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Interpretation of soil phosphorus availability by Mehlich-3 in soils with contrasting phosphorus buffering capacity

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ABSTRACT: Increasingly rational use of phosphate fertilizers by agriculture is important, especially in Brazil, due to its importance for global food security and its high dependence on phosphate fertilizers for crop production. Thus, correlation and calibration researches with soil available phosphorus (P) extractants to improve the recommendation and the use of P are extremely important. Our objectives were (i) to determine soil P recovery rates and critical levels by the extractants Mehlich-1 (M1), Mehlich-3 (M3), and Ion Exchange Resin (RTI); (ii) to adjust predictive models of P recovery rates and critical levels for each extractant, as a function of soil properties related to the soil P buffer capacity, and (iii) to adjust the an interpretation table of soil P availability by M3 taking into account soil P buffer capacity indices. A pot experiment under greenhouse condition was conducted, in which the treatments were generated by the combination of a factorial 12 × 6, being 12 soil samples collected at a layer of 0.00-0.20 m, and six doses of P. The experimental units were constituted by plastic pots with capacity for 2.0 dm³ of soil, in which four hybrid corn plants (*Zea mays* L.) were cultivated for 45 d. The experimental design was a randomized complete block with four replicates. After cultivation, soil samples were collected from each experimental unit, and the determination of soil available P was performed by the extractants. The remaining P and the clay content were the soil properties that best correlated with the P recovery rates and P critical levels in the soil by the M1 and M3. The IER did not show sensitivity to soil P buffer capacity. The M3 had a discontinuous loss of extraction capacity with increasing soil P buffer capacity. Therefore, it is recommended the use of M3 as P extractant in soils with different characteristics, but a measure of soil P buffer capacity such as remaining P or clay content have to be used.

Keywords: critical level, recovery rates, methods of soil analysis.

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INTRODUCTION

Agriculture is responsible for the consumption of approximately 90 % of all P in the world and, due to the increasing consumption of P, the deposits of phosphate rocks with good quality are decreasing and their cost of extraction is increasing (Pantano et al., 2016). In this sense, the rational use of phosphate fertilizers by agriculture is important, especially in Brazil, due to its importance for global food security and its high dependence on phosphate fertilizers for crop production (Roy et al., 2016; Withers et al., 2018). As the recommendation of phosphate fertilizers in Brazil is based on soil chemical analysis, it is essential to perform, periodically, correlation and calibration studies of soil available P extractants, to verify their efficiency with the evolution of cultivation methods, as well as to update important reference values such as soil P critical levels.

The determination of soil P availability to plants in Brazil is performed by Mehlich-1 (M1) (Nelson et al., 1953), and Ion Exchange Resin (IER) (van Raij et al., 1986). As the M1 extractant is sensitive to soil P buffering capacity (PBC), the interpretation of its results requires the knowledge of soil characteristics related to this soil property (Novais and Smyth, 1999; Rogeri et al., 2016), which is not necessary for IER (van Raij et al., 2001). The Mehlich-3 (M3) extractant has been recommended as a substitute for M1, due its following advantages: non-solubilization of naturally occurring forms of P-Ca in some soils less weathered or fertilized with phosphates rocks (Mehlich, 1984; Bortolon et al., 2009), and good extraction of micronutrients, Fe, Mn, Zn, and Cu (Milagres et al., 2007; Silva et al., 2009). Thus, M3 has great potential to be used in routine laboratories for soil analysis in Brazil due to its multi-element extraction, which reduces the costs of analysis (Mallarino, 2003).

The M1 and M3 have similar principles of extraction, mainly based on acidic solubilization and anionic exchange. During the M1 extraction procedure occurs the solubilization of phosphates by H^+ ions, and exchange of SO_4^- by the extractant with the PO_4^- that are adsorbed with lower binding energy. At the same time, the occupation of the PO_4^- adsorption sites by SO_4^-, keeps the desorbed PO_4^- in solution (Nelson et al., 1953). The M3 extraction occurs at a buffered pH of 2.5 due to the presence of acetic acid (Mehlich, 1984; Bortolon et al., 2009), which results in less solubilization of P-Ca forms than M1 in which the pH of soil:solution suspension is around 1.2. Besides, the presence of NH_4F in M3 solution extracts specifically P-Al forms (Mehlich, 1984) and the EDTA, may be responsible for extracting some organic forms of P (Gatiboni et al., 2005; Mumbach et al., 2018). The extraction with IER is based on the process of adsorption of P in soil solution by the anionic resin and, consequently, the desorption of the P adsorbed in soil particles that are in equilibrium with soil solution during the agitation with soil:water (1:10 v/v) for 16 h. This is why some authors state that IER acts similarly to plant roots (van Raij et al., 1986; Silva and van Raij, 1999).

It is still necessary to investigate the values of soil P critical levels (P*cl*), P recovery rates (P*rr*), and tables of interpretation of M3 soil P availability, that is, there is still a lack of calibration work in Brazil. Some works such as Schlindwein and Gianello (2008) in the no-tillage system, and Bortolon and Gianello (2008), who proposed ranges of interpretation of the soil P availability by Mehlich-3 based on the correlation of P availability between the Mehlich-1 and Mehlich-3 extractants, show the effectiveness of M3 in soils of southern Brazil. Some studies demonstrated the sensitivity of the M3 extractant to the soil PBC (Bortolon et al., 2009; Rogeri et al., 2016). In this way, it is necessary to understand how the P*rr* and P*cl* estimated by M3 are influenced by the soil characteristics related to the soil PBC.

Our hypothesis is that soil P extraction by M3 is influenced by soil phosphorus buffer capacity, once M3 and M1 have similar principles of extraction. Our objectives were to determine the P*rr* and P*cl* by M1, M3, and IER extractants; to adjust predictive models of P*rr*, and P*cl* for each extractant as a function of soil characteristics related to the soil PBC, and adjust an interpretation table for soil P availability by M3 extractant taking into account soil P buffer capacity indices.

MATERIALS AND METHODS

Experiment set up

Twelve soil samples with different P buffering capacity were collected at layers of 0.00-0.20 m from cultivated and uncultivated areas (Table 1). The soils were classified as *Latossolo* (Ferralsol): LVd1, LVd2, LVd3, LVdf, LVAd1, LVAd2, and LAd; *Argissolo* (Acrisol): PVd, PVAd1, PVAd2, and PVAd3; *Cambissolo* (Cambisol): CXbd (Table 1), according to SiBCS (Santos et al., 2013) and WRB (IUSS, 2015). After sampling, the samples were passed through a 4.0 mm sieve, air-dried, and stored. A sub-sample was taken from each soil sample, which was passed through a 2.0 mm sieve (ADSS) to carry out the chemical and physical analyses. The granulometric analysis was performed by the pipet method, with chemical dispersion in NaOH 0.1 mol L^{-1} (Teixeira et al., 2017). The soil moisture equivalent (ME) was determined by subjecting the soil samples to a centrifugal force equivalent to 33 kPa for 30 min in the Richards' chamber, as described in Teixeira et al. (2017). The chemical characterization of soil samples was performed according to Lopes and Alvarez V (1999).

The experiment was conducted under greenhouse conditions, and the treatments were generated by the combination of a factorial 12 × 6, with 12 soil samples collected at layer of 0.00-0.20 m, and six doses of P. The experimental units consisted of plastic pots with drainage holes, and with capacity for 2.0 dm^3 of soil, where four hybrid of corn (*Zea mays* L.), Bio Gene 7040, were grown (Figure 1). The experimental design was in randomized blocks, with four replicates.

After the calculation of the lime requirement, we applied a mixture of $CaCO_3$ and $MgCO_3$ with Ca:Mg molar ratio of 4:1. The application was performed in each experimental unit.

