BORON ADSORPTION IN SOILS FROM THE STATE OF SÃO PAULO, BRAZIL[1]

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ABSTRACT - Boron adsorption was studied in five representative soils (Rhodic Hapludox, Arenic Paleudalf and three Typic Hapludox) from the State of São Paulo, Brazil. Adsorption was higher in the clayey Oxisols, followed by the Alfisol and the coarser Oxisols. Calcium carbonate promoted an increase in the amount of adsorbed boron in all soils, with the most pronounced effect in the coarser-textured Oxisols. High correlation coefficients were found between adsorbed boron and clay and amorphous aluminum oxide contents and specific surface area ($r = 0.79$, 0.76 and 0.73, respectively, $p < 0.01$). Clay content, free aluminum oxide, and hot $CaCl_2$ (0.01 mol L^{-1})-extracted boron explained 93% of the variation of adsorbed boron. Langmuir and Freundlich isotherms fitted well to the adsorbed data, and highest values for maximum boron adsorption were found in clayey soils, which were significantly correlated with contents of total, free and amorphous iron and aluminum oxides, as well with the physical attributes. Ninety four percent of the variation in the maximum adsorption could be related to the free iron content.

Index terms: tropical soils, simple correlation, multiple regression analysis.

ADSORÇÃO DE BORO EM SOLOS DO ESTADO DE SÃO PAULO, BRASIL

RESUMO - O objetivo deste trabalho foi avaliar os teores de boro adsorvido em solos representativos do Estado de São Paulo (Latossolo Roxo distrófico argiloso, Latossolos Vermelhos-Escuros álicos textura média e muito argilosa, Latossolo Vermelho-Amarelo álico textura média e Podzólico Vermelho-Amarelo eutrófico textura arenosa/média). A adsorção nos Latossolos argilosos foi superior à do Podzólico que, por sua vez, foi superior à dos Latossolos de textura média. A calagem promoveu aumento na quantidade de B adsorvido, principalmente nos Latossolos de textura média. Altas correlações foram encontradas para teores de argila e de óxido de alumínio amorfo, e superfície específica ($r = 0{,}79$, 0,76 e 0,73, respectivamente, $p < 0{,}01$). Teores de argila, do óxido de alumínio livre e de boro solúvel em $CaCl_2$ (0,01 mol L^{-1}) a quente correlacionaram-se significativamente com o boro adsorvido, com alto coeficiente de determinação na regressão múltipla (0,93). Isotermas de Langmuir e de Freundlich ajustaram-se bem aos dados experimentais, e os maiores valores de adsorção máxima foram dos solos argilosos, que se correlacionaram significativamente com teores totais, livres e amorfos dos óxidos de ferro e de alumínio, com teores de argila e com a superfície específica. Noventa e quatro por cento da variação dos valores de adsorção máxima foram explicados pelo teor de ferro livre.

Termos para indexação: solos tropicais, correlação simples, regressão múltipla.

INTRODUCTION

There are many differences in the behavior of plant species and even some varieties within a species have different responses regarding micronutrient deficiency or toxicity. Fertilizer recommendations in São Paulo State consider only such cases where micronutrient deficiencies are observed, mainly with Zn and B (Raij et al., 1996). Residual effect due to fertilization can be extended for many years, depending on the applied amounts. Therefore,

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when monitoring soil analysis, one can prevent B accumulation, whose probability of toxicity is high. Depending on the available soil B content already present in soils, 0.5 to 2.0 kg ha^{-1} are applied to deficient soils in São Paulo.

When B is released by minerals, by organic matter during its mineralization, or when it is added to soil by fertilization, a large part remains in solution, while another part is adsorbed by soil particles (Gupta et al., 1985). Boron can be adsorbed by iron and aluminum oxides and their hydroxides, or by several clay minerals (Keren & Gast, 1983; Goldberg & Glaubig, 1985). Bingham et al. (1971) found a positive correlation between the content of Al_2O_3 and the adsorption of B in four Mexican soils and six Hawaiian soils. The greater the amounts of amorphous oxides (extracted with ammonium oxalate), the greater the capability for B adsorption (Sims & Bingham, 1968a; Goldberg & Glaubig, 1985). Soil organic constituents also play an important role in soil B adsorption. Available B is found associated mainly with organic matter, and this explains the high available B contents in surface horizons (Evans & Sparks, 1983).

