

MOBILITY OF INORGANIC AND ORGANIC PHOSPHORUS FORMS UNDER DIFFERENT LEVELS OF PHOSPHATE AND POULTRY LITTER FERTILIZATION IN SOILS⁽¹⁾

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SUMMARY

The eutrophication of aquifers is strongly linked to the mobility of P in soils. Although P mobility was considered irrelevant in a more distant past, more recent studies have shown that P, both in organic (Po) and inorganic forms (Pi), can be lost by leaching and eluviation through the soil profile, particularly in less weathered and/or sandier soils with low P adsorption capacity. The purpose of this study was to determine losses of P forms by leaching and eluviation from soil columns. Each column consisted of five PVC rings (diameter 5 cm, height 10 cm), filled with two soil types: a clayey Red-Yellow Latosol and a sandy loam Red-Yellow Latosol, which were exposed to water percolation. The soils were previously treated with four P rates (as KH_2PO_4) to reach 0, 12.5, 25.0 and 50 % of the maximum P adsorption capacity (MPAC). The P source was homogenized with the whole soil volume and incubated for 60 days. After this period the soils were placed in the columns; the soil of the top ring was mixed with five poultry litter rates of 0, 20, 40, 80, and 160 t ha⁻¹ (dry weight basis). Treatments consisted of a 4 x 5 x 2 factorial scheme corresponding to four MPAC levels, five poultry litter rates, two soils, with three replications, arranged in a completely randomized block design. Deionized water was percolated through the columns 10 times in 35 days to simulate about 1,200 mm rainfall. In the leachate of each column the inorganic P (reactive P, Pi) and organic P forms (unreactive P, Po) were determined. At the end of the experiment, the columns were disassembled and P was extracted with the extractants Mehlich-1 (HCl 0.05 mol L⁻¹ and H_2SO_4 0.0125 mol L⁻¹) and Olsen (NaHCO_3 0.5 mol L⁻¹, pH 8.5) from the soil of each ring. The Pi and Po fractions were measured by the Olsen extractant. It was found that under higher poultry litter rates the losses of unreactive

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P (Po) were 6.4 times higher than of reactive P (Pi). Both the previous P fertilization and increasing poultry litter rates caused a vertical movement of P down the soil columns, as verified by P concentrations extracted by Mehlich-1 and NaHCO_3 (Olsen). The environmental critical level (ECL), i.e., the P soil concentration above which P leaching increases exponentially, was 100 and 150 mg dm^{-3} by Mehlich-1 and 40 and 60 mg dm^{-3} by Olsen, for the sandy loam and clay soils, respectively. In highly weathered soils, where residual P is accumulated by successive crops, P leaching through the profile can be significant, particularly when poultry litter is applied as fertilizer.

Index terms: eutrophication, environmental critical level, Mehlich-1, Olsen.

RESUMO: *MOBILIDADE DE FORMAS INORGÂNICAS E ORGÂNICAS DE FÓSFORO SOB DIFERENTES DOSES DE ADUBAÇÃO FOSFATADA E CAMA DE AVIÁRIO EM SOLOS*

A eutroficação de aquíferos está fortemente ligada à mobilidade de P nos solos. Embora essa mobilidade tenha sido considerada, num passado mais distante, como inexpressiva, estudos mais recentes têm mostrado que o P, tanto na forma orgânica (Po) quanto na inorgânica (Pi), pode se perder por percolação e eluviação de partículas através do perfil de solos, particularmente naqueles menos intemperizados e, ou, arenosos com menor adsorção de P. O objetivo deste trabalho foi verificar perdas por lixiviação e eluviação de formas de P em colunas de solos, constituídas por cinco anéis de PVC sobrepostos, com 5 cm de diâmetro e 10 cm de altura cada, submetidas a fluxos de percolação de água. Foram utilizadas amostras de dois Latossolos Vermelho-Amarelos, texturas argilosa e média. Os solos receberam, previamente, quatro doses de P na forma de KH_2PO_4 , correspondentes a 0; 12,5; 25 e 50 % da capacidade máxima de adsorção de P (CMAP), homogêneas com todo o volume de solo das colunas e deixados em incubação por 60 dias. No anel superior, aplicou-se, homogêneas, cama de aviário nas doses equivalentes a 0, 20, 40, 80 e 160 t ha^{-1} , com base no peso do material seco. O experimento foi constituído pelo esquema fatorial: quatro níveis da CMAP, cinco doses de cama de aviário, dois solos, com três repetições dispostas em blocos casualizados. As colunas foram submetidas a 10 percolações com água deionizada, em duas aplicações semanais, durante 35 dias, de modo que se atingisse um volume aproximado de 1.200 mm. Nos lixiviados de cada coluna, foram determinados: P reativo (Pi) e P não reativo (Po). No final do experimento, o P no solo de cada anel foi extraído com Mehlich-1 e com NaHCO_3 0,5 mol L^{-1} , pH 8,5 (Olsen), sendo determinadas, para este último extrator, as formas Pi e Po. Com o aumento das doses aplicadas de cama de aviário, as perdas de P por lixiviação foram, em média, 6,4 vezes maiores na forma de P não reativo (Po) que no P-reativo (Pi). Tanto a fertilização mineral prévia com P quanto a aplicação de doses crescentes de cama de aviário causaram movimentação descendente de P nas colunas de solo, extraído tanto pelo Mehlich-1 quanto pelo NaHCO_3 (Olsen). O nível crítico ambiental (NCA), teor de P disponível no solo acima do qual a percolação de P-reativo aumenta exponencialmente, foi de 100 e 150 mg dm^{-3} para o Mehlich-1 e de 40 e 60 mg dm^{-3} para o Olsen, para os solos de textura média e argilosa, respectivamente. Em solos intemperizados, com acúmulo de P residual ao longo dos cultivos, as perdas de P por lixiviação no perfil podem ser significativas, de modo particular quando fertilizados com cama de aviário.