Table 1. Collection sites, physical and chemical characterization of soil samples

Symbol[1]	Collection sites	pH(H_2O)	P	rem-P	OM	Ca^{2+}	Al^{3+}	H+Al	T	ME	Sand	Clay
			mg dm^{-3}	mg L^{-1}	g kg^{-1}	—— $cmol_c$ dm^{-3} ——				kg kg^{-1}	— g kg^{-1} —	
LVd1^{uc}	Rio Paranaíba	5.15	1.9	4.3	71.1	0.67	0.35	7.69	8.84	320	161	666
LVd2^{c}	Rio Paranaíba	6.92	39.4	8.3	43.5	5.14	0.01	3.02	9.94	300	185	523
LVd3^{c}	Rio Paranaíba	6.78	50.9	8.9	48.7	5.94	0.06	1.87	9.96	310	156	557
PVd^{uc}	Viçosa	5.14	0.5	10.8	17.7	0.32	0.72	3.84	4.17	330	350	620
LVdf^{uc}	Presidente Olegário	5.50	3.8	11.4	44.8	1.39	0.40	7.69	9.98	250	235	490
LVAd1^{uc}	Viçosa	6.16	0.7	12.6	15.2	1.39	0.13	2.65	4.37	275	350	550
LVAd2^{uc}	Três Marias	6.54	0.5	21.9	2.5	0.08	0.16	0.87	0.98	87	800	160
PVAd1^{c}	Viçosa	5.91	96.5	25.0	22.4	4.08	0.25	3.69	9.38	310	354	491
PVAd2^{c}	Viçosa	6.02	21.4	26.1	23.7	4.46	0.11	3.32	9.51	300	399	455
PVAd3^{c}	Viçosa	5.42	11.5	27.0	26.3	2.35	0.23	5.28	8.70	240	461	406
CXbd^{uc}	João Pinheiro	5.24	0.4	28.8	10.5	0.12	0.43	2.87	3.02	90	732	241
LAd^{uc}	Linhares-ES	5.70	7.9	44.1	15.2	3.35	0.13	1.72	6.38	85	740	220

(1) Brazilian System of Soil Classification (SiBCS). ^{uc} – samples collected in uncultivated areas. ^{c} – samples collected in cultivated areas. pH(H_2O) at a soil:water ratio of 1:2.5. P – Mehlich-1 extractant. rem-P – remaining phosphorus. OM – soil organic matter = Org. C. × 1.724 (Walkley-Black). Ca^{2+} and Al^{3+} - KCl extractant 1.0 mol L^{-1}. H + Al – Calcium Acetate extractant 0.5 mol L^{-1} (pH 7.0). T – cation exchange capacity at pH 7.0. ME - Soil moisture equivalent (Ruiz et al., 2003). Sand and clay by the Pipet Method.

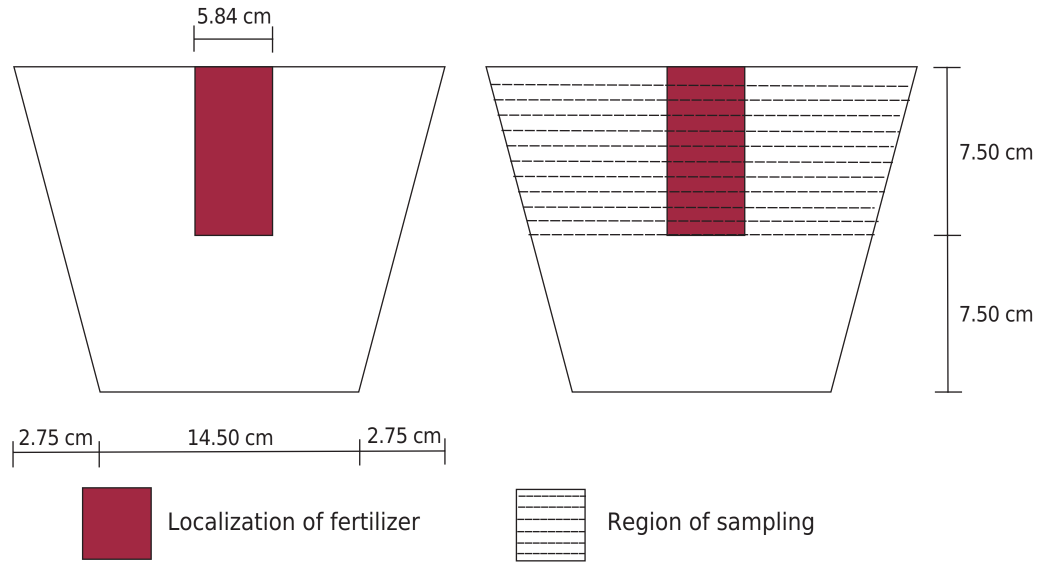

Figure 1. Scheme of the location of P fertilizer in the pots, and the collection of the soil sample after cultivation.

After the application, the soil samples were conditioned in plastic bags and water was added to raise the soil moisture up to 80 % of the maximum water retention capacity. The incubation period was 18 d, after which the soil samples were air-dried, and again passed through a sieve with a mesh of 4.0 mm.

The doses of P applied to each soil were defined according to the remaining P (rem-P) (Alvarez V et al., 2000), and applied in a localized manner, in 10 % of the total volume of soil (Figure 1), so 1/3 of the recommended doses were used. The P sources used were Triple Superphosphate (20.0 % of P), and Bayovar (12.6 % of P). The mixture was composed of 80 % of Triple Superphosphate and 20 % of Bayovar, which were mixed to the soil at the moment of the application. To apply the doses of P localized in 10 % of the soil volume (0.2 dm^3), the pots were divided into two regions. The soils LVd1, LVd2, and LVd3 have received 0.0, 18.7, 37.4, 74.8, 112.2, and 187.0 m dm^{-3}. The soils PVd, LVdf, and LVAd1 have received 0.0, 16.0, 32.0, 64.0, 96.0, and 160.0 m dm^{-3}. The soils LVAd2, PVAd1, PVAd2, PVAd3, and CXbd have received 0.0, 13.7, 27.4, 54.8, 82.2, and 137.0 m dm^{-3}. The soil LAd have received 0.0, 10.0, 20.0, 40.0, 60.0, and 100 m dm^{-3}. The doses of P were mixed at 0.2 dm^3, in which, on the same day, seven corn seeds were sown per pot. After seedlings' emergence, four plants were grown in each pot. The plants were cultivated for 45 d, keeping the soil moisture close to 80 % of the soil's maximum water retention capacity, by irrigations in the upper part of the pots.

The fertilizations with the other nutrients were carried out by applications in the form of nutrient solution, according to some modifications made in the recommendation of Novais et al. (1991). The doses and sources of the other nutrients have corresponded to 300 mg dm^{-3} of N [$(NH_2)_2CO$]; 160 mg dm^{-3} of K (KCl); 80 mg dm^{-3} of S [$(NH_4)_2SO_4$]; 0.81 mg dm^{-3} of B (H_3BO_3); 1.33 mg dm^{-3} of Cu ($CuSO_4.5H_2O$); 1.55 mg dm^{-3} of Fe ($FeCl_3.6H_2O$); 3.66 mg dm^{-3} of Mn ($MnCl_2.4H_2O$); 0.15 mg dm^{-3} of Mo ($NaMoO_4.2H_2O$), and 4.0 mg dm^{-3} of Zn ($ZnSO_4.7H_2O$).

Soil and plant analysis

After 45 d of cultivation, the corn shoot was collected and dried in a forced circulation oven at 65 °C for 72 h, after which the shoot dry matter was determined. The determination of the P content in the plant tissue was performed by nitric-perchloric digestion (3:1) and the dosage performed by colorimetry, using the Vitamin C method, modified by

Braga and Defelipo (1974). After the determination of P content in the plant tissue from the four plants cultivated in each pot, the corn shoot total amount of P was calculated. The soil samples were taken from all experimental units. Sampling was performed at the upper middle part of the pot to obtain a composite sample between the region that have received the P locally, and the region that did not receive P (Figure 1).

The soil samples were air-dried and passed through a sieve with a mesh of 2.0 mm (ADSS) for analysis of available P by M1 (Nelson et al., 1953), M3 (Mehlich, 1984), and IER (van Raij et al., 2001) extractants. The extraction with Mehlich-1 (HCl 50.0 mmol L^{-1} + H_2SO_4 12.5 mmol L^{-1}) and M3 (NH_4F 15 mmol L^{-1} + CH_3COOH 200 mmol L^{-1} + NH_4NO_3 250 mmol L^{-1} + HNO_3 13 mmol L^{-1} + EDTA 1 mmol L^{-1}) was performed in 1:10 soil:solution ratio (5 cm^3 of ADSS to 50 mL of the extractant). The samples were shaken with the extractive solution for 5 min, and then the filtration was carried out with slow filtering paper. For extraction with Ion Exchange Resin we use a mixture of anion exchange resin (Amberlite IRA-400), and cation exchange resin (Amberlite IR-120). The steps of preconditioning and treatment of the resin for use were performed as described in van Raij et al. (2001). The extraction was performed by shaking 2.5 cm^3 of ADSS with 25 mL of water and glass ball for 15 min. Thereafter, the glass ball was removed and 2.5 cm^3 of IER was added and shaken with the soil and water for 16 h. Then, the IER was removed from the soil and shaken for one hour with a solution of NH_4Cl 0.8 mol L^{-1} with HCl 0.2 mol L^{-1} in order to desorb the P. After obtaining the extracts, the determination of P was performed by colorimetry, using the Vitamin C method, modified by Braga and Defelipo (1974), for the three extractants.

