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Establishing environmental soil phosphorus thresholds to mitigate its transfer to water bodies in Mato Grosso State, Brazil

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ABSTRACT: Excessive phosphorus (P) applications can increase nutrient levels in the soil, facilitating its transference to aquatic environments and causing contamination. Thus, the environmental P threshold (P-threshold) is a tool to establish a sound level of P in the soil, in which P values below the threshold are harmless to the environment. This study aimed to establish a P-threshold equation for the soils of Mato Grosso State, Brazil. Twenty samples of representative soils from the main swine production regions of the State were collected. These samples were characterized chemically and in terms of P adsorption capacity, then incubated with P rates for 30 days. After incubation, the water-soluble P content (P-water) and the available P content were determined by Mehlich-1 method (P-Mehlich-1). The relationship between P-water and P-Mehlich-1 allowed the determination of the P-Mehlich-1 content from which the amount of nutrient in water increases abruptly, establishing this point as the limit P (P-limit). Subsequently, the P-limit values were plotted against the clay content of the soils, and the resulting equation was used to calculate the P-threshold by adding a safety margin of 20 % to the P-limit versus clay equation. The model was tested on 120 soil samples from Mato Grosso State, and it was able to separate them into two groups with low and high P-water, classified as below or above P-threshold, respectively. Based on that, the simplified equation “P-threshold (mg dm^{-3}) = 13 + 0.5 * % clay” was proposed.

Keywords: environmental pollution, swine manure, eutrophication, P-thresholds.

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INTRODUCTION

Most Brazilian soils are naturally acidic and deficient in essential chemical elements for plants (Motta and Melo, 2019). In weathered soils, phosphorus (P) is considered one of the most limiting nutrients for agricultural productivity (Roy et al., 2016; Withers et al., 2018) due to its high affinity with solid soil particles (Gérard, 2016). In this scenario, obtaining high yields is conditioned to the supply of this nutrient via fertilizers. However, to meet the nutritional demand of agricultural crops, P application via fertilizers is carried out at rates relatively higher than the required because of the low efficiency of phosphate fertilizers (Dhillon et al., 2017).

The low efficiency of phosphate fertilization is directly related to this element reactions in the soil, which reduce its mobility and availability for plants. Clay content and mineralogical constitution regulate the degree of P availability in the soil (Bortoluzzi et al., 2015; Gérard, 2016; Sousa et al., 2016). Phosphorus concentration in the soil solution, therefore, depends on chemisorption reactions in poorly soluble compounds with iron and aluminum under high acidity conditions or with calcium in high pH conditions (Gypser et al., 2018; Penn and Camberato, 2019), and adsorption on the surface of clay minerals, oxides and iron and aluminum hydroxides (Rodrigues et al., 2016). Most Brazilian soils, especially those from the Cerrado region, express an oxidic mineralogy and a high P retention capacity (Goedert, 1983; Roy et al., 2017).

However, successive fertilizations without technical criteria can substantially increase the P content in the soil beyond the critical soil test value for crops. This problem is common in regions of livestock, where the waste generated is applied to agricultural areas, often in excessive doses (Kleinman et al., 2015; Abboud et al., 2018; Panagos et al., 2022). Pig production is an activity of great importance for Mato Grosso State. Thanks to the tax incentives of the “Granja de Qualidade” program, associated with the edaphoclimatic conditions and the raw material availability for animal food production, the state has a herd of about 2.3 million animals, which corresponds to the largest one in the Midwest Brazil (ABPA, 2022). Furthermore, swine production should show a growth of 193 %, a projected evolution until 2025 (IMEA, 2023).

Increasing the total P content in the soil gradually increases the participation of more labile fractions (Gatiboni et al., 2008; Boitt et al., 2018). The continuity of this process promotes the saturation of the adsorption sites, increasing the concentration of soluble P in water (Gatiboni et al., 2015), which is highly susceptible to losses. Once transferred from cropland to the environment, in addition to economic losses, P can cause serious environmental problems, as it is a precursor to the water eutrophication process (Zhang et al., 2017; Withers et al., 2019). Phosphorus can contaminate surface water (rivers and lakes) and groundwater (deeper aquifers) (Schindler et al., 2016; Cassidy et al., 2017).

Strategies that limit the support capacity of the soil to receive imminent applications of P are needed to avoid environmental issues. Indices have been developed to determine the maximum amounts of P that a given soil can receive without substantial losses (Kleinman et al., 2000; Nair, 2014; Sharpley et al., 2017; Abboud et al., 2018; Gatiboni et al., 2020). In this context, Gatiboni et al. (2015) developed a simple system for assessing environmental risk in soils in Santa Catarina State, Brazil, considering two factors: clay content and available P in the soil, being commonly determined in laboratory routine analyses. The model, named “Environmental Soil Phosphorus Threshold” (P-threshold) (P-threshold = 40 + % clay), considers that more clayey soils, due to the intrinsic greater capacity to adsorb P, can receive higher amounts of phosphate before increasing the risk of P transfer to the environment. The results of this study allowed this model to be included as an environmental risk indicator in Normative Instruction No. 11, which regulates swine farming in Santa Catarina State (IMA, 2022). While the model can be readily utilized for predictions, it is crucial to acknowledge its development using a restricted range of soil quantity and variability, as well as specific soil mineralogy. Consequently, adopting the model in diverse regions may not be feasible.

The design of the P-threshold model and its inclusion in the legislation that regulates swine farming in Santa Catarina State, envisaged the development of an environmental risk assessment system in areas where swine manure is applied in the Mato Grosso State. The definition of this model, based on the most representative soils of the State, will support future regulations on the application of phosphate fertilizers and residues containing P. Based on this, the objective of this study was to establish the P-threshold for soils in Mato Grosso State, Brazil.

MATERIALS AND METHODS

Soil sampling and characterization

Representative soils from the main swine production regions in the Mato Grosso State, Brazil, were selected (Figure 1). Twenty soil samples were collected from the 0.00 to 0.20 m layer, in areas under natural vegetation, where the soils maintain their original physical and chemical characteristics. Soil samples were properly packaged and oven-dried at 65 °C. Subsequently, they were ground, sieved through a 2 mm mesh and subjected to physical-chemical characterization analysis, according to Teixeira et al. (2017).