Termos de indexação: eutrofização, nível crítico ambiental, Mehlich-1, Olsen.

INTRODUCTION

Phosphorus is, in general, one of the most limiting elements for agricultural production in tropical soils. However, the presence of this nutrient can cause environmental problems, such as groundwater contamination. Given the high adsorption of P in most

weathered soils, the leaching of this nutrient through such soils is hardly significant. In areas with less weathered soils, P mobility is verified in the soil profile, both in organic (Toor et al., 2004a,b) as well as in inorganic forms (Turner & Haygarth, 2000; Djodjic et al., 2004). Consequently, little weathered soils fertilized with P are more susceptible to P leaching

(Robins et al., 2000; Sharpley & Moyer, 2000, Whalen & Chang, 2001, Daly et al., 2002; McDowel et al., 2002), particularly in terms of organic P (Po). In general, Po forms are more easily leached due to the low interaction with the soil (Ron Vaz et al., 1993; Eghball et al., 1996, Chardon et al., 1997). Soil solution concentrations about 0.277 mg L^{-1} Po have been found throughout the soil profile (Ron Vaz et al., 1993). This may cause environmental problems, although from the viewpoint of plant nutrition this level can be considered low (Turner & Haygarth, 2000).

Several studies report the effect of organic fertilizers on P performance in soil. Hodgkinson et al. (2002) studied a clay soil in the region of Boxworth (Cambridgeshire, UK) and observed that the application of pig manure was able to increase the P concentration in drainage water when compared with chicken and cattle manure or sewage sludge. Robins et al. (2000) found that in calcareous soils, the organic and inorganic P forms in soil solution increased more after P application in the form of monocalcium phosphate than of waste. On the other hand, Heckrath et al. (1995) found that for the same P content, determined by the Olsen extractant, total P in drainage water from turf was lower after application of animal waste than of the inorganic form of the fertilizer. In this study, low P concentrations were stated in drainage water at levels of 60 mg kg^{-1} P (Olsen), but when these levels exceeded 100 mg kg^{-1} , P concentrations increased rapidly, increasing P soil leaching.

These P soil levels, at which the environmental problems related to water eutrophication become critical, can be considered environmental critical levels (ECL). Along this line of thought, McDowell & Sharpley (2001) found that the ECLs would be 33 to 36 mg kg^{-1} by Olsen, and 185 to 190 mg kg^{-1} by Mehlich-3; Sharpley & Moyer (2000) suggested that soluble P in water would be a good alternative to determine the ECL when animal manure is used.

In little weathered soils in temperate climate, the recommendation of organic sources is based on the N rate recommended to meet crop demands (Sharpley et al., 1993). Since crops generally have a P great demand, this nutrient is accumulated in the soil, which increases the possibility of P losses by leaching, eluviation and runoff (Sharpley et al., 1993, Whalen & Chang, 2001). Along this line, Robinson & Sharpley (1995) found that after the application of poultry litter, based on P crop requirements, the soil organic P forms are more stable, reducing the risk of environmental contamination.

In studies of Elliott et al. (2002), in P-deficient acid soils in the state of Florida (USA), it was observed that the lower the maximum P adsorption capacity (MPAC), the greater is the amount of P lost by leaching, mainly in the inorganic P form.

On the other hand, Field et al. (1985) found that increasing the poultry litter rate could not reduce the MPAC of the soil, but did reduce the bonding energy of P with the soil, causing leaching. Organic

compounds in poultry litter, for example, have a relevant influence on P soil adsorption, since they are capable of coating the Fe and Al oxyhydroxides, reducing the soil adsorption capacity (Mazur et al., 1983, Beauchemin et al., 1996). However, there is little information on the movement of P forms in highly weathered soils.

The purpose of this study was to investigate the movement (leaching) of organic and inorganic P forms in samples of two Oxisols with different texture, treated with poultry litter, after previous P application in inorganic form. It is important to remember that the supply of organic P sources to soils causes increasing concerns about environmental problems such as ground water contamination, which are defused to a certain extent when inorganic P sources, as from mineral fertilizers, are used.

MATERIAL AND METHODS

PVC columns (height 50 cm, diameter 5 cm) were used, with two soil samples (Table 1) from two locations in the state of Minas Gerais: a clayey Red-Yellow Latosol from the region of Viçosa and a sandy loam texture Red-Yellow Latosol from the region of João Pinheiro. The experiment had a $4 \times 5 \times 2$ factorial design, with four previous saturation levels of mineral soil P, based on the maximum P adsorption capacity (MPAC), five fertilization levels with poultry litter and the two soils, with three replications, arranged in a completely randomized block design.

Samples of two soils were collected from subsurface horizons (B horizon), to reduce the interferences of organic matter. To the air-dried fine earth samples (2 mm sieve) P was added as monobasic potassium phosphate to reach the following MPAC values: 0, 12.5, 25 and 50 % of each soil, determined according to Olsen & Watanabe (1957), with a shaking period of 16 h and the P source applied in solution. After 60 days of incubation, with soil moisture maintained at 90 % field capacity and homogenized weekly, the soils were dried and packed in plastic bags.