Statistical analyses

The data were submitted to analysis of variance using the program System for Statistical Analysis (SAEG, 2007) version 9.1, and regression equations of the shoot dry matter production were adjusted as a function of the doses of P applied to each soil. With the equations of shoot dry matter yield as a function of P doses, the recommended doses (RD) were calculated to reach 90 % of the maximum production (0.9-ŷmax). The RD were determined by equating the first derivative of the equations to zero, and then obtaining the dose corresponding to the maximum yield. Once the value of 0.9-ŷmax was obtained, it was replaced in the same equation to obtain the dose corresponding to 0.9-ŷmax. For the soils where the dose corresponding to the maximum yield was outside the experimental space, and for those whose quadratic root model best fitted the data, but there was no maximum point, the highest dose applied in each soil was taken as the dose corresponding to the maximum yield.

The P recovery rates P (P*rr*) corresponded to the angular coefficient of the first degree equations that related the soil available P content as a function of the doses of P applied to the soils. For the soils where models adjusted were equations of the second degree, we calculated the differential P*rr*. The P critical levels (P*cl*) in the soil were calculated by replacing the doses of P corresponding to 0.9-ŷmax in the equations of soil P content recovered by each extractant. After obtaining P*rr* and P*cl*, we made correlations and adjusted predictive models of P*rr* and P*cl* by the extractants with soil characteristics related to soil P buffer capacity.

In the relationship between soil P*cl* by M3 and rem-P, we used the iterative method of Cate and Nelson (1971) to determine the value of rem-P where the region of the plateau was established. Originally, this method is used to determine the critical level as the point that separates soils with a high probability of response from soils with a low probability of response to the addition of a certain nutrient.

The classes of interpretation for soil P availability by M3 extractant as a function of the rem-P and clay content were determined. For this, a correlation was established between the soil available P contents by M1 and M3, and we adjusted a predictive model of the available P content by M3 as a function of the available P contents by M1, obtained in all experimental units. With the relationship between the soil available P by M1 and M3, we used the predictive model to convert the class boundaries established in Ribeiro et al. (1999) for Mehlich-1 into Mehlich-3.

RESULTS

Shoot dry matter yield and phosphorus recovery rates

Except for the soil LVAd2, there was a significant increase in shoot dry matter yield as a function of P doses applied to soils. In the adjustment of the regression equations of the shoot dry matter yield as a function of the P doses applied to the soils, the quadratic and quadratic root models were the models that best fitted to the data (Figure 2). The doses of P applied to the soils caused a major average increment on shoot dry matter yield in the soils collected in uncultivated areas (342 %) in relation to the soils collected in cultivated areas (30 %).

The doses of P applied to soils influenced the available P, and consequently, the P*rr* (Tables 2 and 3). The average of P*rr* by the extractants were 0.451, 0.302, and 0.240 for

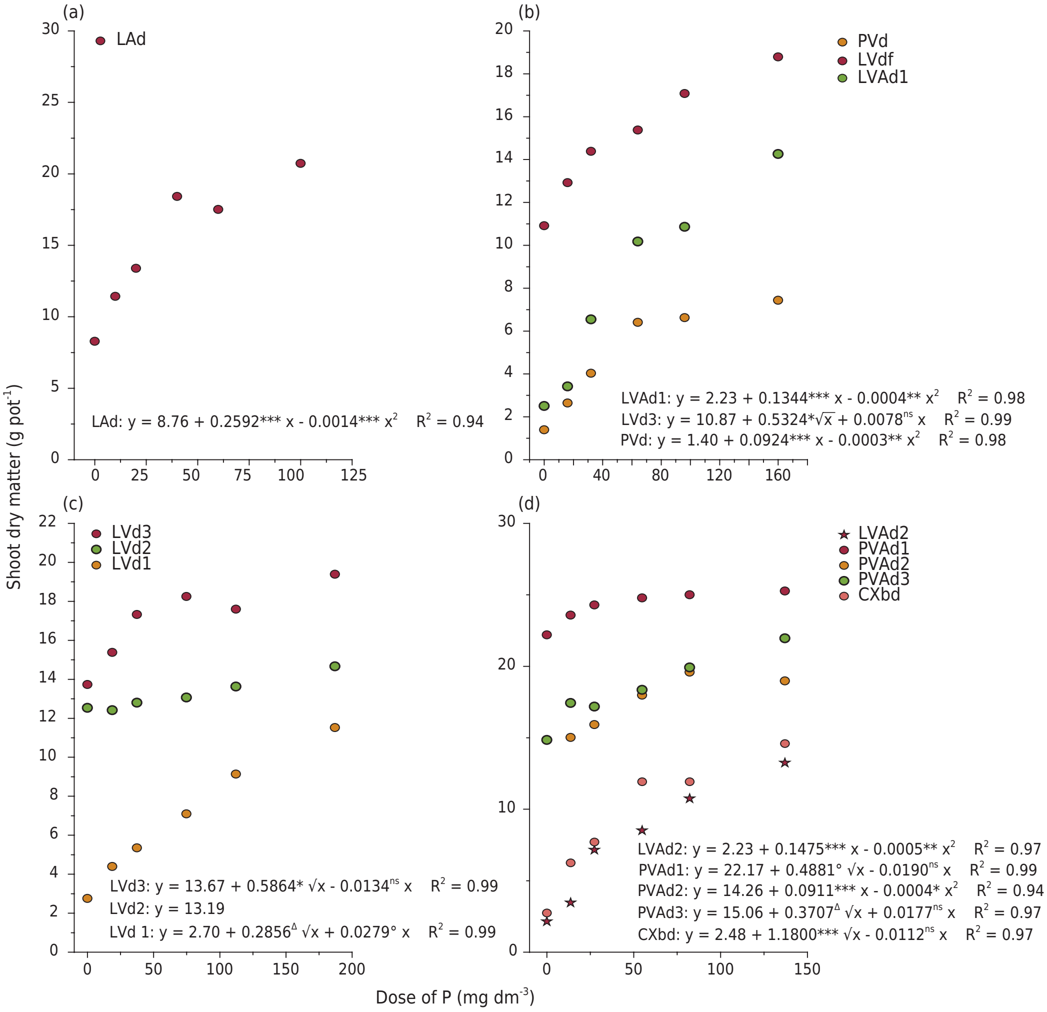

Figure 2. Equations for corn shoot dry matter yield ($\hat{y}$, g pot^{-1}) according to the doses of P (x, mg dm^{-3}) applied to each soil, and coefficient of determination (R^2). The soil samples were grouped according to the doses of P applied: (a) 0 – 100 mg dm^{-3}; (b) 0 - 160 mg dm^{-3}; (c) 0 – 187 mg dm^{-3}; (d) 0 – 137 mg dm^{-3}. ns, Δ, °, *, **, ***: not significant until 25 %, and significant at 25, 10, 5, 1, and 0.1 %, respectively.

M1, M3, and IER, respectively (Table 3). Only in the soil CXbd the P*rr*-M3 and P*rr*-IER were superior to the P*rr*-M1, demonstrating the greater extraction capacity of M1 in relation to the other two extractants. For the three extractants, the lowest P*rr* were obtained in soil LVd1, which is the most buffered soil (rem-P = 4.3 mg L^{-1}) (Table 1). However, the highest P*rr* were obtained in soil PVAd1 (rem-P = 25.0 mg L^{-1}) by M1, in soil LAd (rem-P = 44.1 mg L^{-1}) by M3, and in soil LVd3 (rem-P = 8.9 mg L^{-1}) by IER. Thus, only M3 obtained higher P*rr* in the less buffered soil (Table 3).

We adjusted equation between soil P*rr* by the extractants and soil characteristics related to the soil P buffer capacity: moisture equivalent (ME), clay content, rem-P, soil organic matter (SOM), and potential acidity (H + Al). Since the soils LVd2, LVd3, and PVAd1 presented soil available P content above the critical level by M1 prior to cultivation, the data for these soils were excluded from the adjustment of P*rr* as function of soil P buffer capacity characteristics. After the exclusion of these soils, we found correlation between P*rr*-M1 and P*rr*-M3, and soil characteristics related to soil P buffer capacity, which did not occur with the P*rr*-IER that was correlated only with rem-P (Table 4).