Boron adsorption is highly influenced by pH, increasing as the pH increases, attaining a maximum in the alkaline range and diminishing abruptly at high pH (Keren & Gast, 1983; Goldberg & Glaubig, 1986a; Goldberg, 1997). The maximum development of adsorption sites occurs at a pH equivalent to the pK of boric acid, approximately 9.1 (Schalscha et al., 1973). The agricultural practice that is most often used to raise soil pH is liming. It is expected that after liming, there will be an increase in soil B adsorption, especially in soils that contain high amounts of iron and aluminum oxides. Hatcher et al. (1967) showed that the adsorption of B increased two to five times after liming in various acidic North American soils, accompanied by a pH increase. In a Brazilian medium-textured Oxisol (Cruz et al., 1987), lime applications to increase the pH from 4.2 to 5.6 significant increased (around 14%) the amount of adsorbed boron.

Various models can describe adsorption reactions. Both the Langmuir model and the Freundlich model are empirical, since they provide a description of adsorbed data without theoretical basis (Goldberg, 1995). Even so, their constants have often been used to obtain important information on B availability to plants and on the soil sorption capacity and intensity (Mead, 1981; Elrashidi & O'Connor, 1982; Nicholaichuk et al., 1988; Marzadori et al., 1991).

The objective of this study was to evaluate B adsorption in highly weathered Brazilian soils, and to correlate those values with chemical and physical soil attributes.

MATERIAL AND METHODS

Surface and subsurface samples of five representative São Paulo State soils (designated PV, LE_1, LE_2, LR and LV) were used (Table 1). Chemical and physical analysis followed the methodology described by Camargo et al. (1986), and some selected characteristics are shown in Table 2. More detailed description of the soils are found in Alleoni (1996).

With the objective of testing the effect of liming on B adsorption, a sub-sample of the surface horizon received calcium carbonate, in a quantity theoretically sufficient to raise the base saturation to 70% (Raij et al., 1996). The samples were maintained at field capacity (0.03 MPa) for one month. After this period, they were dried in air and passed through a 2 mm sieve. The quantities of $CaCO_3$ applied, in grams per kg of soil, for the PV, LE_2, LR, LV and LE_1 soils were 0.11, 0.51, 2.29, 3.06 and 4.31, respectively.

In the adsorption study, a modified Okazaki & Chao (1968) method was employed. While these authors used a range of concentrations from 0 to 100 μg mL^{-1}, in the present paper a range from 0 to 16 mg mL^{-1} was used. These concentrations were also used by Correa et al. (1985) in Oxisols from Paraná State, Brazil, and it seems adequate for representing the element contents in solution for Brazilian soils.

To determine the quantity of adsorbed B, 4,000 g of oven dried soil were shaken, in polyethylene tubes, for 24 hours, with 20 mL of a $CaCl_2$ (0.01 mol L^{-1}) solution containing different quantities of B (0, 1, 2, 4, 8 and 16 mg mL^{-1}). The agitation was slow (around 20 rpm) to avoid the intense abrasion of soil particles (Barrow, 1987). The suspension was centrifuged for 15 minutes at 2,000 rpm, filtered, and a 10 mL sample of the supernatant was removed. Subsequently, B was determined by inductively coupled plasma spectrometry. Soil B adsorption was obtained by subtracting B in solution, after centrifugation and filtration, from B added (in the different concentrations). The quantity of B originally present in the samples, although small, was also subtracted to calculate this content.

The Langmuir equation is $x = KCb / (1 + KC)$, where x = amount of adsorbed B (mg g^{-1} soil), C = equilibrium B concentration (mg mL^{-1}), K = constant related to bonding energy (mL mg^{-1}) and b = maximum adsorption (mg B g^{-1} soil). The Freundlich equation is normally written as $x = KC^b$, where K and b are constants correlated with adsorption capacity and intensity, respectively. Langmuir and Freundlich constants were estimated with the program Fitfun.bas (Barrow, 1987), through the use of nonlinear regression approach. The method of least squares for curve fitting has been recommended in recent years, because linearization of the equations tends to bias the regression analysis and the subsequent estimation of the contents (Schultess & Dey, 1996).