Soil samples of each treatment were collected for P analysis by Mehlich-1 extractant ($\text{HCl } 0.05 \text{ mol L}^{-1}$ and $\text{H}_2\text{SO}_4 0.0125 \text{ mol L}^{-1}$); for the sandy loam texture soil, the values 0.15, 12.7, 35.9 and 106.7 mg dm^{-3} of P were found and for the clay texture 0.01, 33.6, 85.8 and 173.4 mg dm^{-3} P, respectively. The soils incubated with the P rates were placed in PVC columns composed of five rings (height 10 cm), fixed to each other with scotch tape, and the inside coated with paraffin to avoid any preferential path of the water along the PVC/soil interface.

Poultry litter with wood shavings was applied to the top ring of each column at dry weight rates of 0, 20, 40, 80 and 160 t ha^{-1} (Table 2). So, different P rates were tested in soils with variable available-P status.

Table 1. Chemical and physical properties of soil samples

Property	Clay texture	Sand loam texture
pH – H ₂ O (1:2,5)	4.80	5.40
Al ³⁺ (cmol _c dm ⁻³) ⁽¹⁾	1.10	0.45
Ca ²⁺ (cmol _c dm ⁻³) ⁽¹⁾	0.02	0.05
Mg ²⁺ (cmol _c dm ⁻³) ⁽¹⁾	0.01	0.01
H + Al (cmol _c dm ⁻³) ⁽²⁾	6.70	3.20
K (mg dm ⁻³) ⁽³⁾	4.10	9.90
P (mg dm ⁻³) ⁽³⁾	0.30	0.30
Equilibrium P (mg L ⁻¹) ⁽⁴⁾	4.20	24.50
MPAC (mg g ⁻¹) ⁽⁵⁾	2.48	0.76
Organic carbon (g kg ⁻¹) ⁽⁶⁾	13.8	6.50
SB (cmol _c dm ⁻³)	0.04	0.08
CEC (t) (cmol _c dm ⁻³)	1.14	0.53
CEC _{pH7.0} (T) (cmol _c dm ⁻³)	6.74	3.28
m (%)	96.50	84.90
V (%)	0.60	2.40
Coarse sand (g kg ⁻¹) ⁽⁷⁾	130.0	260.0
Fine sand (g kg ⁻¹) ⁽⁷⁾	70.0	500.0
Silt (g kg ⁻¹) ⁽⁷⁾	20.0	30.0
Clay (g kg ⁻¹) ⁽⁷⁾	780.0	210.0
Texture class	Very clayey	Franco-sandy-clay
Field capacity (kg kg ⁻¹) ⁽⁸⁾	0.35	0.10

⁽¹⁾ Extractant: KCl 1 mol L⁻¹ (Vettori, 1969). ⁽²⁾ Extractant: calcium acetate 0.5 mol L⁻¹, pH 7.0 (Vettori, 1969). ⁽³⁾ Extractant: Mehlich-1 (Defelipo & Ribeiro, 1997). ⁽⁴⁾ P concentration of the equilibrium solution, after shaking the soil with 0.01 mol L⁻¹ CaCl₂ for 1 h, containing 60 mg L⁻¹ P at a ratio of 1:10 (Alvarez et al., 2000). ⁽⁵⁾ Olsen & Watanable (1957), modified by Alvarez V. & Fonseca (1990). ⁽⁶⁾ Method Walkley & Black (Jackson, 1958). ⁽⁷⁾ Pipette method (EMBRAPA, 1997). ⁽⁸⁾ Method of Richards (-30 KPa) (EMBRAPA, 1997).

Table 2. Total contents of macro and micronutrients and sodium in poultry litter with wood shavings

Macronutrient		Micronutrient	
—g kg ⁻¹ —		—mg kg ⁻¹ —	
N	30.9	Zn	473
P	17.1*	Fe	789
K	24.4	Mn	315
Ca	25.8	C	41
Mg	5.7	B	42
S	14.0	Na	559

The total P content was determined by the method of Bowman (1989). Source: Souza (2004).

A PVC lid was placed at the bottom of each column, covered by a plastic screen on top of which a layer of glass wool and a layer of washed sand were placed to prevent soil loss from the column. A leachate collector tube was coupled to the base of each column, which linked the columns to the collector container. A system was installed on each column to control the water flow, as used for medical applications of drip-feeding, to forward the deionized water.

Deionized water was applied to the columns at a controlled flow of approximately 0.35 mL min⁻¹ for the

sandy and 0.42 mL min⁻¹ for the clay soil texture. The water volume used in sandy loam and clay soil textures were, respectively, 250 and 300 mL of percolation, based on the pore volume of each soil. Ten percolations were performed, two per week, for 35 days, until an approximate value of the average annual rainfall in the region of Viçosa (1,200 mm, approximately) was reached. Throughout the experiment, the top of the columns was kept covered with plastic to prevent evaporation and capillary water rise.

From each of the ten percolations, the leachate was collected and the aliquots centrifuged at 2,606 g for 15 min and the supernatant filtered through millipore membrane, where the P forms were fractionated in reactive (Pi) and non-reactive (Po) forms. The reactive P (Pi) was obtained by direct determination (without additional treatment) of P in solution in an aliquot of the leachate. The inorganic P forms in solution, which form the phosphomolybdic complex (Novais & Smyth, 1999), were determined by the colorimetric method according to Murphy & Riley (1962) Given the very low P concentrations in solution, a large cell (70 mm) was used in a number of determinations, increasing the sensitivity of the method (concentrations equal to or higher than 0.025 mg L⁻¹). In another aliquot, the total P (Pt) was determined after digestion with potassium peroxodisulphate (K₂S₂O₈) in alkaline medium (Cabrera & Beare, 1993), as modified by Doyle et al. (2004). The non-reactive P (Po) was estimated by the difference between Pt and Pi.