After characterization, the soils were incubated with dolomitic limestone to reach a pH(H_2O) of 5.5 (Sousa and Lobato, 2004). Subsequently, the samples were subjected to analyses of remaining P (P-rem), maximum capacity of P adsorption (P-max), P buffering capacity (PBC), P recovery, and total iron and aluminum (Fe-Total and Al-Total). The P-rem was determined by the P concentration in the equilibrium solution right after stirring the samples for 15 min with a 0.01 mol L^{-1} calcium chloride solution containing 60 mg L^{-1}

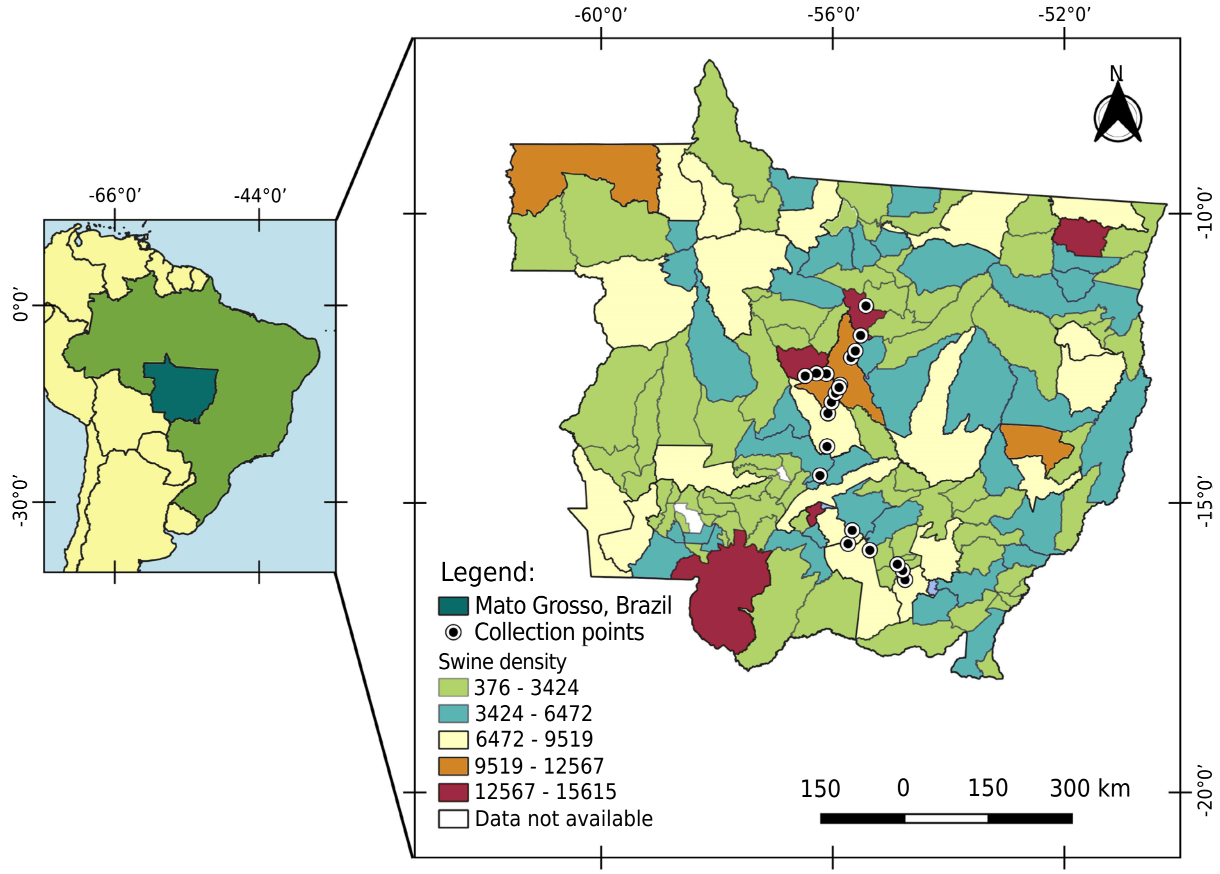

Figure 1. Distribution of swine density and location of soil sample collection points in the Mato Grosso State, Brazil. Geographic coordinate SIRGAS 2000.

of P, in the soil:solution at a ratio of 1:10. The P content in the equilibrium solution was determined by colorimetry (Alvarez et al., 2000). The P-max was obtained by adding 0.5 g of soil in a falcon tube with a capacity of 15 mL (in four repetitions), in which it were added 10 mL of 0.01 mol L^{-1} calcium chloride solution containing seven concentrations of P. The P concentrations used for soils with clay content <300 g kg^{-1} were: 0, 31.25, 62.50, 125, 250, 500, and 1000 mg kg^{-1} of P; for soils with clay content >300 g kg^{-1}: 0, 62.50, 125, 250, 500, 1000, and 2000 mg kg^{-1} of P. After stirring for 16 h, the samples were centrifuged for 15 min (3000 rpm), and the P content in solution was determined by molecular absorption spectrometry with a wavelength of 882 nm (UV-1800, SHIMADZU) according to Murphy and Riley (1962). The P adsorbed was obtained through the difference between the amount added and the amount recovered in the solution. The data was adjusted by the Langmuir model (Equation 1).

$$P = \frac{k \times Pmax \times C}{1 + k \times C} \qquad \text{Eq. 1}$$

in which: k is the constant related to the adsorption energy; Pmax is the maximum capacity of P adsorption, and C is the P concentration in the solution. The PBC was estimated based on the relationship between the applied P dose and the extractable P content by the Mehlich-1 method. The percentage of P recovered was calculated according to equation 2 (Anghinoni and Bohnen, 1974).

$$\%\ of\ recovered\ P = \frac{P_{determined} - P_{natural\ to\ the\ soil}}{P_{added}} \times 100 \qquad \text{Eq. 2}$$

Fe-Total and Al-Total were extracted by sulfuric attack and quantified by atomic absorption spectrophotometry (Teixeira et al., 2017).

Incubation of soils containing P and P-threshold determination

The soils were submitted to incubation with increasing doses of P, corresponding between 0 and 100 % of the P-max values. Therefore, for soils with clay content lower than 300 g kg^{-1}, doses ranged from 0 to 1000 mg kg^{-1} of P, and for soils with clay content greater than 300 g kg^{-1}, the doses varied from 0 to 2000 mg kg^{-1} of P. Doses of P were added through a solution elaborated by dissolving the ground triple superphosphate fertilizer with ultrapure water. For this purpose, 50 g of soil were weighed and placed in plastic bags (with a capacity of 1 kg), and then a solution containing the P concentrations corresponding to each dose tested was added. For each soil, this procedure was performed in three repetitions, and the incubation lasted 30 days.

Immediately after incubation, the water-soluble P content (P-water) and the available P content were determined by the Mehlich-1 method (P-Mehlich-1). The P-water was determined by weighing the equivalent of 2.5 g of soil, adding 25 mL of ultrapure water. After 1 h of agitation, the samples were centrifuged for 15 min (3500 rpm), filtered with a 0.45 µm cellulose acetate membrane, with an aliquot being removed for determination. The P-Mehlich-1 was obtained using 2.5 g of soil and 25 mL of extracting solution. After 5 min of stirring the soil with the extracting solution, the samples remained at rest for 16 h, and then a sample of the supernatant was taken for determination. The P-water and P-Mehlich-1 were determined by the Murphy and Riley method (1962).

The relation between the values of P-Mehlich-1 (independent variable “x”) and P-water (dependent variable “y”) was graphed. Segmented functions (*Pieciwise – 2 segmented linear*) were generated to determine the change point (P-limit), which means, the value of P-Mehlich-1 in which the levels of P-water enhance abruptly. The P-limit values and the content of clay in each soil were related, and the linear equation arising from it was considered as P-threshold.

P-threshold efficacy in soil samples

A total of 118 soil samples were collected for model validation. Sampling was carried out in the layer from 0.00 to 0.20 m, in 12 rural properties of swine raisers in the municipalities of Sinop, Sorriso, Vera, Tapurah, Lucas do Rio Verde, Nova Mutum, Campo Verde, Primavera do Leste and Rondonópolis. In each rural property, areas of pasture or grain crops with and without a history of swine manure application were selected. Finally, the samples were dried in an oven with forced air circulation, set at 65 °C, sieved in a 2 mm mesh, and properly packaged.