Positive correlations were observed between P*rr* and rem-P, and negative correlations with the other characteristics. The best correlations were obtained between the P*rr* and rem-P, and the highest correlation coefficient for this characteristic was obtained with M3 (0.913***), followed by M1 (0.870***), and IER (0.826***). The P*rr* by M1 and M3 presented correlation coefficients above 0.60 for all the studied characteristics, however, coefficients of determination (R^2) higher than 0.70 were obtained only for the relation between P*rr*-M3 and clay content, and between the P*rr*-M1 and P*rr*-M3, and rem-P. The good coefficients of determination ($R^2 > 0.7$) allowed us to establish predictive models of P*rr*-M1 and P*rr*-M3 as a function of rem-P and P*rr*-M3 as a function of clay content (Table 4).

Soil phosphorus critical levels

There was a wide variation in P critical level (P*cl*) by the extractants. On average, the higher P*cl* were obtained with M1 and the lower with M3, following the same tendency of the P*rr*. The highest values of P*cl* for the three extractants were obtained in soil samples collected in cultivated areas (Table 5). The amplitude of variation of P*cl* was from 24.8 to 210.6 mg dm^{-3} for M1, from 17.9 to 99.8 mg dm^{-3} for M3, and from 11.4 to 108.4 mg dm^{-3} for IER. When the soils LVd2, LVd3, and PVAd1 (which had soil available P content above P*cl*-M1 before cultivation) were excluded, the amplitude of the P*cl* was lower. In this case, the amplitude of variation was 24.8 to 50.7 mg dm^{-3} for M1, 17.9 to 39.5 mg dm^{-3} for P-M3 and 11.4 to 35.0 for IER (Table 5). The large amplitude of the P*cl* can also be observed by the high coefficient of variation (CV) obtained for the three extractants, with a higher CV for M1 and IER. When the soils LVd2, LVd3, and PVAd1 were excluded, the CV decreased (22.2 % for P*cl*-M1, 28.8 % for P*cl*-M3, and 41.1 % for P*cl*-RTI; Table 5).

Correlations between P*cl* by the extractants and soil characteristics related to PBC were performed (Table 6). Only the P*cl*-M1 and P*cl*-M3 correlated with these characteristics. For the P*cl*-M1, the linear correlation coefficients were - 0.642° with the clay content, 0.756* with the rem-P, - 0.644° with the SOM, and - 0.613° with H + Al. There was no correlation between P*cl*-M1 and ME. For M3, the linear correlation coefficients were - 0.888** with clay content, 0.826** with rem-P, - 0.644° with SOM, - 0.618° with H + Al, and - 0.744* with ME. The P*cl*-IER was not correlated with these soil characteristics. The best correlations were obtained between the P*cl*-M3 and clay content, and with rem-P (Table 6).

Due to the variation in the P*cl* by the extractants as a function of the soil characteristics related to the PBC, regression equations of the P*cl* by each extractant were established

Table 2. Soil available P by Melich-1, Mehlich-3, and Ion Exchange Resin extractants as a function of the doses of P applied to each soil

Soil	**P level**[1]						**Average**
	0.0	**0.5**	**1.0**	**2.0**	**3.0**	**5.0**	
	Mehlich-1						
	mg dm^{-3}						
LVd1	0.7	1.7	6.0	10.3	16.9	29.4	10.8
LVd2	56.2	60.7	68.2	76.5	106.2	139.1	84.5
LVd3	98.8	114.1	122.3	136.5	163.7	201.7	139.5
PVd	0.4	3.3	8.4	15.7	34.7	71.6	22.4
LVdf	4.6	6.6	9.7	16.9	27.9	53.4	19.9
LVAd1	0.6	3.9	6.5	17.9	28.2	74.3	21.9
LVAd2	0.3	1.9	4.1	15.2	45.1	70.6	22.9
PVAd1	205.7	225.2	228.7	252.6	261.7	311.4	247.6
PVAd2	25.1	29.5	34.7	46.4	60.9	81.9	46.4
PVAd3	13.8	17.3	25.3	35.3	54.5	83.5	38.3
CXbd	0.3	2.8	6.1	20.4	41.7	78.3	24.9
LAd	10.4	14.3	22.3	34.3	55.6	101.9	39.8
Average	34.7	40.1	45.2	56.5	74.8	108.1	59.9
	Mehlich-3						
LVd1	0.9	2.1	3.7	7.7	12.4	21.2	8.0
LVd2	45.4	48.0	48.8	57.0	61.1	73.4	55.6
LVd3	64.2	69.7	72.5	80.0	87.2	96.6	78.4
PVd	0.2	2.0	5.0	12.6	20.9	43.5	14.0
LVdf	6.1	8.2	9.8	14.0	21.2	36.4	16.0
LVAd1	0.3	1.5	2.9	9.4	13.2	29.7	9.5
LVAd2	0.2	4.8	9.3	16.0	37.8	57.7	21.0
PVAd1	96.8	104.2	113.4	125.6	139.9	159.7	123.3
PVAd2	21.7	25.1	28.6	35.1	47.1	64.1	37.0
PVAd3	12.9	16.0	20.5	29.3	36.2	53.5	28.1
CXbd	0.9	3.2	5.7	11.1	29.4	52.9	17.2
LAd	7.1	10.8	12.1	18.8	43.4	68.8	26.8
Average	21.4	24.6	27.7	34.7	45.8	63.1	36.2
	Ion Exchange Resin						
LVd1	2.0	2.9	3.2	7.0	10.1	13.5	6.5
LVd2	49.7	55.5	58.2	70.1	67.6	96.4	66.3
LVd3	87.9	91.5	104.6	109.7	138.2	159.7	115.3
PVd	2.6	4.9	4.4	11.0	19.9	29.1	12.0
LVdf	5.0	7.4	7.8	15.9	17.1	35.1	14.7
LVAd1	2.7	4.0	4.8	8.8	11.6	23.6	9.3
LVAd2	2.9	2.7	5.0	9.1	9.7	15.2	7.4
PVAd1	81.4	83.1	89.7	99.7	116.8	124.3	99.2
PVAd2	25.2	26.4	28.7	37.5	47.2	56.8	37.0
PVAd3	12.5	14.9	19.4	28.1	42.2	50.3	27.9
CXbd	1.7	2.9	3.8	9.8	18.2	52.2	14.8
LAd	5.1	7.4	10.6	13.6	28.3	41.0	17.7
Average	23.2	25.3	28.4	35.0	43.9	58.1	35.7

(1) The P dose corresponding to level 5.0 was 187.0 mg dm^{-3} for the soils LVd1, LVd2 and LVd3; 160.0 mg/dm^{3} for the soils PVd, LVdf, and LVAd1; 137.0 mg dm^{-3} for the soils LVAd2, PVAd1, PVAd2, PVAd3, and CXbd, and 100.0 mg dm^{-3} for the soil LAd.

Table 3. Equations of the recovered P contents by Mehlich-1 (M1), Mehlich-3 (M3), and Ion Exchange Resin (IER) ($\hat{y}$, mg dm^{-3}), according to the doses of P (x, mg dm^{-3}) applied to each soil, coefficient of determination (R^2), and extractants' P recovery rate (P*rr*)

