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Mineralogy and Maximum Phosphorus Adsorption Capacity in Soybean Development

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Abstract

The low natural fertility of tropical soils and the mineralogy almost dominated by iron and aluminum oxides limit the availability of phosphorus (P) to the plants, causing negative impacts on soybean yield. Objective was to evaluate the effect of phosphate fertilization on soils with different maximum phosphorus adsorption capacities (PAC) in soybean development. The experiment was carried out under greenhouse conditions, using Red-yellow Latosol (RYL) and a Typic Hapludalf (TH) soil as substrate. The analyses were performed by a completely randomized experimental design in a 5 × 2 factorial arrangement with three replications. The treatments consisted of 5 doses of P applied, corresponding to 0, 1, 6, 12, and 24% of PAC of each soil. In the soil, the mineralogy of the clay fraction (hematite, goethite, gibbsite and kaolinite) and crystallographic attributes were characterized. In the plant, we evaluated growth and pod production. The PAC of the soils ranged from 220 to 650 mg dm^{-3} with higher value in the RYL associated to clayey oxidic mineralogy and texture in relation to the TH of kaolinite origin and sandy texture, where the higher energy of adsorption observed was to TH. Phosphorus application from 16 to 21% of PAC, independently of the soil, promotes the same pattern of response with improvements in soybean development evidenced by increases in P content in plant tissue, plant height, root volume and aerial dry mass.

Keywords: grain production, oleaginous, langmuir isotherm

1. Introduction

Soybean is one of the most economically important oilseeds. It is growth in large areas, previously cultivated with degraded pastures (Feba, Moro, & Guerra, 2017). Due to its soils are naturally low in fertility, fertilization adjustments are necessary to establish a productive system (Caires, Sharr, Joris, Haliski, & Bini, 2017). In this scenario the Mato Grosso State Cerrado (Savanna) stands out, which holds the Brazilian largest soybean production area. However, the advanced weathering of cerrado soils limits soybean productivity, mainly due to the lack of phosphorus (P) (Souza & Lobato, 2002; Roy et al., 2017), since much of this nutrient is strongly retained in the oxidic mineralogy of these soils (Guedes, Fernandes, Souza, & Silva, 2015; Fink, Inda, Tiecher, & Barrón, 2016).

In tropical soils, clay minerals govern the sorption and adsorption mechanism of P, both supplying this nutrient to the plant and competing for P applied in phosphate fertilizers (Rolim Neto, Schaefer, Costa, Corrêa, Fernandes Filho, & Ibraimo, 2004). Several investigations have shown that goethite (Gt = α-FeOOH) and gibbsite (Gb = γ-Al(OH)$_3$) rich soils provide higher P-fixing power than hematite-governed soils (Hm = α-Fe$_2$O$_3$) and, secondarily, kaolinite (Kt) (Broggi, Oliveira, F. J. Freire, M. B. G. S. Freire, & Nascimento, 2011; Barbieri et al., 2014). In a pioneer study developed in the Brazilian Cerrado, Novais and Smyth (1999) found in clayey Latosols more than 2 mg cm^{-3} of adsorbed P, which is equivalent to 4000 kg ha^{-1} of P, that is, 9.200 kg ha^{-1} of P$_2$O$_5$, incorporated at 0-20 cm. In turn, Paula, Martins, Farias, and Siqueira (2016) found in 1 kg of soil approximately 20 g of goethite and 30 to 60 g of hematite in a Typic Haplortox, with about 401 to 552 mg of adsorbed P.

The kaolinite soils secondary effect on the P adsorption potential, according to Gomes (2017) is due to its low specific surface area, limited only to external surfaces. In fact, unlike iron oxides, kaolinite presents low load and specific surface area, limiting itself only to external surfaces (Melo & Wypych, 2009), conferring low fixation of anionic groups such as phosphate. Besides the type of mineral, the crystallographic attributes such as specific surface (SS), isomorphic substitution (IS), and mean diameter of the crystal (MDC) play an important role in adsorption of P (Fink et al., 2016). Thus, the high SS area, associated with low crystallinity minerals, allows higher retention of P, due to the higher density of OH-charges exposed on the surface.

One of the bottlenecks in tropical agriculture is the discernment of how much of phosphate fertilizers must be used to ensure good soybean yields. This deadlock occurs due to the mineralogical knowledge low utilization of the cultivated soils, and therefore, the decision on the total fertilizer to be used, is still based only on the crop requirement, expected productivity, and soil clay content (Caires et al., 2017). Because of this, the results are many times unsatisfactory, because this fertilization do not meet the requirements of the crop, since much of the P applied can be complexed or fixed by the soil constituents (Pavinato, Merlin, & Rosolem, 2009; Pinto, Souza, Paulino, Curi, & Carneiro, 2013). For example, in a Typic Haplorthox, Valadão Júnior, Bergamin, Reis Venturoso, Schlindwein, and Otomar Caron (2008), and Araújo, Sampaio, and De Medeiros (2008), based on the expected soybean yield, found the maximum plant height at doses 140 kg ha^{-1} of P_2O_5 and 192.07 kg ha^{-1} of P_2O_5, respectively. These differences are probably attributed to soil mineralogy, reinforcing the necessity of better understand the soil mineralogy to estimate PAC and, consequently, to use strategic management to a better planning of phosphate fertilizations in the soil (Peluco, Marques Júnior, Siqueira, Pereira, Barbosa, & Teixeira, 2015).

Mathematical models have been used to describe P adsorption mechanism at a P increasing concentration in the equilibrium solution or varying the time-soil P contact (Novais & Smyth, 1999). Among the models, there is a preference for the Langmuir isotherm, because it allows to obtain the maximum soil phosphorus adsorption capacity (PAC) and the constant "k", related to the energy of this element binding to the soil (Novais & Smyth, 1999). As it turns, the PAC is strongly associated with the clay content and the type of mineral present in the soil (Rolim Neto et al., 2004; Simões Neto et al., 2009; Corrêa, Nascimento, & Tavares, 2011).