The following characterization analyses were carried out: P-water and P-Mehlich-1, following the same methodologies described above. Based on the clay, the P-threshold value was determined, and the soils were separated into two groups: below and above the P-threshold. Finally, they were plotted on a graph relating to P-Mehlich-1 and P-water.

RESULTS AND DISCUSSION

General characterization of soils

Soil properties and their P related characteristics are shown in tables 1 and 2, respectively. The average contents of Fe-Total and Al-Total were 24.7 and 69.5 g kg^{-1}, with amplitudes between 1.4 and 92.3; 6.0 and 147.9 g kg^{-1}, respectively. The minimum and maximum percentages of P recovered by the Mehlich-1 extractor as a function of the P doses fluctuated from 1 to 62 % and 16 to 121 %, respectively.

Table 1. Physical and chemical characterization of the 0.00-0.20 m layers of the soils

Soil	Collection site	pH(H_2O)	SOM	Al^{3+}	H+Al	CEC	Clay	Silt	Sand
			g kg^{-1}		cmol$_c$ dm^{-3}			g kg^{-1}	
1	Nova Mutum	4.5	31	0.1	3.1	5.0	40	20	940
2	Rondonópolis	4.5	21	0.1	3.7	6.0	60	50	890
3	Santo Antônio do Leverger	4.7	28	0.3	5.3	7.3	70	100	830
4	Santo Antônio do Leverger	5.2	34	0.1	4.4	6.2	110	20	870
5	Diamantino	5.1	30	0.0	3.0	4.9	180	80	740
6	Cláudia	4.2	24	0.1	4.3	6.4	180	50	770
7	Juscimeira	5.3	37	0.0	3.8	6.7	200	130	670
8	Sinop	4.2	38	0.3	6.4	8.0	210	40	750
9	Juscimeira	5.6	40	0.0	5.1	8.9	240	200	560
10	Sorriso	4.7	39	0.0	7.1	11.0	370	130	500
11	Sorriso	4.7	32	0.3	7.9	10.0	370	50	580
12	Sorriso	5.5	34	0.0	4.2	7.6	410	80	510
13	Sorriso	4.2	38	0.0	7.3	10.9	420	80	500
14	Chapada dos Guimarães	4.8	34	0.0	5.5	6.8	440	230	330
15	Lucas do Rio Verde	4.1	32	0.6	10.0	12.6	440	50	510
16	Lucas do Rio Verde	4.5	55	1.0	13.0	15.7	510	90	400
17	Lucas do Rio Verde	4.2	52	0.2	10.1	13.0	530	110	360
18	Nova Mutum	4.5	41	0.0	8.1	10.9	570	120	310
19	Lucas do Rio Verde	3.9	35	0.1	8.6	12.2	600	90	310
20	Tapurah	4.3	46	0.0	7.8	10.7	620	90	290

SOM: soil organic matter by wet digestion; Al^{3+}: extracted with KCl 1 mol L^{-1}; H+Al: by the SMP solution; CEC: cation exchange capacity at pH 7.0; clay, silt and sand: the pipette method.

Table 2. Chemical characterization of the soils collected in the 0.00-0.20 m layer in the Mato Grosso State, Brazil

Soil	P-M1	P-water	P-rem	Pmax	k	PBC	P recover		Fe-Total	Al-Total
	mg dm^{-3}	mg L^{-1}		mg kg^{-1}		mg dm^{-3}	% Min	% Max	g kg^{-1}	
1	2.7	0.4	52.1	107.8	0.2	1.3	46	98	8.2	6.0
2	5.7	0.1	44.2	128.3	0.9	0.8	62	121	1.4	6.7
3	10.1	0.1	32.1	208.9	1.5	1.3	49	111	1.8	9.8
4	0.9	0.2	40.6	160.8	1.3	2.1	25	64	8.1	23.8
5	0.6	0.1	30.3	213.4	1.1	3.1	10	45	14.7	30.6
6	1.5	0.2	28.4	228.3	1.2	2.0	28	54	5.8	29.1
7	3.6	0.2	24.7	281.9	1.2	3.1	20	60	45.1	13.0
8	1.8	0.3	27.0	320.7	0.9	2.7	22	53	12.8	33.0
9	10.7	0.4	23.2	362.3	1.0	4.4	8	33	66.5	18.6
10	13.1	0.2	18.5	574.6	0.6	3.3	15	40	10.1	92.8
11	1.0	0.2	13.0	1043.8	0.2	3.6	9	45	30.6	71.5
12	0.6	0.4	21.5	562.9	0.7	4.5	8	30	24.0	89.6
13	0.9	0.2	17.2	541.7	2.0	4.1	12	31	32.4	69.8
14	0.4	0.1	4.2	935.9	2.8	9.1	1	16	92.3	138.9
15	1.6	0.3	17.3	615.4	1.2	3.4	9	34	38.8	84.3
16	1.1	0.3	6.7	830.6	1.1	5.5	8	28	3.8	142.6
17	2.2	0.2	11.3	752.0	0.8	5.2	9	27	18.0	119.3
18	0.5	0.2	4.1	902.9	1.9	5.8	5	21	37.4	147.9
19	0.8	0.4	11.3	748.1	1.4	5.0	8	25	35.9	114.3
20	0.7	0.4	18.2	631.3	0.7	3.8	9	31	6.0	147.9

P-M1: P extracted through Mehlich-1; P-water: P soluble in water; P-rem: remaining P; Pmax: maximum capacity of P adsorption; k: adsorption energy; PBC: P buffering capacity; P recover: Minimum and maximum percentage of recover P. Fe-Total and Al-Total: total Fe and Al extracted through the sulfuric attack.

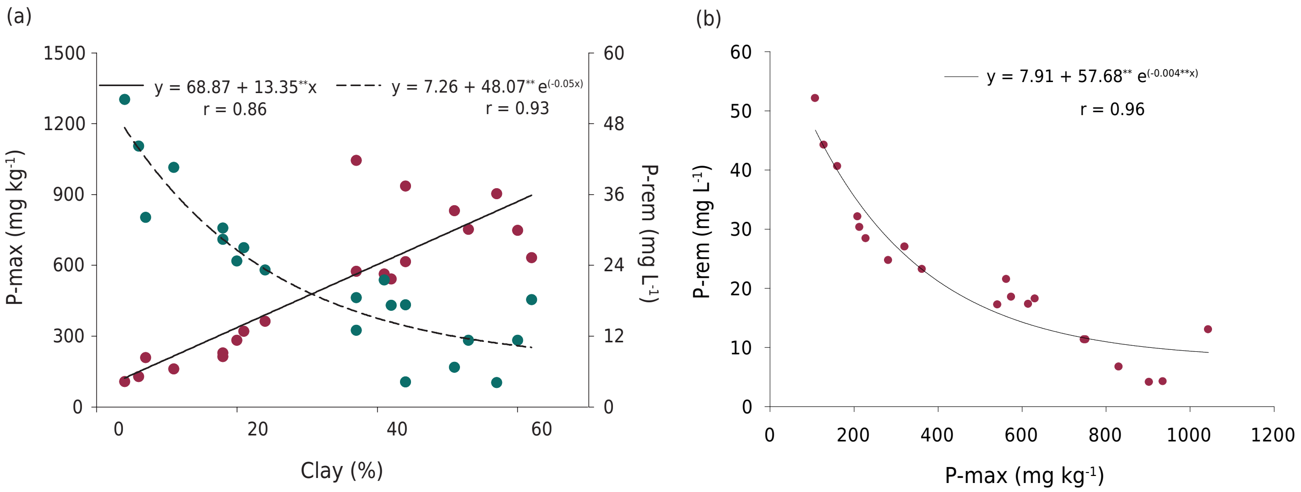

Figure 2. Relations between P-max and clay and P-rem with clay content (a) and P-rem and P-max (b), in soil samples from the Mato Grosso State, Brazil. ** Significant at 1 % error probability.