At the end of the experiment, the columns were dismantled and the soil from the different rings separated, air-dried, crumbled, sieved (2 mm mesh), and then the P levels were determined, extracted by Mehlich-1 and by NaHCO₃ 0.5 mol L⁻¹, at pH 8.5 (Olsen).

For the Mehlich-1 extractions, 100 mL of extractant was added to every 10 cm³ of soil, shaken for 5 min and after 16 h of rest an aliquot was pipetted for P analysis and determined colorimetrically, according to EMBRAPA (1997).

For NaHCO₃ extraction, 25 mL of extractant was used per 2.5 cm³ soil, packed in 50 mL Falcon centrifuge tubes, shaken horizontally at 150 RPM, at 4 °C for 1 h; then the tubes were centrifuged at 2,606 g for 10 min, at 4 °C, and then an aliquot was taken to determine Pi as described by Murphy & Riley (1962), by the so-called Pi- NaHCO₃. A second aliquot was subjected to nitro-perchloric digestion, at a ratio of 4:1, v/v-(nitric: perchloric acid) for determination of total P (Pt). The Po-NaHCO₃ was computed by the difference: Pt–Pi.

The pH values of all extracts were adjusted, taking as reference the indicator p-nitrophenol, to determine the P levels, except for the Mehlich-1 extractant, where the pH was already within the range recommended for the determination (pH about 4.5–5.5)

The statistical analysis was performed using software sigma-plot 8.0, Statistica 6.0 and SAEG 9.0, including ANOVA and regression settings, where appropriate. Subsequently, the significance of the adjusted regression coefficients was t- tested.

RESULTS AND DISCUSSION

Reactive phosphorus (Pi) and non-reactive (Po) in the leachate

The P loss in solution leached from columns occurred both in the form of reactive P (Pi) (Figure 1) as in the form of non-reactive P (Po) (Figure 2) in both soils. The non-application of poultry litter on soil not prefertilized with phosphate (0 % MPAC) promoted

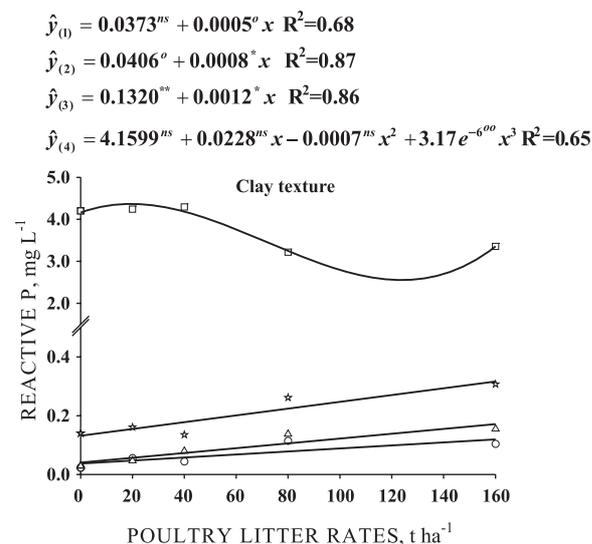
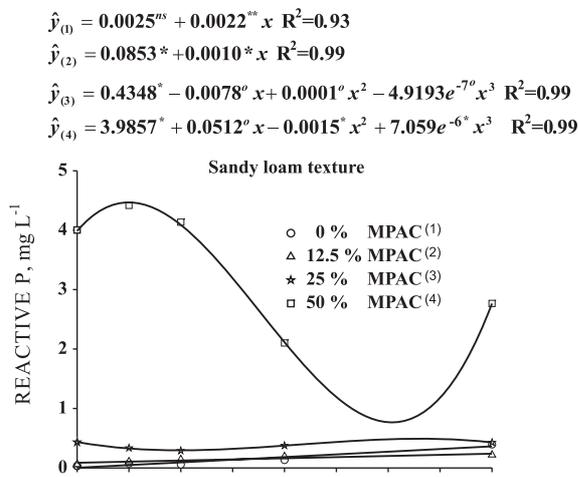


Figure 1. Concentrations of reactive P (Pi) in leachate collected from two Latosols of sandy loam and clay texture, prefertilized with increasing rates of mineral P, as related with the poultry litter rates applied in the top ring. ns, oo, o, *, **: not significant and significant at 15, 10, 5 and 1 %, respectively.