To determine which chemical and physical attributes best correlate with the adsorbed B content as well as the Langmuir and Freundlich constants, simple linear correlation and multiple regression analysis were performed, using the quantity of adsorbed B after addition of 2 µg B mL^{-1}, following the methodology proposed by Harada & Tamai (1968) and Mandal et al. (1993). The program SAS (Statistical Analysis System) was used to perform the correlation (SAS Institute, 1991).

RESULTS AND DISCUSSION

The adsorbed B contents (Table 3) varied from 0.65 to 11.12 µg g^{-1} soil and are similar to the values usually found in the literature. Correa et al. (1985) used solutions with the same B concentra-

TABLE 1. Classification of the soils.

Soil	Brazilian classification	Soil taxonomy	Texture
LR	Latossolo Roxo distrófico	Rhodic Hapludox	Clay
PV	Podzólico Vermelho-Amarelo eutrófico textura arenosa/ média	Arenic Hapludalf	Loamy-sand / sand clay loam
LV	Latossolo Vermelho-Amarelo álico	Typic Hapludox	Sandy loam
LE_1	Latossolo Vermelho-Escuro álico	Typic Hapludox	Clay
LE_2	Latossolo Vermelho-Escuro álico	Typic Hapludox	Sandy loam

TABLE 2. Some selected attributes of the soils[1].

Soil	Horizon	pH	C	CEC	Bsol	Fe_t	Fe_d	Fe_o	Al_t	Al_d	Al_o	Clay	SSA
			(g dm^{-3})	($mmol_c$ dm^{-3})	(mg dm^{-3})	------------------------ (g kg^{-1}) ---------------------							(m^2 g^{-1})
LR	A	4.4	9	108.8	0.38	326	208	3.4	189	36	0.7	610	69.7
	B	4.5	7	79.2	0.28	341	208	4.5	189	29	0.7	670	60.6
PV	A	5.3	5	52.6	0.07	23	10	0.7	29	5	0.2	60	20.7
	B	4.7	4	77.9	0.37	47	27	1.0	114	6	0.2	340	33.2
LV	A	3.2	10	159.5	0.24	18	17	1.0	43	8	0.4	140	7.3
	B	3.6	5	49.4	0.17	21	20	0.7	43	13	0.5	200	8.2
LE_1	A	3.7	13	156.5	0.61	167	120	2.4	179	18	0.6	720	76.9
	B	3.5	9	117.6	0.25	174	144	2.1	179	21	1.3	790	69.9
LE_2	A	4.4	9	61.7	0.17	60	20	1.0	60	13	0.3	170	34.8
	B	3.5	5	83.6	0.21	80	23	1.0	80	12	0.3	220	23.8

[1] pH: in $CaCl_2$ 0.01mol L^{-1}; C: Organic carbon; CEC: Cation exchange capacity, based on exchangeable Ca, Mg, K and H+Al calculated from the pH of the SMP solution; Bsol: hot-$CaCl_2$ (0.01 mol L^{-1}) soluble boron; Fe_t: total iron oxide; Fe_d: free iron oxide; Fe_o: amorphous iron oxide; Al_t: total aluminum oxide; Al_d: free aluminum oxide; Al_o: amorphous aluminum oxide; SSA: specific surface area.

tions as the ones used here, with one additional solution at 0.5 µg mL^{-1} concentration, and they obtained higher adsorbed B values in a red clayey Oxisol than in a red sandy Oxisol. Using another Brazilian soil, B was added in concentrations up to 80 µg mL^{-1}, with pH ranges similar to those of this report. Their values for adsorbed B are in agreement with the values reported here, and they also noted a relationship between adsorbed B and soil texture (Catani et al., 1971).

As expected, there was an increase in the amount of adsorbed B as the quantities of added B increased (Table 3). Nevertheless, the proportion of adsorbed B was gradually less in the more concentrated solutions (last three columns of Table 3). Keren & Gast (1983) and Goldberg & Forster (1991) also observed this.

After the addition of calcium carbonate, the adsorption of B increased in all soils. The average increase in adsorbed B due to liming was 33%. The highest percentage increase occurred in the sandy and medium-textured soils (LE$_2$, followed by LV and by PV), whereas the clayey soils (LR and LE$_1$) had increases of less than 20%.

Apart from the adsorption of B on recently precipitated aluminum hydroxides after liming (Hatcher et al., 1967), a possible cause for the increase in percent-adsorbed B is the bonding of B with calcium

TABLE 3. Concentration of boron in the equilibrium solution (µg mL^{-1}) and adsorbed to the soil (µg g^{-1}), and percentage of adsorbed boron as a function of added boron[1].