Clay content of the soils ranged from 4 to 62 %, whereas P-max ranged from 107.8 to 1043.8 mg kg^{-1}. Both, clay content and P-max are highly correlated (Figure 2a), the P-max value increased at a rate of 69 mg kg^{-1} for each percent of clay increase in the soil. The relation between clay content and P adsorption is well-known for Brazilian soils (Campos et al., 2016; Oliveira et al., 2020). However, the clay mineralogy may disturb this relation as the P-max varies widely among minerals (Fink et al., 2014; Gérard, 2016). Thus, in regions with great variation in mineralogy, the clay content may be a poor predictor of P-max (Pinto et al., 2013; Bortoluzzi et al., 2015; Rogeri et al., 2016; Alovisi et al., 2020).

Another method to quantify the P adsorption capacity is the P-rem, in which the results account simultaneously for all P sorption processes, including clay mineralogy (Alvarez et al., 2000; Rogeri et al., 2016). As seen in the figure 2b, there is a correlation between the P-rem and P-max, through the increase in P-max resulting in an exponential reduction of P-rem, with modest variation in soils with P-max higher than 600 g kg^{-1}, consequently suggesting a minimum value of 8 mg L^{-1}. This behavior is associated with exhausting P in the P-rem solution (60 mg L^{-1}). Therefore, the relationship between P-rem and clay also presents a decreasing exponential curve (Figure 2a), meaning that in soil with higher P-max the P-rem solution must be adjusted (Bolster et al., 2020).

These results suggest that in regions with low variability in the soil mineralogy, such as the region studied here (Rosin et al., 2023), the clay content is a good predictor of the P-max (Sanchez, 2019), with the advantage over the P-rem of no needing adjustment for high adsorbing soils. Based on that, the clay content was selected to predict the P-limit of the soil under study.

P-threshold

The P addition to the soils increased P-Mehlich-1 content linearly and the P-water content for all studied soils (Table 3). Additionally, it was able to identify change points in the linear relationship between these variables, indicating instances where the P-water content experienced a sudden increase with the rise of P-Mehlich-1 levels, as exemplified in Figure 3. The P sorption process can be described in two simplified phases; the first consists of the fast P adsorption on the surface of high-affinity sites, which leaves low P in the solution (Muljadi et al., 1996a,b; Barrow, 2015). In the second phase, the sorption of P slows down due to the lower affinity of the partially saturated surface sites, leaving more P in the solution (Muljadi et al., 1996a,b; Barrow, 2015). This reaction may explain the presence of change points in the P-Mehlich-1 and P-water relation, similar to the studies of Gatiboni et al. (2015, 2020), who described the P-threshold model for Santa Catarina and Rio Grande do Sul States, respectively.

Consequently, the determined change points (P-Mehlich-1) represent the limit levels of P (P-limit), in mg dm^{-3}, for the respective soil samples, from which the release of P from soil to water is substantially increased, enhancing the risk of P transfer to the environment (Grando et al., 2021). The P-water reached the P-limit, a range from 0.075 to 0.626 mg L^{-1}, which is equal to or greater than values of 0.075 and 0.064 mg L^{-1} considered detrimental to the environment as eutrophication precursor for streams (Dodds et al., 1998) and reservoir (Cunha et al., 2013). These values were determined for other regions; therefore, research must be carried out to determine these limits for the Mato Grosso State. Besides that, for security reasons, P should not be applied until this limit is reached, as there is an error associated with the change point estimation intrinsic from the statistic method applied (Muggeo, 2003). Thus, it is reasonable to use 80 % of the P-limit as a criterion to establish the P-threshold.

Table 3. Phosphorus extracted as a function of the applied phosphorus rates, values of the change point of the segmented equations for soil samples from the Mato Grosso State, Brazil

Soil	Region 1	Region 2	Change point
			mg dm^{-3}
1	$y = 0.019 + 0.013^{*}x$	$y = -0.063 + 0.018^{*}x$	17
2	$y = 0.010 + 0.010^{*}x$	$y = -0.366 + 0.028^{*}x$	20
3	$y = 0.018 + 0.003^{*}x$	$y = -0.046 + 0.006^{*}x$	19
4	$y = 0.052 + 0.016^{*}x$	$y = -0.390 + 0.036^{*}x$	23
5	$y = 0.063 + 0.005^{*}x$	$y = -0.075 + 0.010^{*}x$	28
6	$y = 0.060 + 0.002^{*}x$	$y = -0.019 + 0.005^{*}x$	28
7	$y = 0.099 + 0.008^{*}x$	$y = -0.035 + 0.013^{*}x$	28
8	$y = 0.100 + 0.010^{*}x$	$y = 0.009 + 0.013^{*}x$	29
9	$y = -0.026 + 0.014^{*}x$	$y = -0.188 + 0.020^{*}x$	30
10	$y = 0.115 + 0.008^{*}x$	$y = 0.144 + 0.007^{*}x$	34
11	$y = 0.012 + 0.010^{*}x$	$y = -0.062 + 0.012^{*}x$	34
12	$y = 0.246 + 0.010^{*}x$	$y = 0.142 + 0.013^{*}x$	38
13	$y = 0.053 + 0.004^{*}x$	$y = -0.123 + 0.008^{*}x$	38
14	$y = 0.160 + 0.005^{*}x$	$y = -0.181 + 0.014^{*}x$	39
15	$y = 0.154 + 0.002^{*}x$	$y = -0.006 + 0.006^{*}x$	42
16	$y = 0.144 + 0.009^{*}x$	$y = 0.094 + 0.009^{*}x$	45
17	$y = 0.076 + 0.005^{*}x$	$y = -0.383 + 0.015^{*}x$	48
18	$y = 0.051 + 0.006^{*}x$	$y = -0.115 + 0.009^{*}x$	49
19	$y = 0.181 + 0.004^{*}x$	$y = -0.004 + 0.008^{*}x$	51
20	$y = 0.079 + 0.005^{*}x$	$y = -0.759 + 0.021^{*}x$	52

Region 1 and Region 2 represent the linear regressions generated by the relationship between P-Mehlich-1 and P-water. The change point represents the value of P-Mehlich-1 in which the levels of P-water enhance abruptly. * significant at 5 % error probability. Note: the determination coefficient (R^2) was greater than 0.98 for all equations.