The information obtained by the isotherms shows soils with greater or lesser capacity to adsorb P and, consequently, it helps in a more efficient planning of phosphate fertilizations, allowing to minimize costs and also possible impacts to the growth environment (Gomes, 2017). In Cerrado, there is a lack of study that considers the potential of soybean exploration related to the mineralogical aspects of the soil. Aiming to fill this gap, this study proposes to evaluate the effect of phosphate fertilization on soils with different maximum phosphorus adsorption capacities (PAC) in soybean development.

2. Material and Methods

2.1 Experimental Procedure

The experiment was carried out in a greenhouse belonging to the State University of Mato Grosso, Alta Floresta, MT, Brazil. The soil samples used in the cultivation were collected at 0-20 cm of Red-Yellow Distrophic Latosol (RYL) and Typic Hapludalf (TH) (Embrapa, 2013).

After sampling, soil was limed with dolomitic limestone (30% CaO and 21.1% MgO) with 100% total neutralization power (TNP), estimating to raise the soybean soil base saturation to the 60%, following the fertilization recommendations to Brazilian Cerrado (Souza & Lobato, 2002). The soil remained incubated at field capacity moisture for 30 days. After this time, a basic micronutrient fertilization (boron and zinc) was done, using the boric acid and zinc sulfate sources at 0.5 mg dm^{-3} of B and 1 mg dm^{-3} of Zn, respectively. In addition, a potassium fertilization was applied incorporating to the soil 150 mg dm^{-3} of K (Malavolta, 1981), using as source potassium chloride.

2.2 Statistical Design

We used a completely randomized statistical design, in a 5 × 2 factorial arrangement. The treatments were 5 doses of P applied, corresponding to 0, 1, 6, 12 and 24% of PAC in 2 soils, RLY and TH. The doses of P applied, resemble those used by (Simões Neto et al., 2015). To reach the desired percentage of PAC in each soil, it was necessary to apply: 0, 15, 90, 180, and 360 mg dm^{-3} of P_2O_5 in RYL, and 0, 5, 30, 60, and 120 mg dm^{-3} of P_2O_5 in TH, respectively. As a source of P, the TOP PHOS® (Timac Agro Brasil) was used with 28% of P_2O_5. Each experimental plot was composed of a 6 dm^3 polyethylene vessel containing two M 8372 IPRO variety soybean plants (*Glycine max*).

The M 8372 IPRO soybean seeds were previously inoculated with nitrogen fixing bacteria *Bradyrhizobium japonicum* before planting, at 0.5 mL p.w. kg^{-1} of seed—SEMIA 5079 and 5080 strains, inoculant Nitro 1000 soybean® (5.0×10^9 viable cells per ml), being sowed 4 seeds per pot. During the experimental period irrigation was carried out keeping the moisture content close to 60% of the soil water retention capacity by monitoring the weight difference (soil weight with 60% and weight before irrigation).

The soybean plants were grown until full pod formation, at the R4 development stage (Fehr & Caviness, 1977), which occurred at 91 days, being at this time harvested. We evaluated, according procedures suggested by Bouma, Nielson, and Koutstaal (2000), the number of pods per plant, plant height (with a ruler-cm), and the root volume (with a graduated cylinder). The results were expressed in cm^3.

2.3 Soil Analysis

In order to characterize the soils samples they were collected in each 6 dm^3 vessel, then air dried and passed through a 2 mm diameter sieve. According to the Table 1, in the soils were found the chemical attributes where, pH (water), K^+, Ca^{2+}, Mg^{2+}, P, potential acidity (H^++Al^{3+}), T and V%, and granulometric attributes as: sand, silt and clay, all performed according to the methodologies described for Embrapa (2011).

Table 1. Chemical and granulometric soil attributes prior to the fertilization

Atributes	Solos	
	RYL	TH
pH (H_2O)	5.9	5.0
Ca ($cmol_c$ dm^{-3})	2.58	1.40
Mg ($cmol_c$ dm^{-3})	1.09	0.57
K (mg dm^{-3})	193.1	35.9
$P_{mehlich-1}$ (mg dm^{-3})	8.7	4.0
H +Al ($cmol_c$ dm^{-3})	4.24	3.29
T ($cmol_c$ dm^{-3})*	8.4	5.4
V (%)**	49.6	38.5
Clay (%)	64.4	22.9
Silt (%)	8.2	8.1
Sand (%)	31.4	69

Note. * Potential cation exchange capacity; ** Base saturation.

We characterized the main minerals of the clay fraction, *i.e.*, hematite (Hm), goethite (Gt), kaolinite (Ct) and gibbsite (Gb) by X-ray diffraction through the powder method after iron oxides concentration, according to Norrish and Taylor (1961) and the clay fraction deferrification by the method of Mehra and Jackson (1960). The samples were diffracted with a scanning speed of 1° 20 min^{-1} using Mini-Flex Rigaku II (20mA, 30kV), equipped with Cu Kα radiation. The Hm/(Gt + Hm) ratio was estimated by comparing the peak areas obtained from Hm/(Gt + Hm) XRD with the ratio ratios obtained from standard Gt-Hm mixtures. The percentages of Hm and Gt were calculated by allocating the difference between Fed and Feo to these oxides. The Ct/(Ct + Gb) ratio was calculated by the Gb (002) and Ct (001) peak reflection areas.