Soil	Equations	R^2	Prr-M1
	Mehlich-1		
LVd1	$\hat{y} = -0.398 + 0.1565^{***} x$	0.994	0.157
LVd2	$\hat{y} = 51.71 + 0.4569^{***} x$	0.976	0.457
LVd3	$\hat{y} = 100.7 + 0.5402^{***} x$	0.993	0.540
PVd	$\hat{y} = 0.25 + 0.1718^{\Delta} x + 0.0017^{*} x^2$	0.997	$0.343^{1/}$
LVdf	$\hat{y} = 1.02 + 0.3074^{***} x$	0.973	0.307
LVAd1	$\hat{y} = 1.54 + 0.0740^{ns} x + 0.0023^{**} x^2$	0.997	$0.326^{1/}$
LVAd2	$\hat{y} = -6.15 + 0.5528^{***} x$	0.956	0.553
PVAd1	$\hat{y} = 209.48 + 0.7252^{***} x$	0.982	0.725
PVAd2	$\hat{y} = 24.08 + 0.4253^{***} x$	0.997	0.425
PVAd3	$\hat{y} = 10.96 + 0.5204^{***} x$	0.992	0.520
CXbd	$\hat{y} = -1.67 + 0.3283^{*} x + 0.00019^{\circ} x^2$	0.994	$0.348^{1/}$
LAd	$\hat{y} = 10.03 + 0.4656^{*} x + 0.0045^{*} x^2$	0.999	$0.709^{1/}$
		Average	0.451
	Mehlich-3		P*rr*-M3
LVd1	$\hat{y} = 0.052 + 0.1109^{***} x$	0.994	0.111
LVd2	$\hat{y} = 44.76 + 0.1514^{***} x$	0.992	0.151
LVd3	$\hat{y} = 66.06 + 0.1719^{***} x$	0.985	0.172
PVd	$\hat{y} = -2.68 + 0.2726^{***} x$	0.979	0.273
LVdf	$\hat{y} = 4.35 + 0.1891^{***} x$	0.977	0.189
LVAd1	$\hat{y} = -1.81 + 0.1840^{***} x$	0.971	0.184
LVAd2	$\hat{y} = -1.79 + 0.4337^{***} x$	0.977	0.434
PVAd1	$\hat{y} = 99.06 + 0.4612^{***} x$	0.990	0.461
PVAd2	$\hat{y} = 20.44 + 0.3144^{***} x$	0.993	0.314
PVAd3	$\hat{y} = 12.40 + 0.2981^{***} x$	0.999	0.298
CXbd	$\hat{y} = -3.33 + 0.3907^{***} x$	0.962	0.391
LAd	$\hat{y} = 2.26 + 0.6411^{***} x$	0.955	0.641
		Average	0.302
	Ion Exchange Resin		P*rr*-IER
LVd1	$\hat{y} = 1.74 + 0.0657^{*} x$	0.977	0.066
LVd2	$\hat{y} = 49.65 + 0.2316^{***} x$	0.936	0.232
LVd3	$\hat{y} = 86.61 + 0.3998^{***} x$	0.972	0.400
PVd	$\hat{y} = 1.26 + 0.1748^{***} x$	0.974	0.175
LVdf	$\hat{y} = 3.48 + 0.1831^{***} x$	0.956	0.183
LVAd1	$\hat{y} = 1.36 + 0.1286^{***} x$	0.965	0.129
LVAd2	$\hat{y} = 2.51 + 0.0937^{*} x$	0.968	0.094
PVAd1	$\hat{y} = 81.11 + 0.3438^{***} x$	0.951	0.344
PVAd2	$\hat{y} = 23.89 + 0.2489^{***} x$	0.980	0.249
PVAd3	$\hat{y} = 12.27 + 0.2975^{***} x$	0.965	0.298
CXbd	$\hat{y} = -4.24 + 0.3619^{***} x$	0.905	0.362
LAd	$\hat{y} = 4.55 + 0.3561^{***} x$	0.958	0.356
		Average	0.240

Δ, °, *, **, ***: significant at 25, 10, 5, 1 e 0.1 %, respectively. (1) Differential recovery rate obtained from the range of P dose = 0.0 mg dm^{-3} until P dose corresponding to 90 % of the maximum yield (0.9 $\hat{y}$ max) in each soil.

Table 4. Equations of P recovery rate by Melich-1 (P*rr*-M1), Mehlich-3 (P*rr*-M3), and Ion Exchange Resin (P*rr*-IER), according to soil characteristics related to soil P buffering capacity: moisture equivalent, clay content, remaining P (rem-P), soil organic matter (OM), and potential acidity (H + Al). R² = coefficient of determination

Soil characteristics		
	Moisture equivalent (kg kg^{-1})	
P*rr*-M1	$\hat{y} = 0.64 - 0.0010^{\circ} x$	$R^2 = 0.428$
P*rr*-M3	$\hat{y} = 0.59 - 0.0012^{**} x$	$R^2 = 0.647$
P*rr*-IER	$\hat{y} = \bar{y} = 0.212$	
	Clay content (%)	
P*rr*-M1	$\hat{y} = 0.70 - 0.0069^{*} x$	$R^2 = 0.584$
P*rr*-M3	$\hat{y} = 0.63 - 0.0074^{**} x$	$R^2 = 0.704$
P*rr*-IER	$\hat{y} = \bar{y} = 0.212$	
	rem-P (mg L^{-1})	
P*rr*-M1	$\hat{y} = 0.17 + 0.0116^{**} x$	$R^2 = 0.757$
P*rr*-M3	$\hat{y} = 0.07 + 0.0119^{***} x$	$R^2 = 0.834$
P*rr*-IER	$\hat{y} = 0.06 + 0.0074^{**} x$	$R^2 = 0.682$
	OM (g kg^{-1})	
P*rr*-M1	$\hat{y} = 0.54 - 0.0050^{\circ} x$	$R^2 = 0.415$
P*rr*-M3	$\hat{y} = 0.44 - 0.0050^{\circ} x$	$R^2 = 0.423$
P*rr*-IER	$\hat{y} = \bar{y} = 0.212$	
	H + Al ($cmol_c$ dm^{-3})	
P*rr*-M1	$\hat{y} = 0.59 - 0.0446^{*} x$	$R^2 = 0.444$
P*rr*-M3	$\hat{y} = 0.50 - 0.0475^{*} x$	$R^2 = 0.528$
P*rr*-IER	$\hat{y} = \bar{y} = 0.212$	

°, *, **, ***: significant at 10, 5, 1, and 0.1 %, respectively. The soils LVd2, LVd3, and PVAd1 were excluded.

Table 5. Soil P critical level by Mehlich-1 (P*cl*-M1), Mehlich-3 (P*cl*-M3), and Ion Exchange Resin (P*cl*-RTI); average, standard deviation, and coefficient of variation (CV) of P critical level (P*cl*) obtained by each extractant with 12 soils, and 9 soils (after removing the soils LVd1, LVd2, and PVAd1)

Soil		**P*cl*-M1**	**P*cl*-M3**	**P*cl*-RTI**
		mg dm^{-3}		
LVd1		24.8	17.9	12.3
LVd2		51.7	44.8	49.7
LVd3		130.1	75.4	108.4
PVd		34.8	24.8	18.9
LVdf		31.7	23.2	21.8
LVAd1		37.2	18.3	15.4
LVAd2		46.5	39.5	11.4
PVAd1		210.6	99.8	81.7
PVAd2		42.9	34.3	34.9
PVAd3		50.7	35.1	35.0
CXbd		34.0	36.8	32.9
LAd		48.4	36.9	23.8
12 soils	Average	62.0	40.6	37.2
	standard deviation	54.1	24.1	29.8
	CV (%)	87.3	59.4	80.1
9 Soils	Average	39.0	29.6	22.9
	standard deviation	8.6	8.5	9.4
	CV (%)	22.2	28.8	41.1

Table 6. Equations of soil P critical level by Mehlich-1 (P*cl*-M1), Mehlich-3 (P*cl*-M3), and Ion Exchange Resin (P*cl*-IER) according to soil characteristics related to soil P buffering capacity: moisture equivalent, clay content, remaining P (rem-P), soil organic matter (OM), and potential acidity (H + Al)

Soil characteristic		
Moisture equivalent (kg kg^{-1})		
P*cl*-M1	$\hat{y} = \bar{y} = 39.0$	
P*cl*-M3	$\hat{y} = 43.16 - 0.0615^{*} x$	$R^2 = 0.554$
P*cl*-IER	$\hat{y} = \bar{y} = 22.9$	
Clay content (%)		
P*cl*-M1	$\hat{y} = 51.94 - 0.3059^{\circ} x$	$R^2 = 0.412$
P*cl*-M3	$\hat{y} = 47.33 - 0.4180^{**} x$	$R^2 = 0.888$
P*cl*-IER	$\hat{y} = \bar{y} = 22.9$	
rem-P (mg L^{-1})		
P*cl*-M1	$\hat{y} = 27.92 + 0.5328^{*} x$	$R^2 = 0.572$
P*cl*-M3	$x \leq 21.2 : \hat{y} = 9.74 + 1.2293^{*} x$ $x > 21.2 : \hat{y} = \bar{y} = 35.8$	$R^2 = 0.991$
P*cl*-IER	$\hat{y} = \bar{y} = 22.9$	$R^2 = 0.444$
OM (g kg^{-1})		
P*cl*-M1	$\hat{y} = 45.72 - 0.2669^{\circ} x$	$R^2 = 0.415$
P*cl*-M3	$\hat{y} = 36.31 - 0.2639^{\circ} x$	$R^2 = 0.414$
P*cl*-IER	$\hat{y} = \bar{y} = 22.9$	
H + Al (cmol$_c$ dm^{-3})		
P*cl*-M1	$\hat{y} = 47.67 - 2.1743^{\circ} x$	$R^2 = 0.375$
P*cl*-M3	$\hat{y} = 38.31 - 2.1687^{\circ} x$	$R^2 = 0.381$
P*cl*-IER	$\hat{y} = \bar{y} = 22.9$	