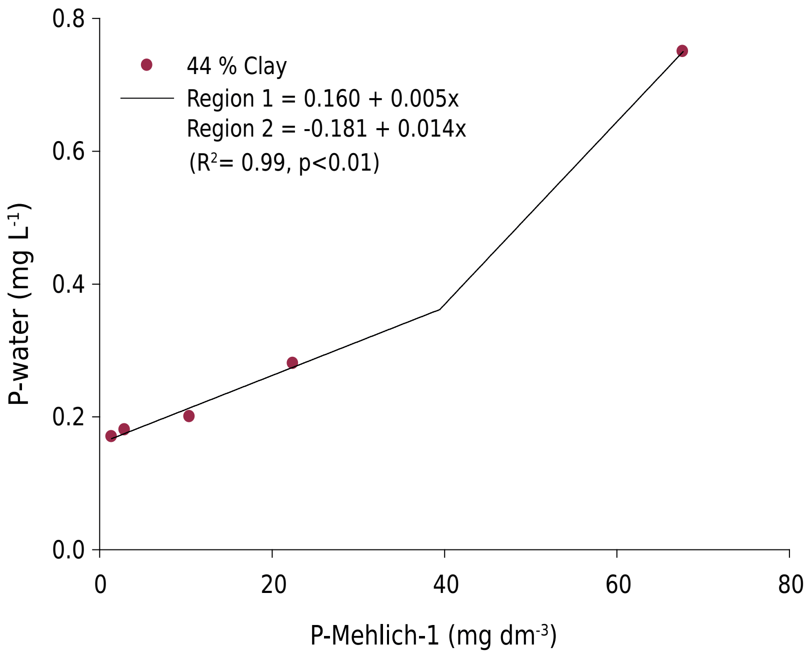

Figure 3. Relationship between P-water and P-Mehlich-1 for the soil 14, exemplifying soils with the significance of segmental equations. The intersection of the equations is the change point value.

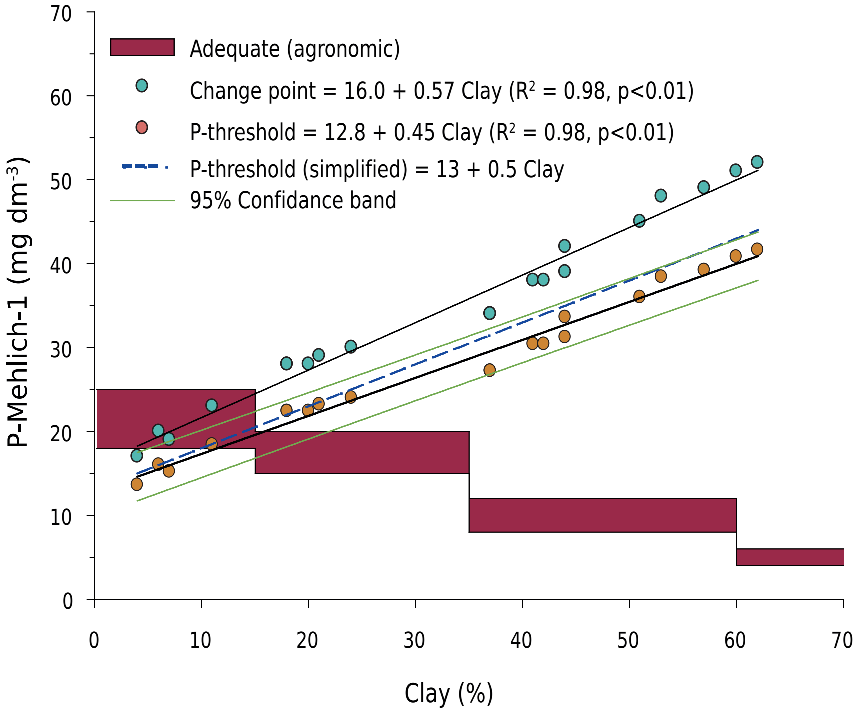

Figure 4. Phosphorus levels assessed by Mehlich-1 extractant at which the P-water rapidly increases upon supplementation with P (change point) and P levels, assessed by Mehlich-1, that are 80 % of the change point (P-threshold). P-threshold simplified is the proposed simplified model to facilitate the calculation of the P-threshold. The values considered adequate for P in the soil for the 0.00 to 0.20 m layer are represented by the green color range (Sousa and Lobato, 2004).

Relating the P-threshold with the soil's clay content confirms the assumption that clayey soil can receive more P addition than sandy soils before an abrupt change in the P release to the water (Figure 4). In other words, in clayey soils, the first phase of P sorption process stands for a wider range of P addition (Gatiboni et al., 2015; Sanchez, 2019). The established P-threshold is denoted by the equation "P-threshold (mg dm^{-3}) = 12.8 + 0.45 * % clay". For practical reasons, it is proposed a simplified P-threshold equation (P-threshold simplified), determined as "P-threshold simplified (mg dm^{-3}) = 13 + 0.5 * % clay" which is within the 95 % confidence interval for the original equation and keep a high determination coefficient (R^2: 0.98). Finally, it should be noted that both indicators were calibrated for the 0.00-0.20 m soil layer, so they must be interpreted considering the soil sampled at this depth. The process presented above agrees with other studies that seek empirical models to describe the environmental soil P threshold that are concomitantly scientific based and user-friendly (Gatiboni et al, 2015, 2020).

Moreover, the figure 4 shows the range of P-Mehlich-1 values considered adequate, from an agronomic point of view, for Cerrado soils under rainfed cultivation (Sousa and Lobato, 2004). Above this range, there is no productivity increase with the use of phosphate fertilizer. For soils with clay content of up to 15 %, the adequate range of P availability for agricultural crops is at approximate values to or even higher than P-threshold and P-limit values. Thus, for these soils, special attention should be paid to the use of phosphate fertilizers (mineral or organic). Hence, the P levels in the soil are close to the lower limit of the appropriate availability class (18 mg dm^{-3}). In addition, it is recommended the mandatory use of soil and crop conservation practices that promote the control of erosion and surface water runoff, mitigating potential P losses in these soils, when exploited agronomically (Grando et al., 2023).

Conversely, for clay-content soils greater than 15 %, the values considered adequate for P in the soil, for the 0.00-0.20 m layer, are below P-threshold and P-limit values. Then, for these soils, P-Mehlich-1 values above the adequate class of P availability can be tolerated, with the condition that these values remain below P-threshold. In this case, there is a low risk of P transfer from soil to water, and so, to the environment, representing a class of safe soil use for P fertilization. However, consecutive applications of phosphate fertilizers (mineral or organic) in amounts greater than the requirements of the cultures intensify the accumulation of P in the soil to values higher than P-threshold (Abdala et al., 2020; Gatiboni et al., 2021), this circumstance must be prevented.