The iron-aluminum isomorphic substitution content calculation in Gt was obtained by the Schulze equation (1984): Al (mol mol^{-1}) = $17.30 - 5.72 \times c_0$. We calculated the iron-aluminum isomorphic substitution content in Hm using the Schwertmann and Taylor (1989) equation: Al (mol mol^{-1}) = $31.09 - 6.17 \times a_0$. The specific surface area (SSA) of Gt was estimated according to Schulze and Schwertmann (1984): SSA (Gt) = (1049/DMC100) – 5 (m^2 g^{-1}), where, DMC100 = DMC (110) × 0.42 nm (Kämpf, 1981). The SSA to Hm was calculated according to (Schwertmann & Kämpf, 1985) by the formula: SSA (Hm) = 2 × (r + h) × d (m^2 g^{-1}). The mean crystal diameter (MCD) of Hm and Gt was calculated from the Half Height Width (HHW) and the minerals reflection position using the Scherrer equation (Schulze, 1984).

2.4 Determination of Maximum Phosphorus Adsorption Capacity (PAC)

In order to determine the potential of phosphorus adsorption in each soil to determine the doses used in each soil the maximum phosphorus adsorption capacity (PAC) was determined in the evaluated soils. For this analysis, 5

cm^3 of soil was added in a 125 ml Erlenmeyer flask together to 50 ml of 0.01 mol L^{-1} $CaCl_2$ solution with the following P concentrations (0, 2, 4, 10, 20, 40, 60, 80, 100, and 120 mg L^{-1} of P) as KH_2PO_4. Then the samples were kept in a horizontal shaker for 4 hours, and after that the supernatant was collected to determine P by spectrophotometry at 660 nm range (Embrapa, 2009).

After the readings, P adsorption was estimated by the difference between the amount of P found in the equilibrium solution and the amount of P added. With the results we constructed the adsorption isotherms, with data of P adsorbed plotted on the ordinates axis and the predetermined concentrations in the equilibrium solution on the abscissa axis.

The Langmuir equation in its hyperbolic form is expressed by: $x/m = (abC)/(1 + aC)$. In order to estimate the constants a and b, the hyperbolic Langmuir equation was linearized: $C/(x/m) = 1/(ab) + (1/b)C$, where, x/m is the amount of P adsorbed by the soil, in mg P (x)/cm^3 of soil (m); b; soil PAC, (mg cm^{-3} of P in soil); C: P concentration in the equilibrium solution (supernatant) expressed in mg L^{-1}; a: constant related to soil P adsorption energy, expressed in mg L^{-1} (Olsen & Watanabe, 1957).

2.5 Plant Analysis

We collected the aerial part of the plant (leaves, stems, pods) and roots, which were dried at 65 °C in a forced air circulation oven, until reaching constant weight, thus obtaining the weight of dry mass. The dry plant material was ground and used for the quantification of P contents in the plant tissue, according to the methodology proposed by (Embrapa, 2009).

2.6 Statistical Analysis

The results were submitted to analysis of variance (F test) and when significant, the Tukey test was performed at 5% probability for the soil and polynomial regression for doses (PAC). Each one of the model component coefficients were tested by choosing the significant models with the highest coefficient of determination (R^2). For statistical analysis, the SISVAR® (Ferreira, 2011) computer program was used.

3. Results and Discussion

3.1 Phosphate Maximum Adsorption Capacity and Clay Fraction Mineralogy

The soils presented different behavior to PAC (Table 2). There was a proportional increase of the adsorbed P as a function of the applied doses in both studied soils. However, in the Red-Yellow Latosol (RYL), the adsorption potential was three fold higher the PAC of the Typic Hapludalf (TH) (Figure 1) that has with a sandy clay loam texture, as expected. In this way, the P adsorption varied, following the specific intrinsic characteristics (texture, mineralogy, and P content) to each soil.

Table 2. Linear equation of the Langmuir isotherm (maximum capacity constant and adsorption energy), maximum phosphorus adsorption capacity (PAC), and adsorption energy in Red-yellow latosol (RYL) and Typic Hapludalf (TH)

Soils	Sand	Silt	Clay	Regression equation(1)	R^2	PAC(2)	Adsorption energy
	-------------- g kg^{-1} --------------					-- mg dm^{-3} --	--------- L mg^{-1} --------
LV	229	81	690	y = 8.7496 + 1.5471x	0.98	650	0.1768
PVA	644	82	314	y = 23.58 + 4.5737x	0.99	220	0.1939

Note. (1) Y = C/x/m (mg/L)/cm³)/mg ad/cm³ (x/m) = mg L^{-1}; x = P solution mg cm^{-3}. (2) PAC = 1/b. Aenergy = 1/(aPAC).

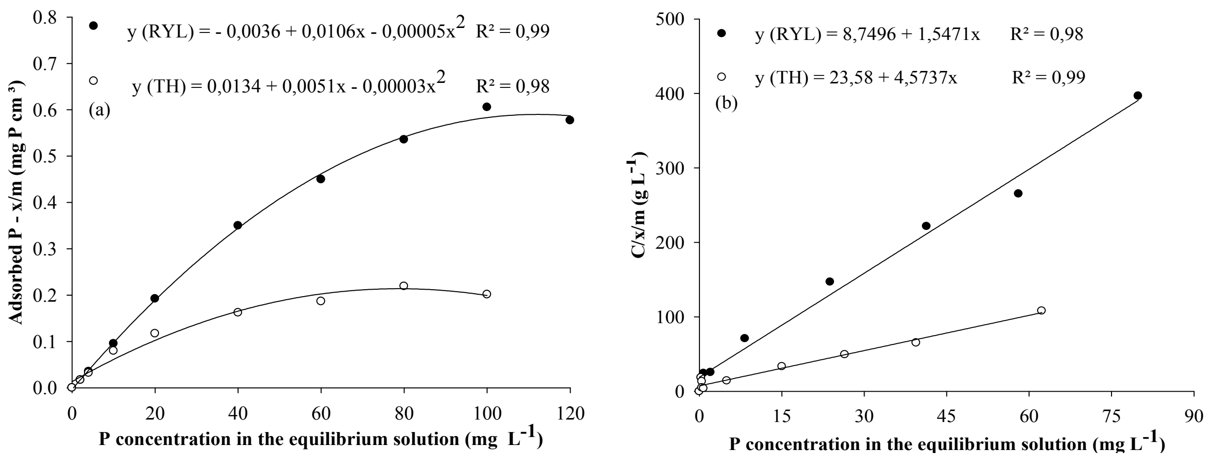

Figure 1. Phosphorus adsorption isotherms in hyperbolic (a) and linear (b) forms of RYL and TH

