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Monitoring of phosphorus levels in soils with long-term application of swine manure

Monitoramento dos níveis de fósforo em solos com aplicação prolongada de dejetos suínos

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ABSTRACT: Continuous applications of liquid swine manure (LSM) in soil can result in high phosphorus (P) contents, especially in surface layers. Excess amounts of this nutrient can be transferred from soil to surface water and contaminate aquatic systems, causing eutrophication problems. To avoid such problems, the objective was to evaluate the environmental critical limit of phosphorus (ECL-P) of the soil of 89 farms with long-term LSM fertilization in Rio Verde-GO, Brazil. In the first stage, the clay and available P contents in the soils were surveyed through the results of soil analysis of pig farms in the region with a history of LSM application for 16 years. Then, the soils were classified according to the P level (very low, low, medium, adequate and high) according to the clay contents. In the second part, ECL-P was applied to the farms. In 32 soils, the P level was considered high, more than 12 mg dm^{-3}. At this level, it was observed that 14 soils exceeded the ECL-P, of which 12 suggested the immediate suspension of P application, as there is a high risk of P losses to water. Only in two farms was the ECL-P exceeded by less than 20 %; therefore, it is recommended to reduce the application of P sources and the use of techniques to reduce the levels of P in these soils. Although beneficial, organic fertilization can exceed adequate limits, which reinforces the need to monitor areas with long periods of fertilization with LSM.

Keywords: Environmental critical limit of phosphorus; Liquid swine manure; Oxisols; Soil phosphorus.

RESUMO: Aplicações contínuas de dejeto líquido de suínos (DLS) no solo podem resultar em altos teores de fósforo (P), especialmente nas camadas superficiais. Quantidades excessivas desse nutriente podem ser transferidas do solo para a água superficial e contaminar os sistemas aquáticos, causando problemas de eutrofização. Visando evitar tais problemas, objetivou-se avaliar limite crítico ambiental de fósforo (LCA- P) do solo de 89 fazendas adubadas com DLS a longo prazo na região de Rio Verde-Goiás. Na primeira etapa, os teores de argila e de P disponível nos solos foram levantados por meio dos resultados de análises de solo de granjas suinícolas da região com histórico de aplicação de DLS durante 16 anos. Em seguida, os solos foram classificados de acordo com o nível de P (muito baixo, baixo, médio, adequado e alto), conforme os teores de argila. Na segunda parte, o LCA-P foi aplicado às propriedades. Em 32 solos, o nível de P foi considerado alto, mais de 12 mg dm^{-3}. Nesse nível, observou-se que 14 solos excederam o LCA-P, dos quais 12 é sugerida a suspensão imediata da aplicação de P, pois há um alto risco de perdas de P para a água. Apenas em duas fazendas o LCA-P excedeu em menos de 20%; portanto, recomenda-se reduzir a aplicação de fontes de P e utilizar técnicas para reduzir os níveis de P nesses solos. Embora a fertilização orgânica seja benéfica, ela pode exceder os limites adequados, o que reforça a necessidade de monitorar áreas com longos períodos de fertilização com DLS.

Palavras-chave: Limite crítico ambiental de fósforo; Esterco líquido de suínos; Latossolos; Fósforo do solo.

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1 INTRODUCTION

Soils in the Brazilian Cerrado, generally, have an acidic pH, high aluminum content and low availability of nutrients (Ferreira *et al*., 2022; Oliveira *et al*., 2023), which limits agricultural production (Araujo *et al*., 2022; Prates *et al*., 2022). Thus, the use of fertilization, especially phosphate, is recurrent because P is a nutrient that is present at very low concentrations in these regions. P plays an important role in the processes of cell division and growth, photosynthesis, respiration, energy storage and transfer (Horta, 2015; Stigter and Plaxton, 2015; Withers *et al*., 2016; Hafiz *et al*., 2022).