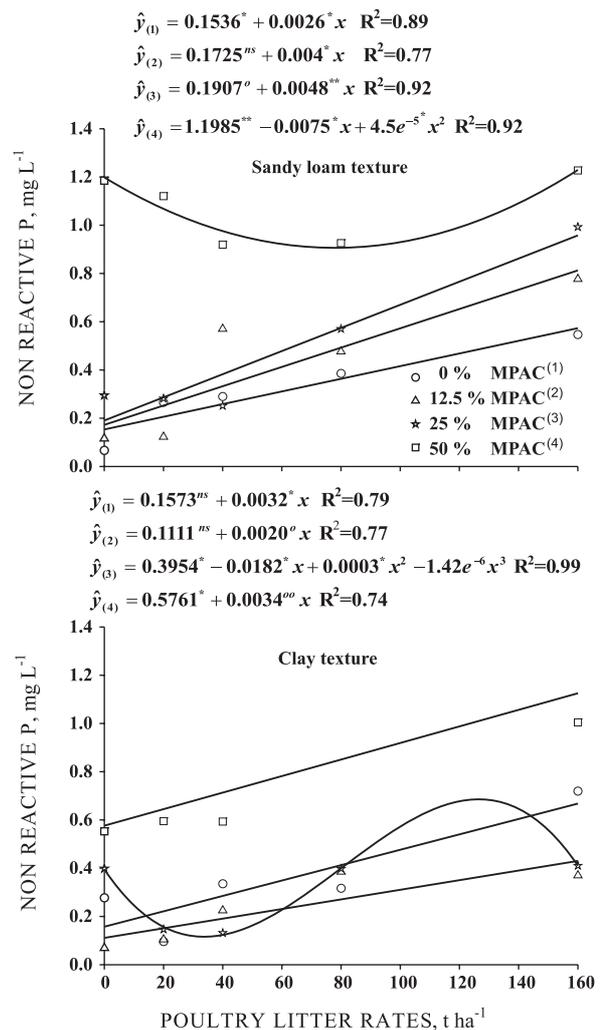


Figure 2. Concentrations of non-reactive P (Po) in leachate from two Latosols of sandy loam and clay texture, prefertilized with increasing rates of mineral P, as related to poultry litter rates applied in the top ring. ns, oo, o, *, **: not significant and significant at 15, 10, 5 and 1 %, respectively.

low P concentrations in the leachate, near zero, with predominance of non-reactive over reactive P.

Despite the different soil adsorption capacity (Table 1), the similarity between P concentrations of reactive and non-reactive P was evident (Figures 1 and 2). This was expected, since the previous P fertilization was based on the MPAC of each soil, with application of different P rates to the soils up to the MPAC saturation level. Possible differences in results as a consequence of different clay contents between soils were therefore compensated.

The increase in the rate of poultry litter applied to soil under original conditions (0 % MPAC) caused higher losses of non-reactive (Po) than of reactive P (Pi) in the clay soil. While the tangential to Po in mg L⁻¹ P/t ha⁻¹ of poultry litter was 0.0032 (Eq. 1 - Figure 2), the equivalent tangent for Pi in the same

soil was 0.0005 (Eq. 1 - Figure 1), indicating higher Po losses, 6.4 times greater than of Pi, in these conditions. This greater Po percolation suggests a lower interaction of this P form with the soil than of the inorganic form Pi, as already shown in several studies (Toor et al., 2004a, b, Anderson & Magdoff, 2005). The same comparison for the sandy loam texture soil indicates similar losses for Po and Pi, with tangents of 0.0022 and 0.0026, respectively.

As the most predominant model, increasing losses of the two P forms in leachate were observed with increasing P poultry litter rates applied to both soils, with exception of Pi at the highest prefertilization rate (50 % MPAC). The Po content in sandy loam texture soil, previously fertilized with phosphorus of 50 % MPAC, also tended to increase with the increasing poultry litter rate.

The lower Pi concentrations observed with increasing P poultry litter rates, according to a cubic model (Figure 1) in both soils, suggest a greater clay dispersion that occurred with increasing poultry litter rates to an intermediate point between the two rates (121.8 t ha⁻¹ for sandy loam and 128.5 t ha⁻¹ for clay soil texture). The increased Pi concentration after the minimum point in the curves suggests a compensation of the negative effect of the lower soil hydraulic conductivity in the column due to the higher total P rate added in the form of poultry litter.

The attempt to perform one more percolation - the eleventh - was unsuccessful because in several columns, most evidently in those treated with higher poultry litter rates, there was no more leachate and the water was accumulated on top of the columns without the expected infiltration.

According to Benites & Mendonça (1998), the application of high rates of organic compounds to soils, as of animal manure, leads to a strong prevalence of negative charges, so aggregation is reduced. It is noteworthy that not only organic compounds are present in poultry litter, as a soil disintegrating agent, but also high levels of Na, a dispersant agent found in animal feed, which is confirmed by the Na contents measured in poultry litter used here (Table 2).

Soil phosphorus in each ring after percolations

Phosphorus extracted by Mehlich-1

With the previous fertilization of soil samples with mineral P source, simulating years of nutrient addition in the field, P levels by Mehlich-1 (Pm) in depth increased significantly, especially in clay soil texture (Figure 3). It was also observed that with the application of poultry litter, Pm levels increased in the first layer (first ring, 0–10 cm) and in depth, although in this case less significantly. These results indicate that the use of poultry litter in soils pre-treated with phosphate fertilizer, resulting in a high soil P status may induce P transport to deeper profile layers. They further indicate P losses in this form P

(Pm) before the MPAC soil was affected as a result of the application of increasing poultry litter rates (Figure 3).

Inorganic and organic phosphorus extracted by NaHCO₃

Opposite to what occurs with the acid extractants such as Mehlich-1 (pH 1.2) (Novais & Smyth, 1999) the extractant NaHCO₃ (pH 8.5) has a strong extraction power of organic P (Po) from the soil (Hedley et al., 1982), which allows a more critical examination of this P form. Similarly as already observed for Mehlich-1, in Pi extracted by NaHCO₃ (Pi-NaHCO₃) the prefertilization of soil samples with the mineral source increased the Pi-NaHCO₃ levels significantly, mainly in clay soil (Figure 4). The application of poultry litter also caused increases in Pi-NaHCO₃ levels in depth; increases were more pronounced according to increases of the previous P soil saturation levels, giving them the status of more fertile soils for this nutrient.