Linearizing data we were able to observe the precision of the results through the coefficient of determination (R^2) values of RYL and TH, in the order of 0.98 and 0.99, respectively (Table 2). However, the TH higher adsorption energy, whose saturation happened at 220 mg dm^{-3} of adsorbed P, reveals difference in the mineralogical constitution of the clay fraction, consistent with similar studies (Simões Neto et al., 2009; Corrêa et al., 2011; Oliveira, Gatiboni, Miquelluti, Smyth, & Almeida, 2014; Camargo et al., 2015).

According to X-ray diffraction spectra (XRD) the clay fraction mineralogy of both soils was constituted by oxides of hematite (Hm), goethite (Gt), gibbsite (Gb), and silicate as kaolinite (Kt), in specific proportions (Table 3 and Figure 2). The Gt and Gb domain at RYL (Figures 2a and 2b), as revealed by the well-defined and more expressive peaks, explaining the higher concentrations of 650 mg dm^{-3} of adsorbed P. Similar results were found in similar studies by Simões Neto et al. (2009), which found high PAC in oxidic soils, compared to kaolinites. This is because the Ct has its adsorption potential limited only to the outer surface, which gives it low specific surface values (Schoonheydt & Johnston, 2011), which resulted in the lowest PAC, that is, 220 mg dm^{-3} in TH (Table 2).

Table 3. Crystallographic parameters and mineral content of the clay fraction of Red-yellow Latosol (RYL) and Typic Hapludalf (TH)

	MCD				HHW		SSE		IS		Ratio	Content			
	°2Θ						m^2g^{-1}		mol%		di*	g kg^{-1}			
Soil	Gt_{110}	Gt_{111}	Hm_{110}	Hm_{012}	Ct	Gb	Gt	Hm	Gt	Hm	Ct/(Ct+Gb)	Fed	Feo	Gt	Hm
RYL	38.6	12.8	39.3	106	0.60	0.29	106	47.58	32.01	18.97	0.62	47.68	0.51	43.4	24.7
TH	22.4	7.12	29.6	56.8	0.53	0.31	78	42.24	20.52	10.41	0.74	16.98	0.26	35.5	8.2

Note. di = dimensionless.

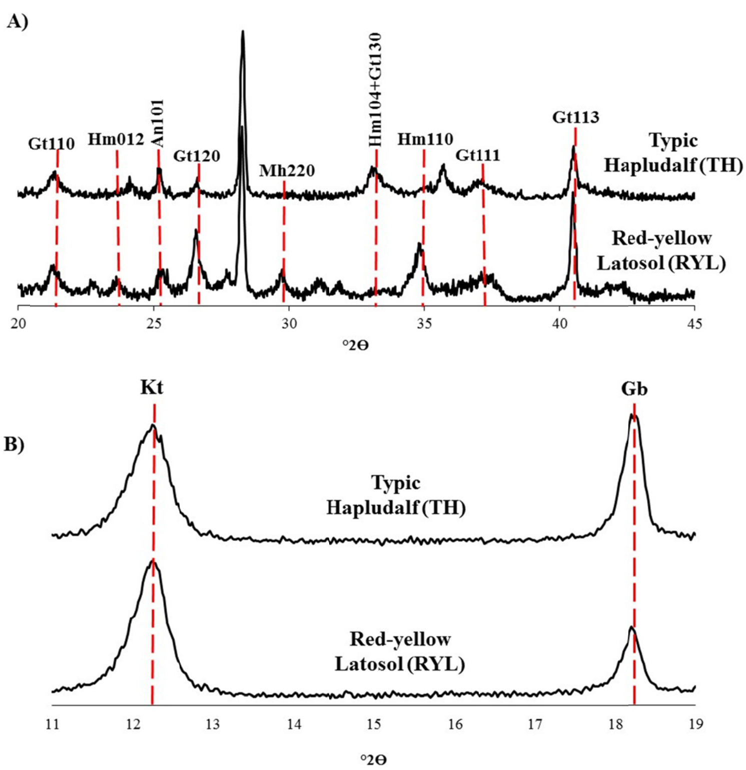

Figure 2. Clay fraction X-ray diffractograms in A): after concentration of goethite iron oxides (Gt), hematite (Hm) and maghemite (Mh) and B): kaolinite (Kt) and gibbsite (Gb) of the soils used in the experiment

When we evaluated the crystallographic parameters, we observed that the lower values of MDC (Mean Diameter of Crystallite) and higher HHW (Half Height Width) indicate Fe and Al oxide forms persistence, which are less crystalline minerals in TH (Table 3). According to Fink et al. (2016), these forms are more reactive in the P adsorption due to the higher exposed surface charge density (OH^-). Probably this may have been the cause of higher adsorption energy value obtained in TH. However, the kaolinite effectiveness Ct/(Ct + Gb) = 0.74, together to the lower clay content in the general balance, gave lower PAC, since 50% of the kaolinite net surface charge is essentially negative, non-reactive with phosphate anionic groups (Santos et al., 2008) and it has limited surface load (Schoonheydt & Johnston, 2011). This indicates the need for smaller phosphate fertilizations to meet the plant need and guarantee the crop productivity in TH. Considering that the P adsorption has a strong relation with the soil clay content (Falcão & Silva, 2004; Machado, De Souza, De Andrade, Lana, & Korndorfer, 2011; Santos, Oliveira, Salcedo, Souza, & Silva, 2011; Barrow, 2015). This fact was also observed, once the higher absorption happened in RYL, a clayed soil (690 g kg^{-1}), governed by the higher content of goethite oxides, hematite, and gibbsite (Table 3).