When P levels are above P-threshold and below P-limit, it can be considered that the risk of P losses is increased, and the P fertilization must be limited only to maintenance or replacement of nutrients exported by crops, according to the specific recommendations of the cultures. However, when the P levels in the soil are above P-limit, there is a high risk of P losses to the environment, making it necessary to discontinue phosphate fertilization in these soils. In addition to that, in both situations, mitigation measures must be adopted. The mitigation measures allow the gradual reduction of P levels in the soil, as well as prevent P losses by surface runoff and erosion, preventing the contamination of water resources, such as: emergency soil preparation, incorporation of phosphate fertilizers in the soil (injection of manure), use of crops with high potential for P extraction, soil conservation techniques, riparian strips of P containment, among others (Schoumans et al., 2014; Alewell et al., 2020). Finally, mitigation measures and restrictions on the use of phosphate fertilizers (mineral or organic) must be used until the P levels in the soil are below P-threshold.

In summary, the figure 5 confirms the validation of the P-threshold model for soil samples from Mato Grosso State, according to the proposed model. Hence, there was a significant exponential adjustment between the levels of P-Mehlich-1 and P-water, indicating that from a certain P level in the soil there is a considerable P release into the soil solution, increasing the risk of P losses by runoff and environmental contamination of water resources (Figure 5a). Therefore, the range of P values from which the P release into the soil solution is increased ranges from 20 to 50 mg dm^{-3} of P-Mehlich-1, consistent with the P-limit values (Figure 4). Finally, it should be noted that the model was able to separate the samples into two groups, classified as below or above the P-threshold, represented by the P-water of 0.38 mg L^{-1} with minimal intersection between them (Figures 5a and 5b). However, despite the efficiency of separating soils, our model should not be the only strategy used to mitigate losses. Since this value was 5.1 and 5.9 times greater than those observed for the eutrophication for streams (Dodds et al., 1998) and reservoir (Cunha et al., 2013), respectively.

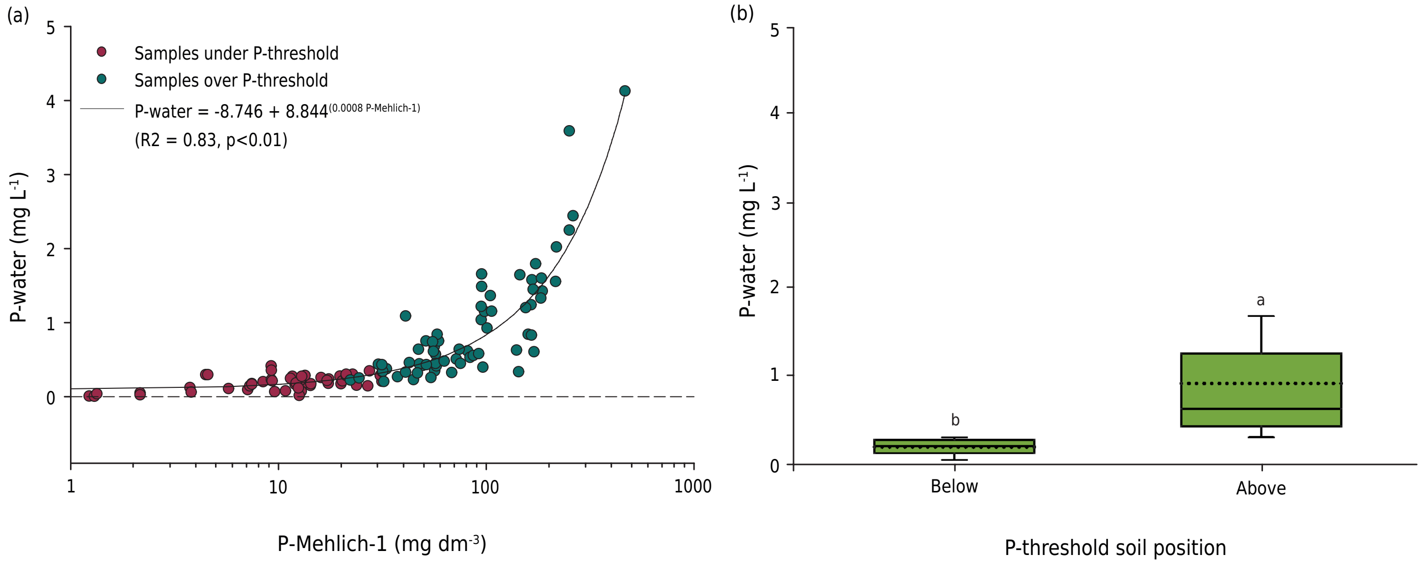

Figure 5. Validation of the P-threshold model for 118 soil samples (a), considering differences in P-water concentrations (b), from the Mato Grosso State, Brazil.

It is worth mentioning, even though it has been accurate to estimate the P solubility in the soil, one of the major factors affecting its transfer from agricultural land to contiguous environments (Heathwaite et al., 2005), the P-threshold approach has limitations in describing all the transfer process (Koopmans et al., 2002; Sharpley et al., 2012). This approach does not account for P transport factors and for characteristics of the receiving water bodies, even so, it represents a first step in the construction of a more robust model to describe the P transfer process. Example given, the study of Dall'Orsoletta et al. (2020), who included the soil slope as a P transport factor in the previous P-threshold model for Santa Catarina State. In this sense, future research may focus on generated local data regarding P transport from agricultural lands to water bodies and the water bodies' capacity to support P addition without harmful effects.

CONCLUSION

Critical environmental limit of phosphorus (P-threshold) for soils in the Mato Grosso State is represented by the equation: "P-threshold = 13 + 0.5 * % clay"; whereas P-threshold is the maximum P content of the soil extracted by the Mehlich-1 method in mg dm^{-3}, and "clay" is the amount of clay determined by the pipette method, in percentage.

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REFERENCES

Abboud FY, Favaretto N, Motta ACV, Barth G, Goularte GD. Phosphorus mobility and degree of saturation in Oxisol under no-tillage after long-term dairy liquid manure application. Soil Till Res. 2018;177:45-53. https://doi.org/10.1016/j.still.2017.11.014

Abdala DB, Gatiboni LC, Schmitt DE, Mumbach GL, Dall’Orsoletta DJ, Bonfada EB, Veiga M. Phosphorus speciation and iron mineralogy in an Oxisol after 11 years of pig slurry application. Sci Total Environ. 2020;743:140487. https://doi.org/10.1016/j.scitotenv.2020.140487

Alewell C, Ringeval B, Ballabio C, Robinson DA, Panagos P, Borrelli P. Global phosphorus shortage will be aggravated by soil erosion. Nat Commun. 2020;11:4546. https://doi.org/10.1038/s41467-020-18326-7

Alovisi AMT, Cassol CJ, Nascimento JS, Soares NB, Silva Junior IR, Silva RS, Silva JAM. Soil factors affecting phosphorus adsorption in soils of the Cerrado, Brazil. Geoderma Reg. 2020;22:e00298. https://doi.org/10.1016/j.geodrs.2020.e00298

Alvarez V VH, Novais RF, Dias LE, Oliveira JA. Determinação e uso do fósforo remanescente. Boletim Informativo da Sociedade Brasileira de Ciência do Solo. 2000;25:27-32.

Anghinoni I, Bohnen H. Avaliação da disponibilidade do fósforo para solos do Rio Grande do Sul. Agronomia Sulriograndense. 1974;10:127-36.

Associação Brasileira de Proteína Animal - ABPA. Relatório anual 2022. São Paulo: ABPA; 2022 [cited 2022 Nov 14]. Available from: https://abpa-br.org/wp-content/uploads/2022/05/Relatorio-Anual-ABPA-2022-1.pdf.