Under the present conditions in the soil columns high mobility of Pi-NaHCO₃ and Po-NaHCO₃ was observed in the deeper soil columns (Figures 4 and

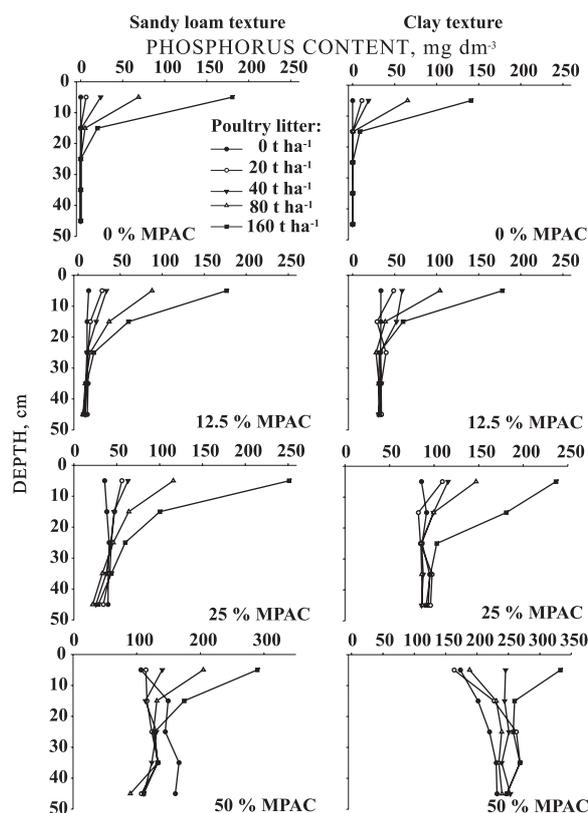


Figure 3. Phosphorus contents by Mehlich-1 (Pm) in samples of two Latosols with sandy loam and clay texture, prefertilized with increasing mineral P rates corresponding to the percentages of Maximum Phosphorus Adsorption Capacity (MPAC), as related to the poultry litter rates applied in the top ring.

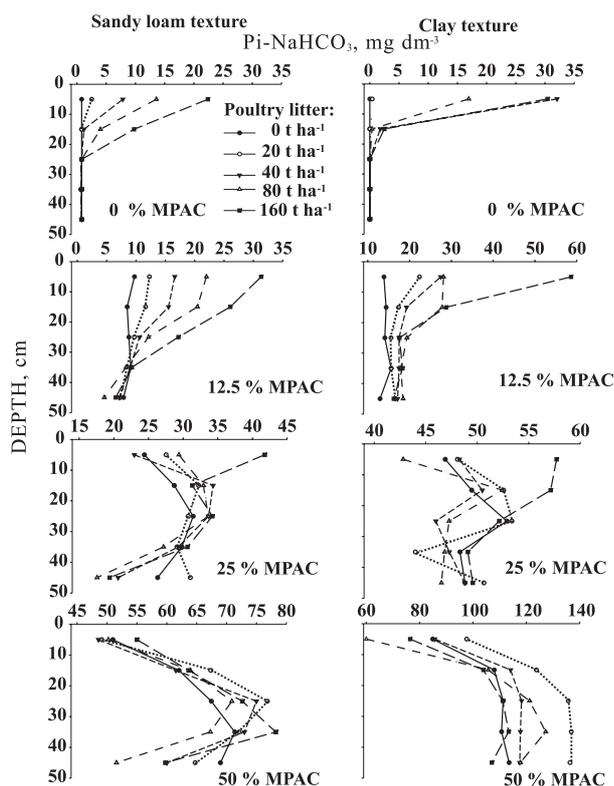


Figure 4. Inorganic phosphorus contents (Pi) extracted by NaHCO_3 (Pi-NaHCO_3) in samples of two Latosols with sandy loam and clay texture, prefertilized with increasing mineral P rates as related to the poultry litter rates applied in the top ring.

5), suggesting the potential eutrophication of water bodies, as widely reported in the literature (Sharpley & Moyer, 2000, McDowell et al., 2002).

The mineral phosphate prefertilization of samples probably increased the competition for adsorption sites of soil P, tending to saturate them and making them less restrictive to P losses by percolation/leaching. This was observed more intensely in the samples phosphated with 50 % of MPAC, regardless of the amount of poultry litter applied, mainly in the clay soil (Figures 4 and 5). It is emphasized that for the same % of MPAC, the P rate applied in the clay soil was 3.16 times higher than in sandy soil (Table 1).

Environmental critical level (ECL) of phosphorus extracted by Mehlich-1 and NaHCO_3

The reactive P (Pi) concentrations remained low until the status of available P in the soil of the first ring reached 100 and 150 mg dm^{-3} of Mehlich-1 P (Pm), approximately, in the soils of sandy loam and clay texture, respectively. From these levels, the increments in concentrations became more than proportional to the increase in the Pm levels, suggesting that the adsorption capacity of soil P was

then reduced drastically for both soils (Figure 6). These Pm levels may indicate the "environmental critical levels" (ECL), as suggested by some authors (Maguire & Sims, 2002, Sharpley et al., 2004). Moreover, the leaching of non-reactive P (Po) increased linearly with increasing Pm levels, which suggests a lower affinity of this P form with the soil, even when soil P saturation is low.