Dealing with the minerals contribution in PAC, regardless the soil type, the MCD110 (22-38 nm) and MCD111 (7-12 nm) crystallites smaller dimensions for Gt related to Hm with MCD110 (29-39 nm) and MCD (56-106 nm) indicated low crystallinity Gt. This behavior is due to the predisposition of Gt to substitute Fe (ionic radius = 0.065) by Al (ionic radius = 0.053) in its structure (McLaughlin, Mulrine, Gresalfi, & McLaughlin, 1981), providing the unit cell contraction and, consequently, the specific surface area (SSA) increasing (Barbieri et al., 2014). The high SSA selected Gt the main oxide responsible for P adsorption and much higher PAC in the studied soils, given the higher predisposition of free adsorption sites to phosphates (Magalhães Moreira, Bastos Mota, Clemente, Moreira de Azevedo, & Vieira do Bomfim, 2006). As an example, Almeida, Torrent, and Barrón (2003) evaluating the hematite and goethite participation in phosphates adsorption by Oxisols developed from Basalt in southern Brazil, verified a lower sorption capacity of P where hematite prevailed to goethite.

3.2 Soybean Response to P Doses in the Soil

The phosphorus application based on PAC of each soil resulted in an increase in available P (Pavail) levels in both soils, influencing directly the height and root volume of soybean plants at 91 days (DAE) (Table 4). In the soil, the Pavail levels increased proportionally with the applied P up to 24% (maximum dose of the treatment), while in the plant, the contents of P presented a maximum content provided by the dose of P applied in 17% of PAC in both soils. Corrêa, Mauad and Rosolem (2004) cultivating soybean in pots also verified increase in soil Pavail as a result of the application of increasing doses of P in Typic Haplorthox. Considering that the P applied doses were only up to (24% of PAC) 1/4 of the expected saturation of both soils, it was expected that the Pavail levels would present such behavior, *i.e.*, a linear increase at the applied doses, however enough to promote maximum absorption by plants.

Table 4. Available phosphorus (Pavail) in soil, Plant P accumulation (PP), and height (H) of soybean plants, as a function of the P doses application based on soil PAC

% of PAC applied	Soil P available	Plant P	H	RV
	mg dm^{-3}	g kg^{-1}	cm	cm^3 $plant^{-1}$
0	3.85	0.85	36.7	6.29
1	10.71	0.87	43.8	16.66
6	11.71	0.96	45.3	18.33
12	23.10	1.07	55.0	19.66
24	36.04	1.05	60.7	19.83
RYL	16.61a	0.93a	47.6a	20.03a
TH	17.33a	0.99a	49.0a	12.01b
	---------- F values ----------			
Soil	0.528ns	4.22ns	0.63ns	30.44**
(P)	130.32**	9.67**	23.47**	11.37**
(P) × Soil	0.96ns	1.44ns	7.16**	5.02**
CV (%)	16.08	8.14	9.96	25.0

Note. F test: ns, *, **, non significant and significant at 5 and 1%. CV%: coefficient of variation. Means followed by the same lowercase letter in the column do not differ between each other respectively by F test and Tukey test at 5% of probability.

Based on this assumption, the Pavail levels in the soils increased linearly as a function of the applied P doses, from 3.85 mg dm^{-3} in the control treatment (0% of PAC) to 36.04 mg dm^{-3} with P at 24 % of PAC, increasing the Pavail levels by 89% (Figure 3). Such event is directly related to the equilibrium promoted by P in the soil when applied, saturating part of the fixation sites. Thus, the application of the P based on PAC provided precise results of P amount to be applied, since the Pavail levels did not differ between the soil classes (Table 4). The increase of Pavail in the soil favored the P uptake by the plants, a fact evidenced by the P contents increase in the plant tissue concomitantly the P doses used in the soil (Table 4). However, unlike the soil, the plant P contents results in adjusted to the quadratic model, with inflection point from the dose estimated in 17% of the PAC, obtaining 1.07 g kg^{-1} of P in the soybean dry matter for both soils (Figure 3).

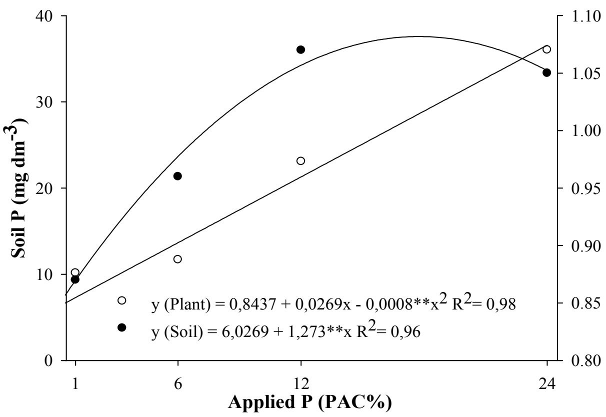

Figure 3. Soil P available and P accumulation in the plant tissue of soybean plants as a function of P application based on percentages of the maximum adsorption capacity of P (PAC) of each soil. **: significant at 1% probability by F test

Corrêa et al. (2004) evaluating crescent doses of P (0, 229, 458, and 687 kg ha^{-1} of P_2O_5) on the P content in the soybean tissue showed a maximum content of 1.3 g kg^{-1} of P in the dry matter, provided at 206 kg ha^{-1} P_2O_5 dose. The results obtained in this study suggest that, at 17% of PAC, soil Pavail levels reach the critical range for higher P uptake by soybean. When this occurs, phosphate fertilizations in later crops can be made in equivalence to that exported by grains and plant (Vieira, Fontoura, Bayer, Moraes, & Carniel, 2015; Yang, Xu, Wang, Ma, Wei, & He, 2017).