°, *, **: significant at 10, 5, and 1 %, respectively. The soils LVd2, LVd3, and PVAd1 were excluded. R^2: coefficient of determination

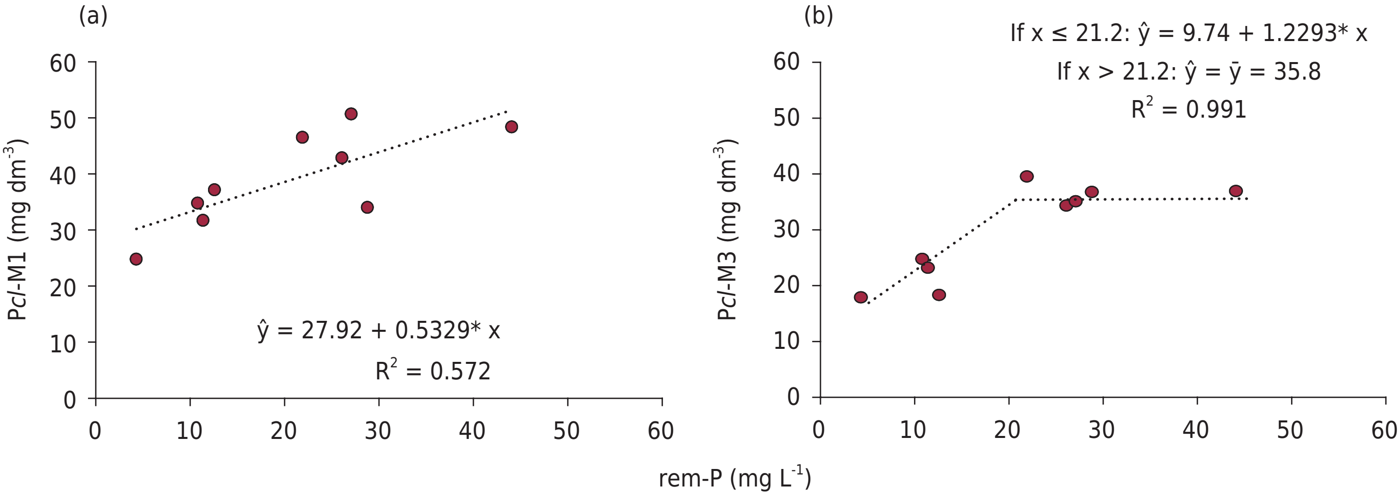

Figure 3. Soil P critical levels by a) Mehlich-1 (P*cl*-M1), and b) Mehlich-3 (P*cl*-M3) as a function of remaining P (rem-P) in nine soil samples cultivated with corn. *Significant at 5 %.

with these characteristics (excluding the soils LVd2, LVd3, and PVAd1) (Table 6). The linear model was the model that best fitted to the data, except for the relation between the P*cl*-M3 and rem-P, in which the discontinuous model (linear plateau) was the one that best explained the phenomenon (Table 6 and Figure 3b). The P*cl*-M3 was dependent on the rem-P up to the value of 21.2 mg L^{-1}, from which there was no more dependence of the P*cl*-M3 of this measure of soil PBC (Figure 2b). It suggests that there is no continuous loss of extraction capacity of the M3 extractant with the increase in the soil PBC.

Classes of interpretation of soil phosphorus availability by Mehlich-3 extractant

Correlations were made between the soil available P contents obtained by the extractants in the controls and all doses of P (Figure 4). There was a high correlation between P-M1 and P-M3 (r = 0.976*** for controls, and r = 0.982*** for all treatments), as well as between P-M3 and P-IER (r = 0.963*** for the controls, and r = 0.909*** for all treatments), and between P-M1 and P-RM (r = 0.898*** for controls, and r = 0.896*** for all treatments).

Due to the sensitivity of M3 to the soil PBC, demonstrated by the influence of soil characteristics related to the soil PBC in the P*rr*-M3 and in the P*cl*-M3, we proposed interpretation ranges for the soil available P content by M3 as a function of the clay content and rem-P (Table 7). The clay content and rem-P were the soil characteristics that most influenced the P*rr*-M3 and in the P*cl*-M3 (Tables 4 and 6). The equation used to determine the limits of class definition was the one that relates the P-M3 as a function of the P-M1 obtained in all the experimental units: P-M3 = 6.34 + 0.4989*** P-M1 (R^2 = 0.965) (Figure 4d). Thus, the limits of the class definition in the interpretation table of P availability by M1 in the recommendation of Ribeiro et al. (1999) were substituted in the above equation to obtain the limits of class definition by M3 extractant.

DISCUSSION

Shoot dry matter yield and phosphorus recovery rates

In general, the differences in shoot dry matter yield as a function of doses of P applied to the soils was mainly due to the soil P availability prior to the cultivation. The highest corn shoot dry matter yield was obtained in cultivated soils, due to the higher P availability in these soils (Table 1), since the other nutrients were applied to guarantee sufficiency for plants. The absence of response for shoot dry matter yield in LVd2 is due to the high available P content in this soil (Figure 2c). Although, there was a response in soils LVd3 and PVAd1 (Figure 2), which also presented available P content above the critical level (Table 1). The set of soil samples to be used in a study should be based on the objectives to be achieved. If the objective is to relate soil characteristics to the nutrient availability, a soil population with variable characteristics should be selected, especially regarding the availability of the nutrient under study, which in some cases may exceed the critical level in some soil sample (Novais et al., 1991). Our objective is, in addition to establish shoot dry matter production curves in response to P doses, to evaluate the predictive capacity of the M3 extractant in soils with different P availabilities, so we collected soils with available P content above the critical level, as observed in samples LVd2, LVd3, and PVAd1.

The higher P*rr* by the M1 extractant show that, for the set of studied soils, there was no significant loss of extraction capacity, unlike the results of several works with this extractant (Bortolon et al., 2009; Novais et al., 2015; Valadares et al., 2017). This result can be explained by the fact that the extractions were carried out in the soil samples collected after the cultivation, when the soils had been incubated with the mixture of $CaCO_3$ and $MgCO_3$. The variation between the soil available P contents by the extractants was due to their characteristics, the initial soil P availability, and soil physicochemical characteristics, as well as due the influence of the P sources applied. The highest soil P content by M1 extractant (P-M1) may have occurred due to the high initial acidity of this extractant (pH = 1.2), and due its higher capacity to solubilize P-Ca forms (Valadares et al.,