Fertilization is performed through different sources, the most common being phosphate fertilizers, such as monoammonium phosphate, single super-phosphate and triple superphosphate, and agro-industrial residues, such as swine manure and poultry litter (Oliveira *et al*., 2020; Singh *et al*., 2021). About 2.0 billion tons of agricultural waste are generated globally each year, with an estimated average increase rate of 5 to 10% per year (Horta, 2015). Swine manure has become an alternative to phosphate fertilization due to the high P content in its composition. However, continuous use without technical recommendations may exceed the P adsorption capacity of the region's soils, and loss to the springs may occur (Gatiboni *et al*., 2020).

Excess P can be transferred from soil to surface water and contaminate aquatic systems present in the ecosystem, causing problems with eutrophication and thus decreasing water quality (Khan and Mohammad, 2014). This situation is not as common due to the high cost of mineral phosphate fertilizers, which limits the availability of excess P to the soil. However, with the availability of waste, this problem becomes more common, and the complications can be greater if liquid swine manure (LSM) is applied successively in the same place and in quantities greater than the requirements of the planted crop.

Thus, it is important to monitor the P contents of farms with swine manure applications. Monitoring can be done through the evaluation of the environmental critical limit of phosphorus (ECL-P). ECL-P is a predefined equation for each region of Brazil and is aimed at calculating the limit content of P present in the soil that will not interfere in surface waters and consequently in watersheds (Gatiboni *et al*., 2020). Therefore, the objective was to evaluate the ECL-P of the soil of 89 pig farms in the region of Rio Verde, GO, Brazil, which have been fertilizing the soil with LSM for approximately 16 years.

2 MATERIALS AND METHODS

2.1 SURVEY OF CLAY AND PHOSPHORUS CONTENTS

The study was conducted from April 2020 to May 2021. The soils of 89 pig farms located in Rio Verde, Goiás, Brazil, and its surroundings (Figure 1), of the Farrow-to-wean systems (FWS – from birth to 27 kg piglets) and Wean-to-finish systems (WFS- fattening system from 27 to 100 kg) were collected. The soils had a history of sprinkler application of approximately 180 m^3 ha^{-1} per year of LSM for 16 years. The average P concentration in LSM is 0.14 kg m^{-3}. The samples of the soils were subjected to physicochemical analyses to quantify P and clay contents. Soils in this region are generally classified as Oxisols (Ferreira *et al*., 2022). P was extracted according to the method described by Tedesco *et al*. (1995) and Franklin *et al*. (2006).