Barrow NJ. Soil phosphate chemistry and the P-sparing effect of previous phosphate applications. Plant Soil. 2015;397:401-9. https://doi.org/10.1007/s11104-015-2514-5

Boitt G, Schmitt DE, Gatiboni LC, Wakelin SA, Black A, Sacomori W, Cassol PC, Condron LM. Fate of phosphorus applied to soil in pig slurry under cropping in southern Brazil. Geoderma. 2018;321:164-72. https://doi.org/10.1016/j.geoderma.2018.02.010

Bolster CH, McGrath JM, Rosso E, Blombäck K. Evaluating the effectiveness of the phosphorus sorption index for estimating maximum phosphorus sorption capacity. Soil Sci Soc Am J. 2020;84:994-1005. https://doi.org/10.1002/saj2.20078

Bortoluzzi, EC, Pérez CAS, Ardisson JD, Tiecher T, Caner L. Occurrence of iron and aluminum sesquioxides and their implications for the P sorption in subtropical soils. Appl Clay Sci. 2015;104:196-204. https://doi.org/10.1016/j.clay.2014.11.032

Campos M, Antonangelo JA, Alleoni LRF. Phosphorus sorption index in humid tropical soils. Soil Till Res. 2016;156:110-8. https://doi.org/10.1016/j.still.2015.09.020

Cassidy R, Doody DG, Watson CJ. Impact of legacy soil phosphorus on losses in drainage and overland flow from grazed grassland soils. Sci Total Environ. 2017;575:474-84. https://doi.org/10.1016/j.scitotenv.2016.07.063

Cunha DGF, Calijuri MC, Lamparelli MC. A trophic state index for tropical/subtropical reservoirs (TSItsr). Ecol Eng. 2013;60:126-34. https://doi.org/10.1016/j.ecoleng.2013.07.058

Dall’Orsoletta DJ, Gatiboni LC, Mumbach GL, Schmitt DE, Boitt G, Smyth TJ. Soil slope and texture as factors of phosphorus exportation from pasture areas receiving pig slurry. Sci Total Environ. 2020;761:144004. https://doi.org/10.1016/j.scitotenv.2020.144004

Dhillon J, Torres G, Driver E, Figueiredo B, Raun WR. World phosphorus use efficiency in cereal crops. Agron J. 2017;109:1670-7. https://doi.org/10.2134/agronj2016.08.0483

Dodds WK, Jones JR, Welch EB. Suggested classification of stream trophic state: distributions of temperate stream types by chlorophyll, total nitrogen, and phosphorus. Water Res. 1998;32:1455-62. https://doi.org/10.1016/S0043-1354(97)00370-9

Fink JR, Inda AV, Bayer C, Torrent J, Barrón V. Mineralogy and phosphorus adsorption in soils of south and central-west Brazil under conventional and no-tillage systems. Acta Sci Agron. 2014;36:379-87. https://doi.org/10.4025/actasciagron.v36i3.17937

Gatiboni LC, Brunetto G, Kaminski J, Rheinheimer DS, Ceretta CA, Basso CJ. Formas de fósforo no solo após sucessivas adições de dejeto líquido de suínos em pastagem natural. Rev Bras Cienc Solo. 2008;32:1753-61. https://doi.org/10.1590/S0100-06832008000400040

Gatiboni LC, Nicoloso RS, Mumbach GL, Souza Junior AA, Dall'Orsoleta DJ, Schmitt DE, Smyth TJ. Establishing environmental soil phosphorus thresholds to decrease the risk of losses to water in soils from Rio Grande do Sul, Brazil. Rev Bras Cienc Solo. 2020;44:e0200018. https://doi.org/10.36783/18069657rbcs20200018

Gatiboni LC, Smyth TJ, Schmitt DE, Cassol PC, Oliveira CMB. Soil phosphorus thresholds in evaluating risk of environmental transfer to surface waters in Santa Catarina, Brazil. Rev Bras Cienc Solo. 2015;39:1225-34. https://doi.org/10.1590/01000683rbcs20140461

Gatiboni LC, Souza Junior AA, Dall'Orsoletta DJ, Mumbach GL, Kulesza SB, Abdala DB. Phosphorus speciation in soils with low to high degree of saturation due to swine slurry application. J Environ Manage. 2021;282:111553. https://doi.org/10.1016/j.jenvman.2020.111553

Gérard F. Clay minerals, iron/aluminum oxides, and their contribution to phosphate sorption in soils - A myth revisited. Geoderma. 2016;262:213-26. https://doi.org/10.1016/j.geoderma.2015.08.036

Goedert WJ. Management of the Cerrado soils of Brazil: A review. J Soil Sci. 1983;34:405-28. https://doi.org/10.1111/j.1365-2389.1983.tb01045.x

Grando DL, Gatiboni LC, Mumbach GL, Dall'Orsoletta DJ, Souza Junior AA, Schmitt DE. Phosphorus in the runoff of soils with contrasting textures influenced by soil slope and pig slurry application. Agr Water Manage. 2021;258:107178. https://doi.org/10.1016/j.agwat.2021.107178

Grando DL, Gatiboni LC, Mumbach GL, Silva WC, Souza Junior AA, Pietroski M, Pessoto PP, Iochims DA. Slope and pig slurry rate may increase the transfer of chemical elements by surface water runoff. Environ Qual Manage. 2023;32:281-92. https://doi.org/10.1002/tqem.22004

Gypser S, Hirsch F, Schleicher AM, Freese D. Impact of crystalline and amorphous iron-and aluminum hydroxides on mechanisms of phosphate adsorption and desorption. J Environ Sci. 2018;70:175-89. https://doi.org/10.1016/j.jes.2017.12.001

Heathwaite AL, Sharpley A, Bechmann M, Rekolainen S. Assessing the risk and magnitude of agricultural nonpoint source phosphorus pollution. In: Sims JT, Sharpley AN, editors. Phosphorus: agriculture and the environment. Madison: ASA/CSSA/SSSA; 2005. p. 981-1020.

Instituto do Meio Ambiente - IMA. Instrução Normativa Nº 11: Suinocultura. Florianópolis: IMA; 2022 [cited 2023 Fev 02]. Available from: https://in.ima.sc.gov.br/.

Instituto Mato-Grossense de Economia Agropecuária - IMEA. Projeções do agronegócio em Mato Grosso para 2025. Cuiabá: IMEA; 2023 [cited 2023 Jan 25]. Available from: http://sistemafamato.org.br/portal/arquivos/01122015043104.12.2015.pdf.

Kleinman PJA, Bryant RB, Reid WS, Sharpley AN, Pimentel D. Using soil phosphorus behaviour to identify environmental thresholds. Soil Sci. 2000;165:943-50. https://doi.org/10.1097/00010694-200012000-00004

Kleinman PJA, Sharpley AN, Withers PJA, Bergström L, Johnson LT, Doody DG. Implementing agricultural phosphorus science and management to combat eutrophication. Ambio. 2015;44:297-310. https://doi.org/10.1007/s13280-015-0631-2

Koopmans GF, McDowell RW, Chardon WJ, Oenema O, Dolfing J. Soil phosphorus quantity-intensity relationships to predict increased soil phosphorus loss to overland and subsurface flow. Chemosphere. 2002;48:679-87. https://doi.org/10.1016/S0045-6535(02)00146-7

Motta ACV, Melo VF. Química dos solos ácidos. In: Melo VF, Alleoni LRF, editors. Química e mineralogia do solo: conceitos básicos e aplicações. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2019. p. 1009-76.