For plant height, there was interaction between doses of P × soil (Table 5). In the absence of P application (dose 0) in the soils, the highest height of plants was observed in TH. On the other hand, in 12% of the PAC, the highest height occurred in RYL. There were no differences between soils in the other doses evaluated.

Table 5. Effect of P doses based on PAC of two soils, on the soybean plant height (cm)

Soil	P doses in % of PAC					F value
	0	1	6	12	24	
RYL	27.5 bC	42.5aB	46.2aB	60.0 aA	61.8aA	25.6 **
TH	45.8 aB	45.2aB	44.5aB	50.0 bAB	59.5aA	5.1 **
F value	21.8 **	0.46 ns	0.18 ns	6.49 *	0.35 ns	
MSD line	11.75					
Column	8.19					

Note. F test: ns, *, **, non significant and significant at 5 and 1%. Means followed by the same lowercase letter in the column do not differ between each other respectively by F test and Tukey test at 5% of probability.

Observing the interaction unfolding results in each soil (Figure 4) we observed that in RYL the quadratic function was adjusted, obtaining maximum height (63.65 cm) at the estimated P-dose in 19% of PAC. On the other hand, in TH this response was linear, corroborating the results of Soares, Sediyama, Neves, Júnior and Silva (2016). Such observed characteristic in TH can be attributed to a more kaolinite mineralogy, due to the lower adsorption potential of this mineral. Valadão Júnior et al. (2008), and Araújo et al. (2008), applying P in a Typical Haplorthox, based on the expected soybean yield, found maximum plant height at 140 kg ha^{-1} P_2O_5 and 192.07 kg ha^{-1} P_2O_5, respectively. These possible differences found for the same soil class are strongly influenced by mineralogy, which differentiates between soils, reinforcing the need to know this attribute, in order to estimate PAC and, consequently, conduct the strategic management of phosphate fertilizers (Peluco et al., 2015; Withers et al., 2018).

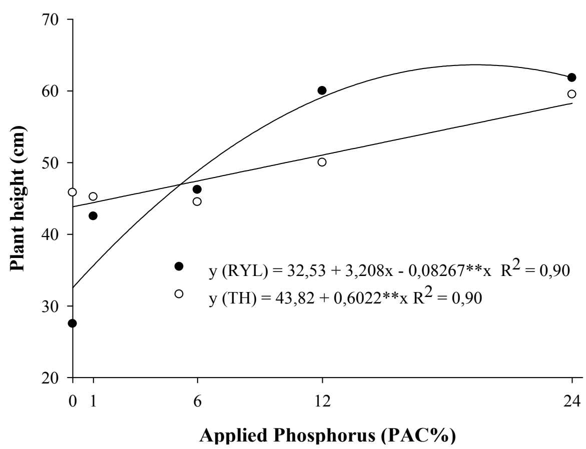

Figure 4. Soybean plants height as a function of phosphorus application based on percentages of the maximum adsorption capacity of P (PAC) of each soil. **: significant at 1% probability by F test

Similar to plant height, there was interaction between doses of P × soil, on root volume (Table 4). Except to the P absence where the root volume was higher in RYL. The root volume in this soil (20.03 cm^3), in average, was

60% higher than that found in TH (12.01 cm^3). When we observed the effect of the doses on each soil (Table 6), there was a linear increase of the root volume at TH. We can infer that this soil, besides being more responsive to phosphate fertilizers, presented better conditions for the roots development, like lower resistance to penetration and higher soil exploration by roots due to its lower clay content (Figure 5).

Table 6. Effect of P doses based on the PAC of two soils, on the root volume (cm^3 $plant^{-1}$) of soybean

Soil	P applied in % of PAC					F value
	0	1	6	12	24	
RYL	3.83aB	23.33 aA	23.67 aA	26 aA	24.66 aA	15.22**
TH	8.75aA	10.0 bA	13.0 bA	13.33 bA	15 bA	1.16 ns
F value	2.14 ns	15.76**	10.10**	14.23**	8.28**	
MSD line	10.05					
Column	7.004					

Note. F test: ns, *, **, non significant and significant at 5 and 1%. Means followed by the same lowercase letter in the column do not differ between each other respectively by F test and Tukey test at 5% of probability.

In turn, there was a quadratic function adjustment in RYL, with an estimated maximum root volume in 16% of PAC (Figure 5). According to Pavinato et al. (2009), phosphorus has low mobility in the soil and high capacity of fixation by the clays. This certainly hinders root contact with the nutrient and its absorption, thus inhibiting root growth. However, we could observed that increasing the P doses, part of the adsorptive sites were saturated, weakening the P affinity for the soil, which resulted in an increase in the Pavail, and consequently the root development improvement regardless of the soil.

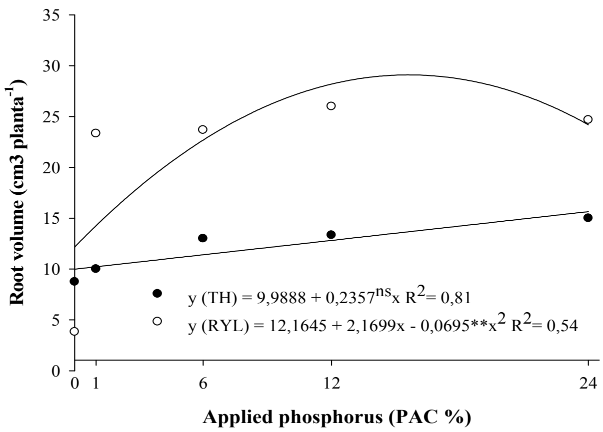

Figure 5. Soybean root volume as a function of phosphorus application based on percentages of the maximum adsorption capacity of P (PAC) of each soil. **: significant at 1% probability by F test

P doses applied using PAC as a parameter provided increases in the number of pods per plant (PP), root (RDM) and aerial (ADM) dry mass, and total dry mass (TDM) (Table 7). However, a variable behavior was observed for the different soils evaluated in this study. Similar responses were observed in the number of PP, ADM and TDM, which were higher in TH, whereas RDM decreased.