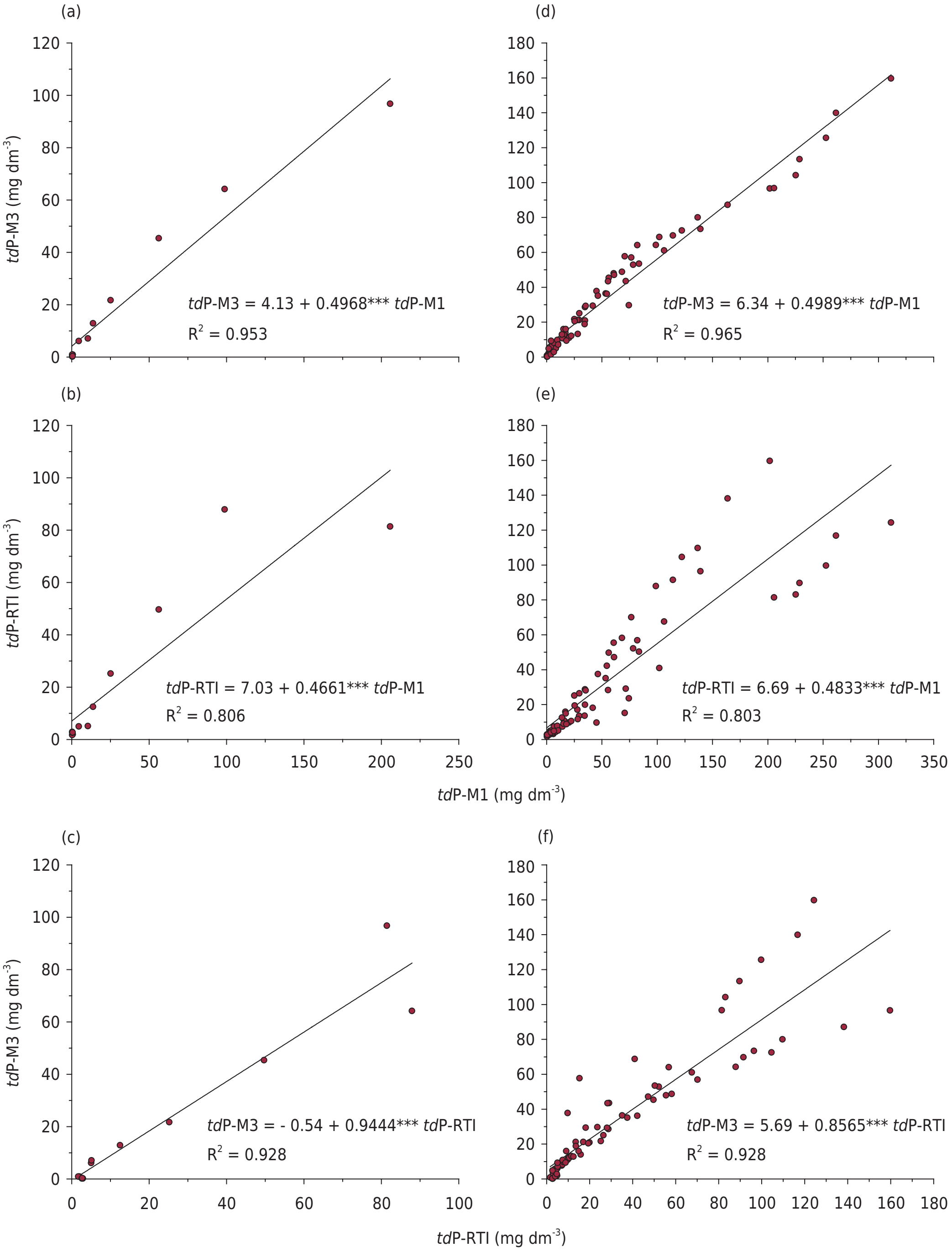

Figure 4. Correlation between soil available P content by Mehlich-1 (P-M1), Mehlich-3 (P-M3), and Ion Exchange Resins (P-IER) in 12 soils cultivated with corn. Correlation performed with the available P contents of the controls (no P application) (a, b, and c), and correlation with the available P contents of all the experimental units (d, e, and f). *** significant at 0.1 %.

2017), besides the addition of natural phosphate (Byóvar) and liming before cultivation. In these soils, M1 may overestimate available P contents, since plants, particularly those with shorter growth and development cycles, may not be efficient in absorbing P-Ca forms (Novais and Kamprath, 1978). The soil pH is important in the determination of soil P availability by M1 due its dependence on soil PBC, being the soil characteristic that most influenced soil P content by in a clayey and sandy soil treated with rates of humic acid concentrations (Rosa et al., 2018).

On average, P-M1 was also higher than the P-IER and P-M3 in the controls (Table 2), although this result occurred due to the large amount of P extracted by this extractant in

Table 7. Classes for soil P availability interpretation by Mehlich-3 extractant (P-M3), according to the proportion of clay content or rem-P

Characteristics	**Classes**				
	Very low	**Low**	**Medium**(1)	**Good**	**Very good**
			P-M3		
			mg dm^{-3}		
Clay content (g kg^{-1})					
600 – 1000	≤ 7.7	7.8 – 9.0	9.1 – 10.3	10.4 – 12.3	> 12.3
350 – 600	≤ 8.3	8.4 – 10.3	10.4 – 12.3	12.4 – 15.3	> 15.3
150 – 350	≤ 9.6	9.7 – 12.3	12.4 – 16.3	16.4 – 21.3	> 21.3
0 – 150	≤ 11.3	11.4 – 16.3	16.4 – 21.3	21.4 – 28.8	> 28.8
rem-P (mg L^{-1})					
0 – 4	≤ 7.8	7.9 – 8.5	8.6 – 9.3	9.4 – 10.8	> 10.8
4 – 10	≤ 8.3	8.4 – 9.3	9.4 – 10.5	10.6 – 12.6	> 12.6
10 – 19	≤ 9.3	9.4 – 10.5	10.6 – 12.0	12.2 – 15.1	> 15.1
19 – 30	≤ 10.3	10.4 – 12.0	12.1 – 14.2	14.3 – 18.3	> 18.3
30 – 44	≤ 11.8	11.9 – 14.2	14.3 – 17.2	17.3 – 22.8	> 22.8
44 – 60	≤ 13.8	13.9 – 17.2	17.3 – 21.3	21.4 – 28.8	> 28.8

(1) The upper limits of this class represent the soil P critical levels.

the soils LVd2, LVd3, PVAd1, and PVAd3, which were collected in cultivated areas. These soils had high levels of available P, higher pH values than those collected in uncultivated areas (values ranging from 5.42 to 6.92), and higher levels of Ca^{2+} (Table 1). Thus, with the exception of soil PVAd2 in which the P-M1 and P-IER were practically the same, 25.1 and 25.2 mg dm^{-3}, for all soils collected in cultivated areas the P-M1 were higher than the P-IER and P-M3. In the controls of those soils collected in uncultivated areas, more acidic and with lower levels of Ca, P-IER were higher in the soils LVd1, PVd, LVAd1, and LVAd2, while P-M3 were higher in the soils LVdf and CXbd, in comparison to the P-M1. Thus, by the analysis of the soil available P content by the extractants in all doses, and only in the controls, it is possible to state that the higher averages of P-M1 are due to the greater solubilization of P-Ca forms present in cultivated soils. In soils with low Ca contents, IER and M3 extractants tend to extract larger amounts of P than M1 (Simões Neto et al., 2009; Valadares et al., 2017).

The P*rr* by a specific extractant allows us to estimate the doses of P to be applied in the soil to increase the soil P availability until to reach the P*cl* (Alvarez V et al., 2014). Therefore, it is important to know whether the P*rr* is influenced by soil characteristics that reflect its P buffer capacity. The equations in table 4 indicate that the recovery of P applied to the soil is higher in soils with lower P buffer capacity than in the soil more buffered, for M1 and M3. Similar result was found by Bortolon and Gianello (2008), who showed the need to generate interpretation tables for soil available P content by M3 that take into account the soil P buffer capacity, estimated by easily obtainable characteristics, like rem-P. Studies evaluating the P availability in soils of tropical regions show that, in addition to the correlation between the nutrient content available by a given method, and the nutrient content in the plant, it is desirable that the method behaves predictably in relation of the variation of soil P buffer capacity (Alvarez V, 1996).

In the correlations established between P*rr* and soil characteristics related to PBC, the highest correlation coefficients obtained between P*rr*-M1 and P*rr*-M3 with rem-P is due the rem-P be an estimate not only on the clay content, but also on the quality of the clay, or the P adsorption capacity by adsorption sites present in the soil (Novais and Smyth, 1999).

Soil P critical levels

The great variation in the P*cl* by the extractants is due to the differences in the soil P availability before cultivation, in addition to the different soil PBC. Thus, in soils with higher available P contents before cultivation, higher P*cl* were obtained (Table 5). The tables for interpretation of the soil P availability established in Ribeiro et al. (1999) stratify the soil P availability according to the clay content in four classes, or with the rem-P in five classes, considering the sensitivity of M1 to the soil PBC. In the tables for interpretation of the soil P availability for crops, in general, the P*cl*-M1 ranges from 8.0 to 30.0 mg dm^{-3} according to the clay content and from 6.0 to 30.0 mg dm^{-3} according to rem-P (Ribeiro et al., 1999). Thus, the soil P*cl* obtained under greenhouse conditions for corn in this study approximated to the P*cl* obtained in calibration studies conducted under field conditions. Although the average of the P*cl* obtained with all soils was higher, when the soils LVd2, LVd3, and PVAd1 were removed, the mean of the P*cl* was 39.0 mg dm^{-3} for M1, 29.6 for M3, and 22.9 for IER (Table 5).

In the tables of interpretation for soil P availability by IER (van Raij et al., 1997) there are stratifications in the soil P availability in five classes according to crop. For forest species, the P*cl*-IER is 8.0 mg dm^{-3}, for perennial crops 30.0 mg dm^{-3}, for annual crops 40.0 mg dm^{-3}, and for vegetables 60.0 mg dm^{-3}. Considering that the P*cl*-IER ranged from 11.4 to 35.0 mg dm^{-3} when the soils LVd2, LVd3, and PVAd1 were removed, the P*cl*-IER obtained in this study are also in agreement with the P*cl*-IER obtained in calibration work carried out under field conditions for the corn crop.

In general, the soil P*cl* obtained in under greenhouse conditions, with cultivation in pots are superior to those obtained in field experiments (Leite et al., 2006), which makes it necessary to perform calibration experiments in the field to define the P*cl* and P*rr* to obtain the recommended doses (Alvarez V, 1996). In the soil fertility evaluation program, the field experiments are performed after correlation studies conducted under greenhouse conditions. The soils and the sites for the assembly of the experiments should be carefully chosen and it is necessary to perform repetitions of the experiments in different years to minimize the effects that can not be kept constant, which increases the costs of these studies (Cantarutti et al., 2007).