Muggeo VMR. Estimating regression models with unknown break-points. Stat Med. 2003;22:3055-71. https://doi.org/10.1002/sim.1545

Muljadi D, Posner AM, Quirk JP. The mechanism of phosphate adsorption by kaolinite, gibbsite, and pseudoboehrnite. Part I. The isotherms and the effect of pH on adsorption. J Soil Sci. 1966a;17:222-9.

Muljadi D, Posner AM, Quirk JP. The mechanism of phosphate adsorption by kaolinite, gibbsite, and pseudoboehrnite. Part II. The location of the adsorption sites. J Soil Sci. 1966b;17:230-7.

Murphy J, Riley JP. A modified single solution method for determination of phosphate in natural waters. Anal Chim Acta. 1962;27:31-6. https://doi.org/10.1016/S0003-2670(00)88444-5

Nair VD. Soil phosphorus saturation ratio for risk assessment in land use systems. Front Environ Sci. 2014;2:6. https://doi.org/10.3389/fenvs.2014.00006

Oliveira JS, Inda AV, Barrón V, Torrent J, Tiecher T, Camargo FAO. Soil properties governing phosphorus adsorption in soils of Southern Brazil. Geoderma Regional. 2020;22:e00318. https://doi.org/10.1016/j.geodrs.2020.e00318

Panagos P, Köningner J, Ballabio C, Liakos L, Muntwyler A, Borrelli P, Lugato E. Improving the phosphorus budget of European agricultural soils. Sci Total Environ. 2022;853:158706. https://doi.org/10.1016/j.scitotenv.2022.158706

Penn CJ, Camberato JJ. A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. Agriculture. 2019;9:120. https://doi.org/10.3390/agriculture9060120

Pinto FA, Souza ED, Paulino HB, Curi N, Carneiro MAC. P-sorption and desorption in Savanna Brazilian soils as a support for phosphorus fertilizer management. Cienc Agrotec. 2013;37:521-30. https://doi.org/10.1590/S1413-70542013000600005

Rodrigues M, Pavinato PS, Withers PJA, Teles APB, Herrera WFB. Legacy phosphorus and no tillage agriculture in tropical oxisols of the Brazilian savanna. Sci Total Environ. 2016;542:1050-61. https://doi.org/10.1016/j.scitotenv.2015.08.118

Rogeri DA, Gianello C, Bortolon L, Amorim MB. substitution of clay content for P-remaining as an index of the phosphorus buffering capacity for soils of Rio Grande do Sul. Rev Bras Cienc Solo. 2016;40:e0140535. https://doi.org/10.1590/18069657rbcs20140535

Rosin NA, Demattê JAM, Poppiel RR, Silvero NEQ, Rodriguez-Albarracin HS, Rosas JTF, Greschuk LT, Bellinaso H, Minasny B, Gomez C, Marques Júnior J, Fernandes K. Mapping Brazilian soil mineralogy using proximal and remote sensing data. 2023;432:116413. https://doi.org/10.1016/j.geoderma.2023.116413

Roy ED, Richards PD, Martinelli LA, Coletta LD, Lins SRM, Vazquez FF, Willig E, Spera SA, VanWey LK, Porder S. The phosphorus cost of agricultural intensification in the tropics. Nat Plants. 2016;2:16043. https://doi.org/10.1038/nplants.2016.43

Roy ED, Willig E, Richards PD, Martinelli LA, Vazquez FF, Pegorini L, Spera SA, Porder S. Soil phosphorus sorption capacity after three decades of intensive fertilization in Mato Grosso, Brazil. Agr Ecosyst Environ. 2017;249:206-14. https://doi.org/10.1016/j.agee.2017.08.004

Sanchez PA. Properties and management of soils in the tropics. 2nd ed. Cambridge: Cambridge University Press; 2019.

Schindler DW, Carpenter SR, Chapra SC, Hecky RE, Orihel DM. Reducing phosphorus to curb lake eutrophication is a success. Environ Sci Technol. 2016;50:8923-9. https://doi.org/10.1021/acs.est.6b02204

Schoumans OF, Chardon WJ, Bechmann ME, Gascuel-Odoux C, Hofman G, Kronvang B, Rubæk GH, Ulén B, Dorioz JM. Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review. Sci Total Environ. 2014;468:1255-66. https://doi.org/10.1016/j.scitotenv.2013.08.061

Sharpley A, Beegle D, Bolster C, Good L, Joern B, Ketterings Q, Lory J, Mikkelsen R, Osmond D, Vadas P. Phosphorus indices: Why we need to take stock of how we are doing. J Environ Qual. 2012;41:1711-9. https://doi.org/10.2134/jeq2012.0040

Sharpley A, Kleinman P, Baffaut C, Beegle D, Bolster C, Collick A, Easton Z, Lory J, Nelson N, Osmond D, Radcliffe D, Veith T, Weld J. Evaluation of phosphorus site assessment tools: Lessons from the USA. J Environ Qual. 2017;46:1250-6. https://doi.org/10.2134/jeq2016.11.0427

Sousa DMG, Lobato E. Cerrado: correção do solo e adubação. 2. ed. Brasília, DF: Embrapa Informação Tecnológica; Planaltina, DF: Embrapa Cerrados, 2004.

Sousa DMG, Nunes RS, Rein TA, Santos Junior JDG. Manejo do fósforo na região do Cerrado. In: Rilner AF, Cunha PP, editors. Práticas de manejo do solo para adequada nutrição de plantas no Cerrado. Goiânia: UFG; 2016. p. 291-358.

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. Manual de métodos de análise de solo. 3. ed. rev e ampl. Brasília, DF: Embrapa; 2017.

Withers PJA, Rodrigues M, Soltangheisi A, Carvalho TS, Guilherme LRG, Benites VM, Gatiboni LC, Sousa DMG, Nunes RS, Rosolem CA, Andreote FD, Oliveira Jr A, Coutinho ELM, Pavinato PS. Transitions to sustainable management of phosphorus in Brazilian agriculture. Sci Rep. 2018;8:2537. https://doi.org/10.1038/s41598-018-20887-z

Withers PJA, Vadas PA, Uusitalo R, Forber KJ, Hart M, Foy RH, Delgado A, Dougherty W, Lilja H, Burkitt LL, Rubæk GH, Pote D, Barlow K, Rothwell S, Owens PR. A global perspective on integrated strategies to manage soil phosphorus status for eutrophication control without limiting land productivity. J Environ Qual. 2019;48:1234-46. https://doi.org/10.2134/jeq2019.03.0131

Zhang W, Jin X, Liu D, Lang C, Shan B. Temporal and spatial variation of nitrogen and phosphorus and eutrophication assessment for a typical arid river - Fuyang River in northern China. J Environ Sci. 2017;55:41-8. https://doi.org/10.1016/j.jes.2016.07.004