Table 7. Soybean pod production per plant (PP), root dry mass (RDM), root volume (RDM), aerial dry mass (ADM), and total dry mass (TDM) as a function of the application of P doses based on the soil PAC

(P) applied % of PAC	PP	RDM	ADM	TDM
	unit	------------------------------ g $plant^{-1}$	------------------------------	
0	8.0	0.74	2.76	3.50
1	17.0	2.36	6.37	8.72
6	21.0	2.76	8.79	11.56
12	25.0	2.92	10.03	12.95
24	27.0	2.94	12.06	14.99
Soil				
RYL	13.0b	2.62a	6.0b	8.62 b
PH	26.0a	2.06b	10.0a	12.07 a
	---------------------------------- F values	----------------------------------		
Soil	87.31**	10.26**	60.75**	33.16**
(P)	23.25**	23.04**	39.05**	44.38**
(P) × Soil	0.45ns	4.09**	0.13ns	0.76ns
CV (%)	19.65	20.16	17.54	15.83

Note. F test: ns, *, **, non significant and significant at 5 and 1%. CV%: coefficient of variation. Means followed by the same lowercase letter in the column do not differ between each other respectively by F test and Tukey test at 5% of probability.

In both soils, pod production responded linearly to P doses (Figure 6), from 8 pods per plant in the control treatment (0% of PAC) to 27 at the maximum P dose tested (24% of PAC). This is a 70% increase due to the P fertilization. This way, in agreement to other investigations (Zhang et al., 2010; Cruz, Souza Filho, & Pelacani, 2015), soils with low P availability provide lower number of flowers and a higher pod abortion, compromising productivity. In this sense, Batistella Filho, Ferreira, Vieira, and Cruz (2013) also obtained a linear response for soybean pod production in Typic Haplortox up to the maximum test dose of 160 kg ha^{-1} of P_2O_5. Being pod the main organ responsible for the grain formation and development, it is expected that the linear increase of pods into the P doses up to 24% of PAC, will result in higher grain yield per plant.

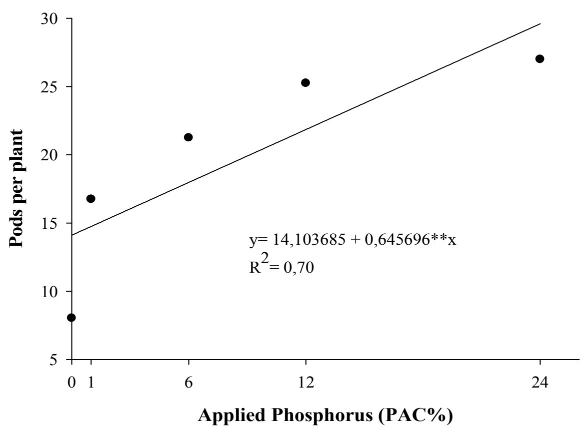

Figure 6. Number of pods per soybean plant as a function of phosphorus application based on percentages of the maximum adsorption capacity of P (PAC) of each soil. **: significant at 1% probability by F test

Regarding to RDM, we observed interaction between P doses × soil (Table 7). Among the soils, the highest root dry mass weight was in RYL, provided by the 1%, 6%, and 12% of PAC when compared to TH. In addition, there were no differences between soils in the absence of P and in 24% of PAC (Table 8).

Table 8. P doses effect based on PAC of RYL and TH on the soybean root dry weight (g $plant^{-1}$)

Soil	P applied % of PAC					F value
	0	1	6	12	24	
RYL	0.35aB	2.77 aA	3.20 aA	3.54 aA	3.23aA	22.60**
TH	1.13aB	1.94 bB	2.32 bA	2.29 bA	2.64aA	4.53**
F value	4.05 ns	4.66*	5.12*	10.49**	2.28 ns	
MSD line	1.15					
Column	0.80					

Note. F test: ns, *, **, non significant and significant at 5 and 1%. Means followed by the same lowercase letter in the column do not differ between each other respectively by F test and Tukey test at 5% of probability.

However, when we verified the effect of the doses in each soil, the RDM production in TH increased linearly until the maximum dose tested (24% of PAC) equivalent to 220 kg of P_2O_5 ha^{-1}, considering the 0-0.20 m layer. On the other hand, the RDM in RYL production adjusted in a quadratic manner, with maximum yield obtained at the P-dose estimated at 15% of PAC, corresponding to 450 kg of P_2O_5 ha^{-1} (Figure 7a), which resulted in the increase of 91% in the RDM (3.98 g $plant^{-1}$) compared to the absence of P application (0.35 g $plant^{-1}$). The TH results resemble those of Corrêa et al. (2004), who also observed a linear adjustment in the RDM to soybean up to the dose of 150 kg ha^{-1} of P, equivalent to 343 kg of P_2O_5 ha^{-1}.

The aerial part responses were different from those obtained in the roots, between the soils. The TH PAC (10 g $plant^{-1}$) was 60% higher than the RYL (4.0 g $plant^{-1}$) (Table 7). This fact can be attributed to the mineralogical characteristic of TH, which was predominantly kaolinite, and therefore the specific surface area of kaolinite is limited only to external surfaces, which gives it low adsorption value (Schoonheydt & Johnston, 2011). However, the effect of employed P doses showed the same behavior in both soils, with PAC adjusting the quadratic function, and maximum yield (12.10 g $plant^{-1}$) estimated in 21% of PAC (Figure 7b). This production represents an increase of 77% when compared to the 0% of PAC (2.76 g $plant^{-1}$). These results are similar to Bonfim-Silva et al. (2014) ones, which obtained a 55% increase in the dry mass of aerial part of the soybean in relation to the control soil.