The high P*cl* obtained under greenhouse conditions are a consequence of the doses of P being applied to the total volume of soil. In this condition, the critical levels would only be compatible with those obtained in the field experiments if field sampling were performed only in the region of the pit or the planting furrow. Thus, critical levels are variables that depend not only on the extraction method, on the crop, or on the soil characteristics, but also on the nutrient application, and the way the soil is sampled (Alvarez V, 1996; Leite et al., 2006, 2009).

The soil P*cl* obtained under greenhouse conditions was similar to soil P*cl* obtained in field experiments due to the way the doses of P were applied in the pots and the way of sampling the soil after the cultivation. The application of the P doses was performed simulating the pit, or the furrow of planting realized for the corn crop in the field. For this, the doses of P were applied to 10 % of the total soil volume (0.2 dm^3) in the upper half part of the pot (Figure 1). After cultivation, sampling was performed by mixing the part that received P with the part that did not receive P in the upper half part of the pot (Figure 1), simulating the composite sampling performed in the field.

The results of this work were similar to those obtained by Leite et al. (2006), who studied the variation of P*cl* according to forms of P doses location and soil sampling for corn cultivated in pots under greenhouse conditions. They observed that when P is located in the central part of the pot, simulating the pit in the field, and when sampling is performed by mixing the region of the pit with the region that did not receive P (upper half of the pot), simulating the filed sampling, we can obtain P*cl* compatible with those obtained in calibration work carried out under field conditions. Similar results were also obtained for soybean (Muniz et al., 1987) and eucalyptus (Leite et al., 2009).

The coefficient of variation (CV) can be used as a measure of extractant's sensitivity to the soil PBC. In this case, the higher the CV, the higher the extractant's sensitivity to the soil PBC. When the CV was calculated with all soils, the most sensitive extractant, by this criterion, was M1, while M3 was the less sensitive (Table 5). When soils that presented available P content above critical level were eliminated, the most sensitive extractant was the IER, and the less sensitive the M1. However, shown in table 4, there was a significant correlation only between P*rr*-IER and rem-P, showing that this extractant is less sensitive to soil PBC than M1 and M3, which correlated better with the rem-P and also, with other characteristics.

Similar behavior to the P*cl*-M3 of the present work was obtained by Novais and Smyth (1999) when they plotted the P*cl*-M1 data obtained in nine soils of Cerrado region (Brazil), cultivated with soybean from the work of Muniz et al. (1987) as a function of rem-P (using rem-P = 30 mg L^{-1}). Muniz et al. (1987) used the linear model ($\hat{y} = 11.2 + 0.9550^{**} x$, $R^2 = 0.880$) to express the relationship between P*cl*-M1 and rem-P. Novais and Smyth (1999) observed that, despite the significance, the linear model was not the most adequate to express the relationship between the variables and, with the same data, adjusted the linear plateau model (for $x \leq 5.33$ mg L^{-1}: $\hat{y} = 5.31 + 3.51^{**} x$, and for $x > 5.33$ mg L^{-1}: $\hat{y} = 24.02$ mg dm^{-3}, $R^2 = 0.949$). This simulation shows that there was no continuously wear of the M1 extractant according to the rem-P, but that from the intermediate rem-P values (5.33 mg L^{-1}) there was no further loss of extraction capacity by the extractant.

In a study of loss of M1 extraction capacity in 20 soils samples with marked variation of rem-P, Novais et al. (2015) also observed that the loss of the extraction capacity was discontinuous in relation to rem-P (60 mg L^{-1}) (for $x \leq 19.7$ mg L^{-1}: $\hat{y} = 128.9 + 8.77^{**} x$, and for $x > 19.7$: $\hat{y} = \bar{y} = 301.86$ mg L^{-1}, $R^2 = 0.904$). The value of rem-P from which there is no further loss of extraction capacity was 19.7 mg L^{-1}, close to the value of 21.2 mg L^{-1} found for the M3 extractant in the present work (Figure 3b).

Although the linear model fitted better to the data of P*cl*-M1 as a function of the rem-P (Figure 3a), it can be observed that there was no good adjustment ($R^2 = 0.572$). This indicates that there was also a soil PBC dependence on the determination of P*cl*-M1 from a certain rem-P value (close to 20 mg dm^{-3}), even though the trend of the linear plateau model was not well characterized for M1 as it was for M3. These results suggest that soil PBC measurements, such as rem-P for interpretation of P availability in soils with different PBC, may be losing importance in soils with available P enrichment scenario, as suggested by Novais and Smyth (1999). This occurs due to the gradual decrease of the P binding energy to the soil as it is enriched with P. Thus, when extractants that are sensitive to the soil PBC are used, such as M1 and M3, a discontinuous model must be used to interpret soil P availability, as proposed by Novais et al. (2015).

Classes of interpretation of soil phosphorus availability by Mehlich-3 extractant

As there was a high correlation between P-M1 and P-M3 (Figure 4d), and both were sensitive to the soil PBC, expressed by the high correlation values obtained between the P*rr* (Table 4) and the P*cl* (Table 6) with clay content and rem-P, interpretation ranges of P-M3 were proposed as a function of these two soil characteristics (Table 7).

In general, several studies show a close correlation between the soil P contents extracted by M1 and M3. When comparing P-M1 and P-M3 in 360 soil samples from the Rio Grande do Sul state, with a wide range of physical and chemical characteristics, Bortolon and Gianello (2008) obtained a high degree of correlation between the extractants (r = 0.95**). A similar result for the same extractants was obtained in a study with six soils from the Rio Grande do Sul State (r = 0.99*) (Bortolon et al., 2009). Lower correlation coefficients were observed between P-M1 and P-M3 in a study of five soils from Amazon, cultivated with cowpea and rice, where r = 0.521** were obtained in samples collected before sowing of cowpea, and r = 0.572** in samples collected before sowing rice (Brasil and Muraoka, 1997). In this same work, the best correlations were obtained between M3 and Bray-1, with a lower correlation between P-M1 and P-IER (r = 0.496** and r = 0.529** for each crop).

Interpretation ranges of P-M3 were proposed for soils of Rio Grande do Sul State, where the limits of classes were also determined by predictive models established between P-M1 and P-M3 (Bortolon and Gianello, 2008). However, these authors considered only the clay content as a measure of soil PBC. Because of a lack of information on clay quality, and incomplete clay dispersion in some tropical soils (Donagemma et al., 2003), textural analysis is not as suitable for stratification of P availability as rem-P is. The rem-P, besides being determined routinely in the laboratories that officially adopt M1, is a better measure of soil PBC, as can be observed in the correlations between P*rr* and P*cl* by M1, and M3 extractants in this work.

The rem-P is a dynamic measure, so the value of rem-P is altered due to agricultural practices that modify soil PBC (Fontana et al., 2008) and, consequently, the soil P*cl*. The rem-P was the measure that best correlated with the soil characteristics that reflect the soil PBC in 200 soil samples from the Rio Grande do Sul State, in a study which the authors proposed the use of rem-P, besides the clay content, for the interpretation of the soil P availability by M1 and M3 (Rogeri et al., 2016).

As shown in table 7, the soil P critical level by M3 is stratified according to the rem-P at smaller intervals above rem-P of 19 mg L^{-1} (14.2 - 21.3 mg dm^{-3}) in comparison to the recommendation of Ribeiro et al. (1999) for M1 (15.8 - 30.0 mg dm^{-3}). Thus, the interpretation ranges of the P-M3 proposed in this work take into account the discontinuous loss of P extraction capacity of the M3 extractant (Figure 3b), as proposed by Novais et al. (2015) for the M1. Lower availability ranges were also obtained for clay as a measure of soil PBC compared to the ranges proposed by Ribeiro et al. (1999) (Table 7).

CONCLUSION

The soil phosphorus recovery rates and critical levels obtained by Mehlich-1 and Mehlich-3 extractants are influenced by the soil P buffer capacity, assessed by soil clay content and remaining phosphorus. What does not occur with Ion Exchange Resin.

The Melhlich-3 extractant suffers a discontinuous loss of extraction capacity with increasing soil phosphorus buffer capacity, which results in lower intervals of soil phosphorus availability in the table of interpretation.

Mehlich-3 is recommended as an available P extractant in soils with different characteristics if a measure of soil phosphorus buffering capacity such as remaining phosphorus or clay content is used to interpret the results.

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