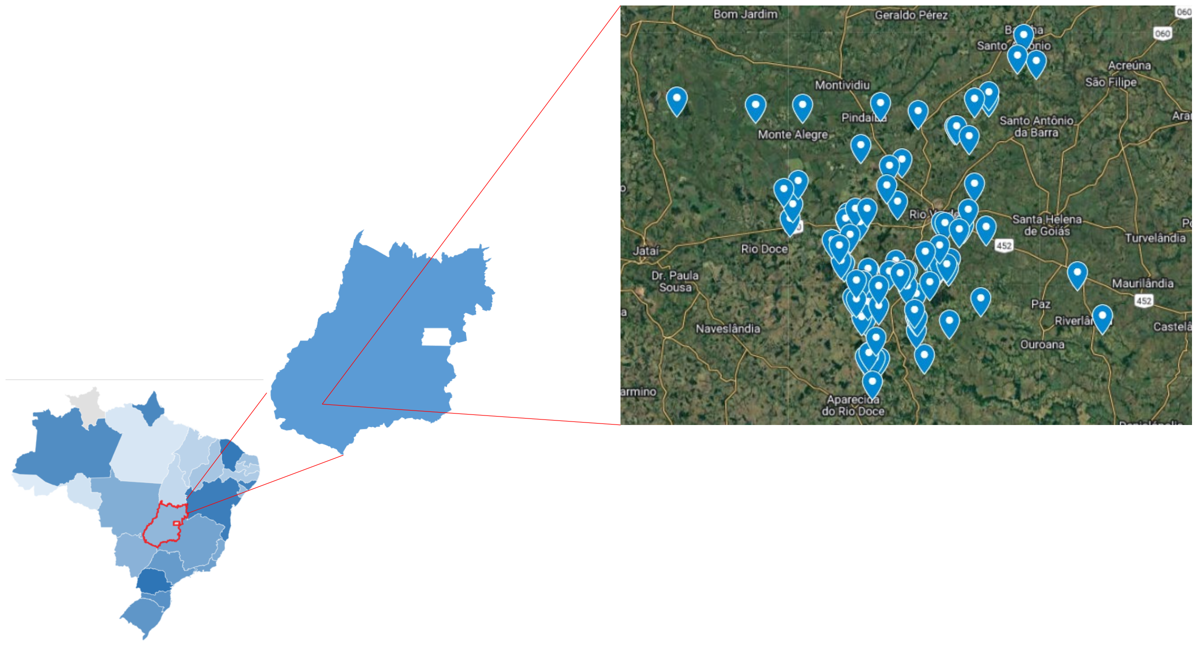

Figure 1. Location of farms where soil P and clay content analyses were carried out

During the environmental licensing process of each farm, soil samples were taken from each farm. The soils that received annual swine manure were divided into homogeneous areas, and 20 single samples of the same volume were randomly collected in each area. The single samples were taken uniformly with a probe at a depth of 20 cm, covering the entire length of the area. This process was repeated at all sampling points within each homogeneous area until the entire farm was sampled. Finally, the soil from the bucket was pounded to break up clods and homogenized to form a composite sample of around 500 g. This sample was sent to the laboratory for P and clay analysis.

The soil samples were scooped with volume of 5 dm^{-3}, and 50 mL of Mehlich^{-1} extractant solution was used. The samples were stirred for 5 minutes on a horizontal shaker with 120 oscillations per minute, followed by decantation for 16 hours. P content in the extract was determined by UV/Vis molecular absorption spectrometry (colorimetry) at 660 nm (Tedesco *et al*., 1995). Clay content was determined following the granulometric method (Teixeira *et al*., 2017).

The data on the farms and the chemical composition of swine manure (1.3, 0.8, 1.0, 12.2 and 1,008 kg m^{-3} of N, P, K, Dry Matter and density, respectively) where the soils were collected were made available by the Municipal Secretariat of the Environment of Rio Verde, GO. After the analyses, the P contents were classified into very low, low, medium, adequate and high levels according to the clay contents of each property (Table 1).

Table 1. Interpretation of soil analysis for P (Mehlich-1) contents according to clay content and recommendation of corrective P fertilization for annual crops as P availability in savannah soils

Clay content	Soil P content (mg dm^{-3})				
(g kg^{-1})	Very low	Low	Medium	Adequate	High
< 150	< 6.0	6.1 to 12.0	12.1 to 18.0	18.1 to 25.0	> 25.0
160 to 350	< 5.0	5.1 to 10.0	10.1 to 15.0	15.1 to 20.0	> 20.0
360 to 600	< 3.0	3.1 to 5.0	5.1 to 8.0	8.1 to 12.0	> 12.0
> 600	< 2.0	2.1 to 3.0	3.1 to 4.0	4.1 to 6.0	> 6.0

Source: Adapted from Souza and Lobato (2004).

2.2 ENVIRONMENTAL CRITICAL LIMIT OF PHOSPHORUS (ECL-P)

The methodology of the ECL-P defined for Cerrado soils was applied: ECL-P (mg dm^{-3}) = 20 + 0.5 x clay (%) (Hemielevski *et al.*, 2025). After the definition of the ECL-P, the contents were classified as adequate and not adequate, with soils below the ECL-P considered adequate and soils above the ECL-P considered inadequate according to the P and clay contents of the soil analysis of each property. Following the levels determined in Normative Instruction 11, about environmental rows of pig farming of the South Region of Brazil (FATMA, 2014), recommendations were made to limit or suspend P applications in soils until the levels were adequate for the ECL-P.

2.3 STATISTICAL ANALYSIS

The data of the P and clay contents were subjected to descriptive statistical analysis to obtain the means and standard deviation according to the classification of the P levels and simple linear regression analysis to verify the relationship between the P contents and clay contents as methods for interpreting the results using the SISVAR program (Ferreira, 2019).