Soil	Boron added	Boron in solution			Adsorbed boron					
		A	A*	B	A	A*	B	A	A*	B
		(µg mL^{-1} solution)			(µg g^{-1} soil)			(%)		
	1	0.77	0.76	0.71	1.15	1.18	1.45	23	24	29
LR	2	1.63	1.58	1.53	1.85	2.10	2.33	18	21	23
	4	3.46	3.33	3.23	2.71	3.35	3.84	13	17	19
	8	7.05	6.86	6.75	4.75	5.69	6.26	12	14	16
	16	14.46	14.35	14.16	7.69	8.27	9.21	10	10	11
	1	0.81	0.78	0.63	0.95	1.11	1.84	19	22	37
PV	2	1.67	1.60	1.42	1.63	1.98	2.89	16	20	29
	4	3.58	3.49	3.16	2.09	2.53	4.20	10	13	21
	8	7.45	7.23	6.95	2.76	3.85	5.25	7	10	13
	16	15.30	15.06	14.74	3.51	4.71	6.29	4	6	8
	1	0.87	0.84	0.85	0.65	0.78	0.73	13	16	15
LV	2	1.82	1.74	1.78	0.91	1.29	1.09	9	13	11
	4	3.72	3.64	3.70	1.40	1.79	1.49	7	9	7
	8	7.64	7.58	7.61	1.78	2.32	1.96	4	5	5
	16	15.56	15.40	15.46	2.19	2.98	2.72	3	4	4
	1	0.59	0.45	0.39	2.07	2.74	3.05	41	55	61
LE$_1$	2	1.30	1.16	1.01	3.52	4.19	4.93	35	42	49
	4	3.10	2.91	2.69	4.50	5.44	6.57	22	27	33
	8	6.74	6.51	6.16	6.31	7.43	9.22	16	19	23
	16	14.39	14.27	13.78	8.05	8.65	11.12	10	11	14
	1	0.87	0.80	0.85	0.65	1.01	0.75	13	20	15
LE$_2$	2	1.79	1.64	1.74	1.05	1.80	1.32	10	18	13
	4	3.74	3.55	3.63	1.30	2.26	1.84	6	11	9
	8	7.67	7.38	7.46	1.65	3.12	2.70	4	8	7
	16	15.56	15.24	15.38	2.20	3.81	3.12	3	5	4

[1] A: A horizon; B: B horizon; A*: A horizon with lime.

carbonate. This can lead to the precipitation of calcium borate, substitution of carbon by B in $CaCO_3$ or adsorption of B on $CaCO_3$. Goldberg & Forster (1991) observed a reduction of 10% in the sorption maximum of B in a calcareous Entisol after calcite removal with a solution of sodium acetate (0.5 mol L^{-1}).

The values of adsorbed B did not present a statistically significant correlation with any of the chemical attributes found in the usual chemical analysis for fertility (pH, organic carbon, calcium, magnesium, potassium, aluminum, H+Al, CEC, base saturation and aluminum saturation). The absence of correlation between the attributes can be explained by the fact that B retention as a function of pH has a maximum value between 7.5 and 8.5 (Sims & Bingham, 1968b), and the pH reached only 5.3. Knowing this, the isolated effect of soil pH on the B retention seems to be relatively small in acid soils. Harada & Tamai (1968) studied soils with pH varying from 4.4 to 7.0, and also did not obtain correlation with adsorbed B in Japanese soils originated from different geological formations. It is important to note that, in the acid range, B is predominantly in the form of boric acid and not in its ionic form $H_2BO_3^-$ (Bingham et al., 1971). At pH of 6.8, the ionic form corresponds to only 0.4% of all soluble forms of B (Evans, 1987).

The correlation between adsorbed B and exchangeable Ca was not statistically significant. Harada & Tamai (1968) found a large variation in Ca contents of various soils (20 to 350 $mmol_c\ dm^{-3}$), and did not observe a significant correlation between Ca content and adsorbed B. Organic C also was not correlated with adsorbed B ($r = 0.29$). According to Mezuman & Keren (1981), the effect of organic matter seems less pronounced when the soil content is less than 15 g dm^{-3}.