The results indicate that organic residues, e.g., poultry litter, reduce the MPAC and/or adsorption energy of P forms (Pi and Po) by the soil.

The reactive P concentrations in leachate also remained low until a status of available soil P of 40 and 60 mg dm^{-3} Pi- NaHCO_3 in sandy loam and clay soil texture, respectively, was reached in the first ring. From this point on, P losses from the columns increased exponentially (Figure 7) in a model similar to that observed for Pm (Figure 6).

These Pi- NaHCO_3 levels also indicated the ECLs for this extractant, which are close to those suggested

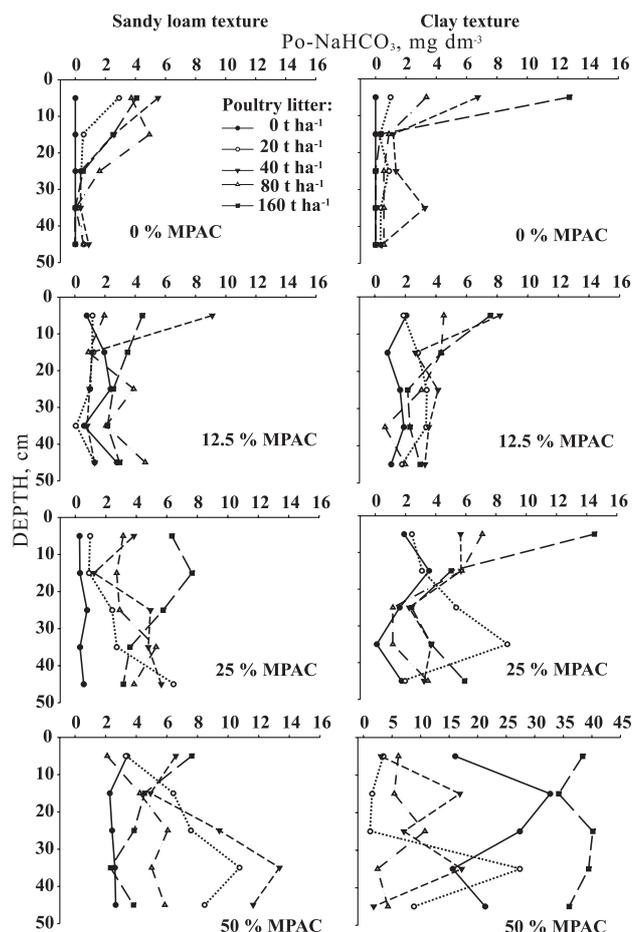


Figure 5. Organic phosphorus contents (Po) extracted by NaHCO_3 (Po-NaHCO_3) from samples of two Latosols with sandy loam and clay texture, prefertilized with increasing mineral P rates as related to the poultry litter rates applied in the top ring.

in the literature. McDowell & Sharpley (2001) found ECLs of around 33 to 36 mg kg⁻¹ P for Olsen. These values are close to the 40 mg dm⁻³ P for sandy loam soil texture observed here. McDowell & Sharpley (2001) found ECLs of 185 to 190 mg kg⁻¹ P by the Mehlich-3 extractant, close to the ECL values found here (Figure 6) by Mehlich-1 (150 mg dm⁻³).

Similarly as for Mehlich-1 (Figure 6) there was a linear increase of non-reactive P due to the increased Pi- NaHCO₃ levels in the soil in the first ring (Figure 7). The losses of non-reactive P per unit of P- NaHCO₃ were higher for sandy loam (0.0202 mg L⁻¹/ mg dm⁻³) than for clay texture soil (0.0056 mg L⁻¹/ mg dm⁻³) (Figure 7).

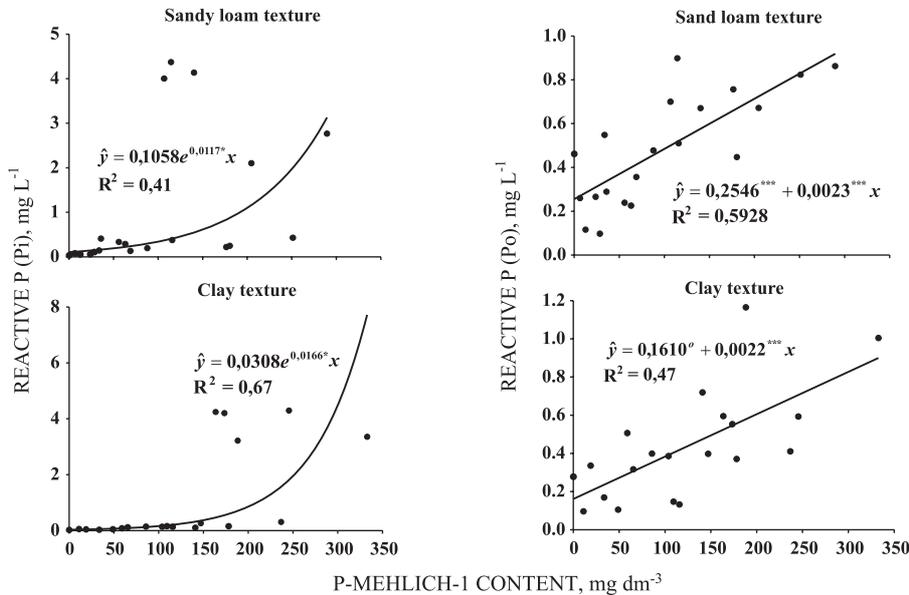


Figure 6. Variation in P reactive (Pi) and P non-reactive (Po) contents in the leachates according to the P contents extracted by Mehlich-1 in the top ring (0–10 cm) in two soil samples of Latosols of sandy loam and clay texture, prefertilized with increasing mineral P rates corresponding to the percentages of Maximum Phosphorus Adsorption Capacity (MPAC), as influenced by the application of increasing poultry litter rates. *, ***: significant at 5 and 0.1 %, respectively.