3 RESULTS AND DISCUSSION

Of the 89 farms evaluated, 36, 23, 23 and 7 had sandy, medium, clayey and very clayey textures, respectively (Table 2). 14 farms exceeded the ECL-P (6, 18, 24, 25, 28, 32, 35, 36, 40, 49, 50, 54, 67 and 81), which represents 16% of the total, of which 12 had sandy texture (0-15% clay) and two had medium texture (16-35% clay). Of the 14 farms that exceeded the ECL-P, 12 had ECL-P levels above 20% of the adequate level, and immediate interruption of the application of P sources was recommended. In areas where ECL-P levels are below 20% of adequate, it is recommended to use only 50% of the recommended dose of phosphate fertilization for the crop to be planted in the area (FATMA, 2014). It is important to emphasize that, for all soils in which the ECL-P was higher than the critical level of the plants, the reduction in fertilization will not result in a loss of production potential, because P is present in the soil.

Excess P in the environment can have negative effects, especially on water quality. The presence of high concentrations of nutrients stimulates the growth of algae and plants, interfering with the use of drinking water, and may increase P concentration in the water, causing oxygen depletion and ecological imbalance (Jia *et al*., 2023; Xu *et al*., 2023).

Clay contents were very variable among the sampled farms (Table 2), ranging from 2% (sandy soil) to 72% (very clayey soil). The textural class of the soil has a direct effect on the availability of P (Corbett *et al*., 2023). It is observed that the higher the clay content, the lower the P content, which is due to the higher P sorption capacity in clayey soils.

Table 2. Phosphorus (P) and clay contents, and environmental critical limit of phosphorus (ECL-P) calculated by the formula: ECL-P = 20 + 0.5 x clay (%) (Hemielevski *et al*., 2025) of the 89 farms

Farm	P (mg dm^{-3})	Clay (%)	ECL-P (mg dm^{-3})	Farm	P (mg dm^{-3})	Clay (%)	ECL-P (mg dm^{-3})	Farm	P (mg dm^{-3})	Clay (%)	ECL-P (mg dm^{-3})
1	11.1	59	49.5	31	5.8	49	44.5	61	23.1	42	41.0
2	11.4	15	27.5	32	115.7	13	26.5	62	2.1	67	53.5
3	1.3	7	23.5	33	0.7	33	36.5	63	8.1	8	24.0
4	42.4	58	49.0	34	23.1	8	24	64	23.7	42	41.0
5	13.6	14	27.0	35	62.2	6	23	65	2.1	17	28.5
6	59.3	10	25.0	36	51.3	12	26	66	14.3	61	50.5
7	1.7	24	32.0	37	14.5	14	27	67	33.5	3	21.5
8	2.3	11	25.5	38	35.7	43	41.5	68	6.7	40	40.0
9	8.9	20	30.0	39	4.9	45	42.5	69	18.6	56	48.0
10	14.9	72	56.0	40	54.2	3	21.5	70	19.3	69	54.5
11	8.4	31	35.5	41	2.4	46	43	71	15.6	28	34.0
12	2.6	12	26.0	42	7.7	18	29	72	3.4	21	30.5
13	2.2	30	35.0	43	8.8	8	24	73	1.6	17	28.5
14	28	21	30.5	44	2.0	34	37	74	2.3	13	26.5
15	3.7	53	46.5	45	16.3	6	23	75	5.5	10	25.0
16	9.5	59	49.5	46	2.3	28	34	76	12.1	57	48.5
17	7.0	68	54.0	47	15.7	7	23.5	77	4.2	37	38.5
18	31.4	13	26.5	48	1.9	18	29	78	2.7	56	48.0
19	12.4	21	30.5	49	76.2	7	23.5	79	2.35	58	49.0
20	22.9	9	24.5	50	31.6	23	31.5	80	12.9	60	50.0
21	8.0	7	23.5	51	18.1	65	52.5	81	46.09	16	28.0
22	9.1	6	23.0	52	30.9	34	37	82	1.84	8	24.0
23	4.3	9	24.5	53	7.7	27	33.5	83	3.92	12	26.0
24	43.0	13	26.5	54	37.2	13	26.5	84	7.21	5	22.5
25	68.8	6	23.0	55	8.2	7	23.5	85	11.72	27	33.5
26	3.3	8	24.0	56	2.7	43	41.5	86	1.35	51	45.5
27	2.1	7	23.5	57	1.4	33	36.5	87	0.18	16	28.0
28	31.5	2	21.0	58	25.0	60	50	88	1.65	59	49.5
29	28.6	37	38.5	59	5.1	30	35	89	0.91	72	56.0
30	1.4	8	24.0	60	20.9	40	40	-	-	-	-