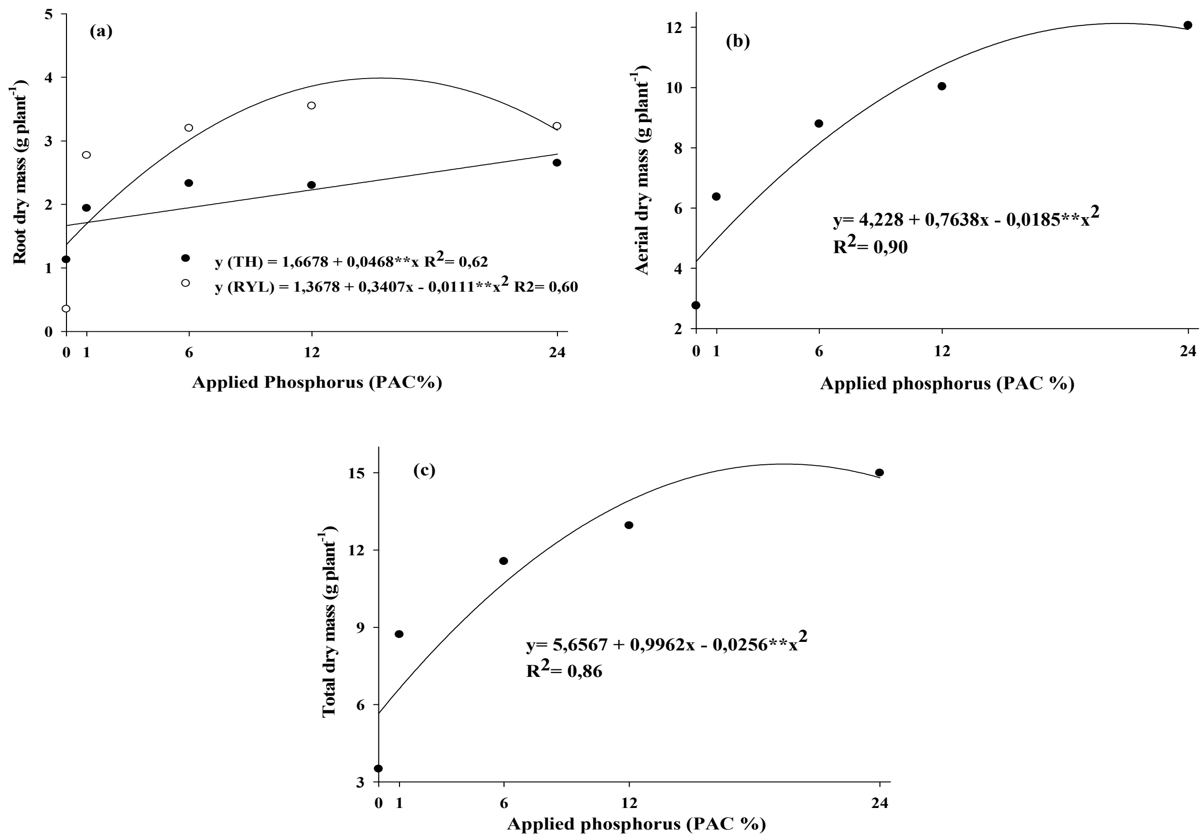

Figure 7. P doses Effect based on PAC of RYL and TH on root dry mass (7a), aerial dry mass (7b) and total dry matter (7c) production in soybean plants at R4 (full pod formation)stage of development (pods full formation). **: significant at 1% probability by F test

Regarding to the Total Dry mass of the plant (TDM) in the different soils (Table 7) we could verify that in TH the average TDM (12.07 g plant^{-1}) was 28% higher than that observed in RYL (8.62 g plant^{-1}). This result is directly related to root and shoot development. Facing this, the strong increase in PAC occurred in TH certainly contributed to the mentioned increase. However, the P doses effect based on PAC were similar to both soils (Table 7). The maximum accumulation of TDM occurred in 19.45% of PAC, decreasing thereafter (Figure 7c), that is, for the development of soybean independently of the soil, the greater probability of dry mass gains can be reached when P fertilization is done aiming 19% of PAC. The P fertilization effect is very important, especially in new crop regions, where soil phosphorus levels are low, such as Amazon and Cerrado soils (Cantarella, Correa, O. Primavesi, & A. C. Primavesi, 2002; Guedes et al., 2018).

In a general way, the aforementioned results indicate that the use of soil PAC as a P quantity factor to be applied is able to aid the current methods of phosphate fertilization recommendation to soybean in Cerrado soils. The PAC provided the range in which the plants have a better response to fertilization, mitigating the soil expected variations. Thus the recommendations based on PAC allowed compartmentalizing different production environments, when we considered the soil potential to adsorb phosphate based on its mineralogy.

4. Conclusions

The soils PAC ranged from 220 to 650 mg dm^{-3}, with higher value in RYL associated to the oxidic mineralogy and clay texture in relation to TH of kaolinite origin and sandy texture.

Phosphorus fertilizing from 16 to 21% of PAC, regardless the soil, promotes the same pattern of response with improvements in soybean development, evidenced by plant height, root volume, and aerial dry mass increases.

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Abbreviations

PAC: maximum phosphorus adsorption capacity; RYL: Red-yellow Latosol; TH: Typic Hapludalf; Pavail: available phosphorus; P: phosphorus; RDM: Root Dry Mass; ADM: Aerial Dry Mass; TDM: Total Dry Mass; PH: Plant Height; RV: Root Volume; PP: Pods per Plant.

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