Among oxides, only total and amorphous Al correlated significantly with adsorbed B, with correlation coefficients equal to 0.71 ($p < 0.05$) and 0.76 ($p < 0.01$), respectively. The correlation coefficient between adsorbed B and amorphous Al oxide was higher than with free Al, with values similar to those obtained in volcanic Chilean soils (Schalscha et al., 1973). A higher correlation coefficient for the aluminum oxides in comparison to the iron oxides was expected, based on the high affinity of B with the OH groups of the aluminum hydroxide (Sims & Bingham, 1968a) and on the higher specific adsorption of B in comparison with the iron hydroxides. Significant correlation was also expected with amorphous iron, due to its relatively larger exposed surface area (Goldberg & Glaubig, 1985). Nevertheless, the combined effect of C and clay contents may have masked this effect on B adsorption.

The correlation coefficient between adsorbed B and clay content was highly significant ($r = 0.79^{**}$), and the values were similar to those obtained by Elrashidi & O'Connor (1982). The positive correlation was favored by the similar mineralogy of these soils, since there was a predominance of kaolinite and gibbsite in the deferrified clay fraction of these soils. These clay minerals, as well as goethite, form inner-sphere complexes with B, confirming the hypothesis regarding specific adsorption of the element (Goldberg et al., 1993). This phenomenon does not occur with montmorillonite or in montmorillonitic soils, reinforcing the importance of knowing the soil mineralogy. In addition, one must also take care when extrapolating results of soils with permanent charge to tropical soils which have variable charges.

Specific surface area also correlated positively with adsorbed B, in similar manner to the correlation between B and clay content, although the correlation coefficient was somewhat lower ($r = 0.73^{*}$). This value of this coefficient was close to that found by Schalscha et al. (1973) and was somewhat lower to the ones obtained by Hatcher et al. (1967) and Goldberg & Glaubig (1986b).

In the multiple regression analysis, the adsorbed B was placed in the model as a function of pH, organic carbon, exchangeable cations, base saturation, Al saturation, B soluble in hot $CaCl_2$ solution (B_{sol}), iron and aluminum oxides (in their various forms), clay content and specific surface area. The obtained equation (1) was:

$$B_{ads} = 1.65 - 0.11Al_{free} - 3.03B_{sol} + 8.23.10^{-2}\ \text{clay} \quad r^2 = 0.93 \tag{1}$$

Clay content accounted for 62% of the variation of the adsorbed B values. The inclusion in the model of free Al content made the determination coefficient increase to approximately 88%, whereas after adding the soluble B content the r^2 reached 93%. In one of the few papers in which a group analysis equation was presented, Elrashidi & O'Connor (1982) observed a significant effect of total iron oxide, organic carbon and CEC, explaining 98% of the adsorbed B contents. The significant effect of clay content in the quantity of adsorbed B was shown by group analysis, confirming what was observed in the simple correlation, where the correlation coefficient was high and significant ($p < 0.01$). The concentration of free aluminum oxide was significant in affecting adsorbed B in the multiple regression, although the same was not observed in the simple correlation. For Elrashidi & O'Connor (1982), a similar situation occurred, and the lack of a significant simple correlation was the result of the small number of samples, that represent a small spectrum of data.

Another attribute that influenced equation 1 was the soluble B content extracted in a hot $CaCl_2$ (0.01 mol L^{-1}) solution. Although the simple correlation between adsorbed B and B extracted with calcium chloride was not significant, it was expected that the quantity originally present in the soils would influence the quantity of adsorbed B. According to Harada & Tamai (1968), who obtained similar results working with Japanese soils, it seems reasonable to suppose that a negative correlation could be found between the soluble B content and the quantity of adsorbed B.

Boron adsorption was described with both the Langmuir and Freundlich models over the range of B concentrations (0 to 16 mg mL^{-1}) for all five soils (Table 4). These results were expected because B sorption data deviate from the Langmuir model only at higher B concentrations, up to 30 mg mL^{-1} (Evans & Sparks, 1983). Nevertheless, the lower concentrations used in this work conform to practical B application rates. The emphasis on higher values used by other workers is due to the fact that they were working with soils where B toxicity was a problem. However, in the State of São Paulo, which has a humid climate, deficiencies are more prevalent. The Freundlich model exhibited a lower sum of deviation

TABLE 4. Langmuir and Freundlich constants for the five selected soils.