The variation in the clay contents is justified by the different locations of the farms analyzed, located within a radius of 70 km from the town of Rio Verde. In addition, the type of clay also influences the retention of P in the soil (Chen *et al*., 2023), and most soils of the savannah have nonsilicate clay with a high concentration of Fe and Al oxides due to high weathering (Rolim Neto *et al*., 2004).

The adoption of strategies to avoid environmental problems caused by excess P is fundamental and necessary. The implementation of these strategies can avoid contamination of water sources, as well as helping in areas that have already exceeded the ECL-P and should reduce nutrient levels. Some suggestions for mitigating the environmental problem of P excess are the adoption of preventive and conservative practices.

Another technique to control P levels in the soil is to follow the recommendation of the manure dose to be applied based on the P content of the residue. The rate of manure application to meet P demand is usually half the dose that would be applied based on the N content of the waste. When the soil has P contents within the very low to medium ranges, LSM can be applied in quantities greater than the demand of the crop, but when the P content in the soil is equal to or higher than adequate and/or high, the manure recommendation should take into account the nutritional demand of P by the crop (Corrêa *et al*., 2011). If the P content in the soil is twice the maximum (high) level, the manure recommendation should be made with caution, giving priority to nonapplication in the soil. In the latter situation, it is prudent to recommend the reduction of part of the P in the soil until the contents decrease to medium values, and from this moment return to fertilization, using organic or mineral sources (Corrêa *et al*., 2011).

The average ECL-P in soils with clay content of 0-15, 16-35, 36-60 and > 60% were, respectively, 24.44, 32.33, 45.00 and 53.86 mg dm^{-3} (Figure 2). Applying and respecting the ECL-P is a fundamental preventive attitude, but not the only one. The use of mitigation techniques is also an option and can help farmers who need to dispose of LSM as a management option for fertilization. The no-tillage system, when well-managed, helps in erosion control and causes greater water infiltration (Carretta *et al*., 2021).

The P content ranged from 0.2 to 115.7 mg dm^{-3}, corresponding to very low and high levels of P in the soil, respectively (Table 3). Only in six farms are the P contents in the soil in the appropriate range, which represents approximately 7 % of the number of farms evaluated. In 29 of the farms, the P contents were classified as low, and in 15 farms, the P contents were very low. And in 31 farms, the P content was classified as high. According to Boaventura *et al*. (2023), P is one of the scarcest elements in the soils of the Cerrado, corroborating the results found because in 58% of the farms, the P level is below adequate. This is due to the high fixation capacity of P. Oxisols, one of the predominant classes in the Brazilian Cerrado, due to their low P contents and their high degrees of weathering, 1:1 clays and iron and aluminum oxides, work as P sink and are able to adsorb more than 2 mg g^{-1} of P (Pinto *et al*., 2013).

This causes farmers to often resort to fertilization with LSM, as it is a rich source of P and is available in large quantities in the Brazilian southwest region due to the large number of farms. It is a mutual benefit, as farmers need to improve soil fertility and farm owners need to properly dispose of waste. In many cases, the farmers are also producers of soybeans, corn, sorghum, and pasture and end up using the waste on their own farms.