Soil / horizon[1]		Langmuir		Freundlich	
		K (mL mg^{-1})	b (mg g^{-1})	K	b
LR	A	0.0646	15.7854	1.2418	0.6818
	A^*	0.1038	13.7535	1.6494	0.6107
	B	0.1115	14.9141	1.9280	0.5941
PV	A	0.3564	3.9946	1.2519	0.3814
	A^*	0.2740	5.7617	1.5400	0.4228
	B	0.4815	7.0330	2.6423	0.3342
LV	A	0.3177	2.5758	0.4023	0.6656
	A^*	1.1653	2.4805	0.9835	0.4066
	B	0.3812	2.8293	0.8433	0.4232
LE_1	A	0.3634	9.2882	2.9701	0.2789
	A^*	0.6116	9.3979	3.9787	0.3026
	B	0.5220	12.3454	4.8401	0.3247
LE_2	A	0.3466	2.4691	0.7745	0.3803
	A^*	0.3456	4.4140	1.3786	0.3814
	B	0.2775	3.8681	1.0474	0.4158

[1] A: A horizon; B: B horizon; A*: A horizon with lime.

than the Langmuir model in both the A (with and without liming) and B horizons for all soils. Higher values of deviation were observed in LE_1 and LV soils for both models.

Maximum B adsorption (b), estimated by Langmuir isotherm, varied from 2.47 to 15.78 mg g^{-1} soil (Table 4). These values are generally similar to those found by Mezuman & Keren (1981), but are lower than the values reported by Okazaki & Chao (1968) and Nicholaichuk et al. (1988). Maximum adsorption decreased from the LR to the PV to the LV soil. This behavior was expected, based on the differences in chemical and physical attributes of the soils, mainly the decreasing clay and oxide contents (Alleoni, 1996).

Highest values for maximum adsorption (ranging from 9.3 to 15.8 mg g^{-1}) were found in the clayey soils (LR and LE_1). The correlation between b and clay content was highly significant ($r = 0.89^{**}$). Since the clay mineralogy was similar in all soils, with predominance of kaolinite and gibbsite, the comparison based only on clay contents is allowed (Keren & Bingham, 1985). Total, free and amorphous iron and aluminum oxides were significantly correlated with b as well. The correlation coefficients varied from 0.69^{*} (amorphous aluminum) to 0.97^{**} (free iron). As pointed out by Mezuman & Keren (1981), higher free oxide content is characterized by higher values for the B maximum adsorption, indicating that a considerable fraction of the adsorbed B in soils can be accounted for by the oxides that are present.

The Freundlich constant K varied from 0.40 to 4.84 (Table 4), following the tendency of higher values in fine-textured soils, in conformity with Elrashidi & O'Connor (1982) and Nicholaichuk et al. (1988). These data reinforce the observation of Mead (1981), who indicated that the constant may be correlated with adsorption capacity, as adsorption is essentially a surface phenomenon and therefore is closely related to particle size.

In the multiple regression analysis (equation 2), free iron oxide was practically the only attribute to account for the variation of B adsorption maximum (94%), confirming the tendency observed in simple correlation and supporting its importance on B adsorption in soils. Exchangeable Ca also was part of equation 2, explaining 3% of the b variation.

$$\underline{b} = 1.28 + 0.07Fe_{free} + 0.08Ca_{exch}, \quad r^2 = 0.97 \qquad (2)$$

CONCLUSIONS

1. Total and amorphous Al contents, specific surface area and clay contents are significantly correlated with adsorbed B; in the multiple regression, clay, free aluminum oxide and soluble B contents are correlated with B adsorption by soils, explaining 93% of its variation.
2. As the values of adsorbed B are mainly explained the concentration of soluble B (B_{sol}) in soils and by texture, B fertilization recommendation in São Paulo State, can be based on these soil factors, as it is already for cotton and coffee.
3. Amounts of total, free and amorphous iron and aluminum oxide can be taken into account when recommending B fertilizers in highly weathered soils.
4. The addition of calcium carbonate promotes an increase in B adsorption by all soils, an effect more pronounced in medium textured Oxisols.
5. Highest values for maximum adsorption predicted by the Langmuir isotherm (from 9.3 to 15.8 mg g^{-1}) are found in clayey soils, and they are significantly correlated with specific surface area, clay content, total, free and amorphous iron and aluminum oxides contents; ninety four percent of the variation in the maximum adsorption can be related to free iron content in the multiple regression.

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