In the distribution of P contents in the levels, the standard deviation and the coefficients of variation were high, indicating great variation in the P contents at the same level (Table 3). High coefficients of variation imply a high degree of variation within the same level of P, showing great heterogeneity in the contents of P in the soils. Most likely, the management of waste disposal, the amount applied or the concentration of P in the applied waste are variable on the farms.

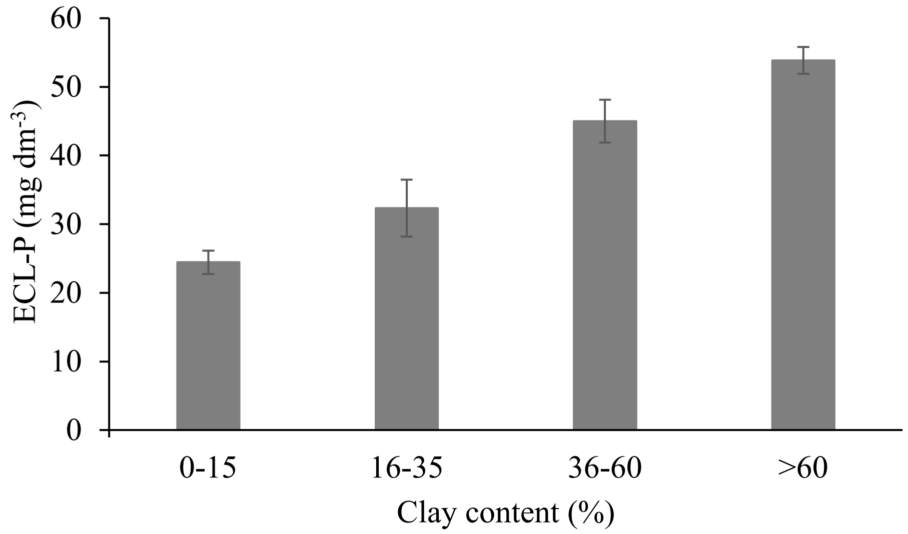

Figure 2. Average environmental critical limit of phosphorus (ECL-P) of soils from 89 farms as a function of clay content (%)

Even with the discrepancy in the variation in P contents, it can be stated that most of the soils analyzed had excessive P contents in the most superficial layer. These results may be due to the superficial application of LSM in areas of the no-tillage system and absence of incorporation, in addition to the fact that these residues are distributed in restricted areas and close to storage sites. This practice over time will promote changes in the chemical attributes of the soil, such as an increase in the contents of nutrients, such as P, K, Ca and Mg. Excessive levels of P in the soil indicate the risk of contamination of water resources if there is a loss of P (Gatiboni *et al*., 2020).

Table 3. Phosphorus levels as a function of soil P and clay contents of pig farms sampled in the southwest region of Goiás, Brazil

Characteristic	Parameters	Phosphorus level					General
		High	Adequate	Medium	Low	Very low	
		------ mg dm^{-3} ------					
Phosphorus	Minimum value	12.1	7.0	5.8	2.1	0.2	0.2
	Average value	35.9	11.8	12.1	7.0	2.2	23.5
	Maximum value	115.7	23.1	16.3	11.4	5.5	115.7
	Standard deviation	22.30	6.48	3.92	2.48	1.17	-
	CV (%)	62.1	54.8	32.4	35.4	53.7	90.2
		-------- % --------					
Clay	Minimum value	2.0	8.0	6.0	5.0	7.0	2.0
	Average value	31.1	45.0	22.3	23.5	26.2	29.2
	Maximum value	72.0	68.0	49.0	67.0	72.0	72.0
	Standard deviation	23.15	24.93	15.53	19.36	18.90	-
	CV (%)	74.5	55.4	69.8	82.3	72.0	75.1
	n1	31	6	8	15	29	89.0

CV = coefficient of variation; n1 = number of farms.

In clay soils, P has lower mobility and remains more abundant in the surface layers, creating a concentration gradient in the deeper layers. The greatest environmental concern is the loss of excess P to water sources in soils that are more conducive to erosion.

A downward trend in P levels was observed when higher clay contents occurred (Figure 3). This is because the inorganic form (Pi) fixed more strongly to the colloids of the soil will predominate in soils that are strongly affected by the action of weathering. In the equation obtained by simple linear regression (phosphorus = 22.7527 – 0,2193 * clay), the coefficient of determination of the equation was low due to the great dispersion of the P contents in relation to the clay contents.

Currently, one of the great challenges of pig farms is the proper disposal of the large amount of waste that is generated daily due to its great polluting potential. One of the first alternatives is its use as organic fertilizer, but respecting the limit supported by the soil and plants. However, this purpose does not support the large amount of waste that is generated, and some farms have also sought to treat their waste, separating the solid from the liquid part, with the liquid part usually used in soil fertilization and the solid part used in composting, biogas production from anaerobic digestion, and as renewable fuel, which can be used on the property itself, in addition to the removal and physical-chemical recovery of P and biological removal of nitrogen by nitrification/denitrification (Cândido *et al.*, 2022).

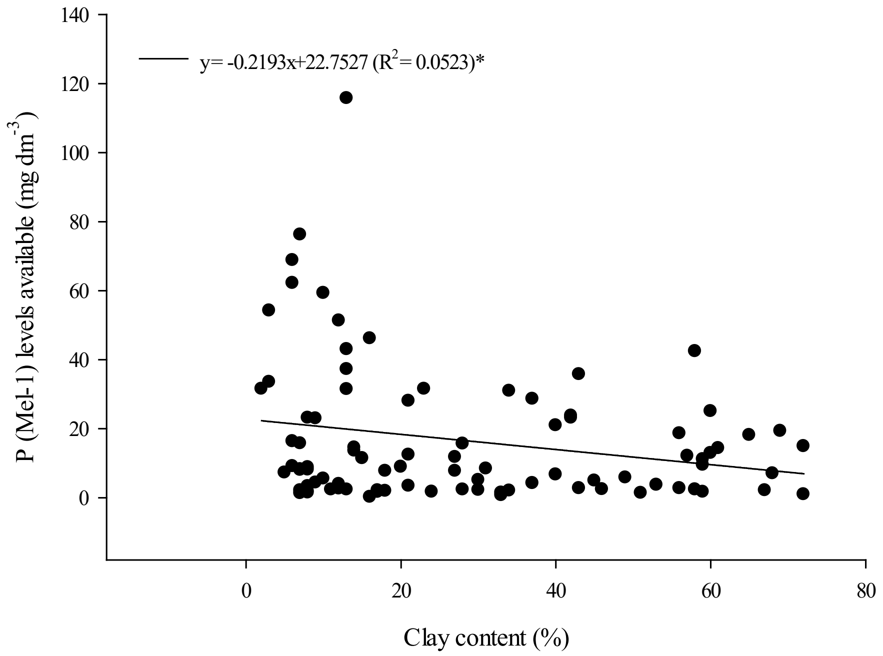

Figure 3. Simple linear regression of the relationship between clay and phosphorus contents for 89 soil samples from pig farms in the southwest region of Goiás, Brazil. ** Significant difference at 1% probability level by the T test

Thus, it is important to monitor the P content in areas with prolonged disposal of LSM, even in areas where the content of this nutrient is low, because continuous use raises the P content, which may exceed the appropriate limit and result in environmental problems. In areas where the P content is above adequate, more rigorous monitoring is necessary to ensure more sustainable production without risks to the environment and humans and to indicate to producers the most appropriate management technique.

4 CONCLUSION

On 14 of the 89 pig farms sampled in the southwest region of Goiás, P was at an excessive level, of which 12 received the recommendation of immediate interruption of the application of P sources to avoid contamination of watersheds. Although beneficial, organic fertilization can also exceed adequate limits, as observed in the present study, which reinforces the need to monitor areas with long periods of fertilization with pig manure. Constant monitoring helps in decision-making, mainly by providing the maximum capacity of phosphate fertilizer, whether organic or mineral, that the soil supports without causing harm to humans and the environment. P levels tend to reduce with increasing clay content, which is an important point to be observed when developing strategies to reduce P loss.

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