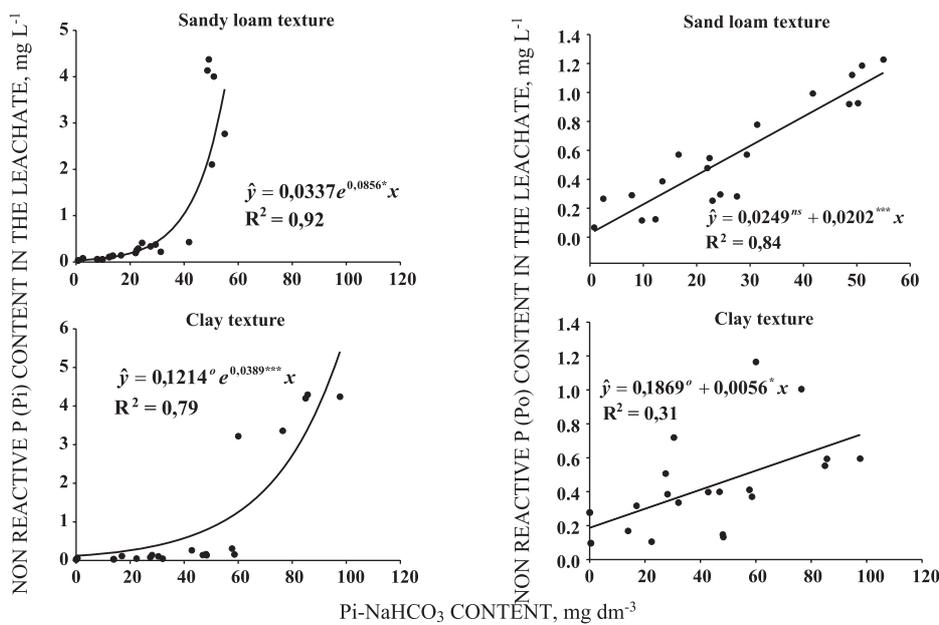


Figure 7. Variation in P reactive (Pi) and P non-reactive (Po) contents in the leachates according to the contents of Pi-NaHCO₃ in the first ring (0–10 cm) in samples of two Latosols with sandy loam and clay texture, with increasing mineral P rates corresponding to the percentages of Maximum Phosphorus Adsorption Capacity (MPAC), under the influence of increasing poultry litter rates. ^{ns}, ^o, *, ***: not significant and significant at 10, 5, and 0.1 %, respectively.

Environmental Critical Rate (ECR) of phosphorus

The change of the values of reactive P (Pi) caused by total P rates applied in the first ring (0–10 cm) was curvilinear but linear in the case of non-reactive P (Po). The values were computed by the sum of the rates applied as soluble phosphate prefertilizer and as poultry litter (Figure 8), assuming that 61 % of the total P is in inorganic form, as previously determined by Souza (2004) in a sample of the same poultry litter. From this relationship it was possible to estimate a “environmental critical rate” (ECR), or rate above which the environmental problems caused by P percolation in the profile, reaching groundwater and surface waters, could become a concern (Figure 8).

The increase of reactive P loss (Pi) from sandy loam texture soil begins at P rates two to three times lower than for clay soil, indicating differences in the MPAC between the two soils. On the other hand, an increase of the total P rates leads to linear increases in the percolation of non-reactive P (Po), even in conditions

of no previous phosphating (0 % MPAC). However, at higher rates, losses of reactive P (Pi) are more than proportional. While there are practically no losses of reactive P from the soil columns at the lowest pre-applied mineral phosphate rates, the loss of non-reactive P (Po) is between 1.76 mg L⁻¹ for clay soil and 1.82 mg L⁻¹ for sandy loam texture soil (Figure 8). By the model of alteration of reactive P (Pi) as variable of the mineral P rates applied, it can be estimated, approximately, that reactive P concentrations increased exponentially at rates above 300 to 350 mg dm⁻³ mineral P in sandy loam and above 900 to 1,050 mg dm⁻³ in clay soil texture.

The lower angular coefficient for losses of non-reactive P as variable of the P rates (0.0028 mg L⁻¹/mg dm⁻³) indicates that the clay texture soil is less susceptible to P loss than the sandy loam texture soil (0.0095 mg L⁻¹/mg dm⁻³) (Figure 8).

CONCLUSIONS

1. In natural conditions of low soil P availability, the loss of soil P by percolation of non-reactive P (Po) was higher than of reactive P (Pi).

2. The downward movement of P extracted by Mehlich-1 in the soil column increased greatly with higher rates of mineral P prefertilization and also with the amount of poultry litter.

3. The use of poultry litter in soil pre-treated with phosphate fertilizer, resulting in a high soil P status, induced increasing percolation of P, mainly in the non-reactive form (Po).

4. The environmental critical levels (ECL) for the P-extractant Mehlich-1 were approximately 100 and 150 mg dm⁻³ and 40 and 60 mg dm⁻³ for the extractant NaHCO₃ (Olsen) for sandy loam and clay soil texture, respectively.

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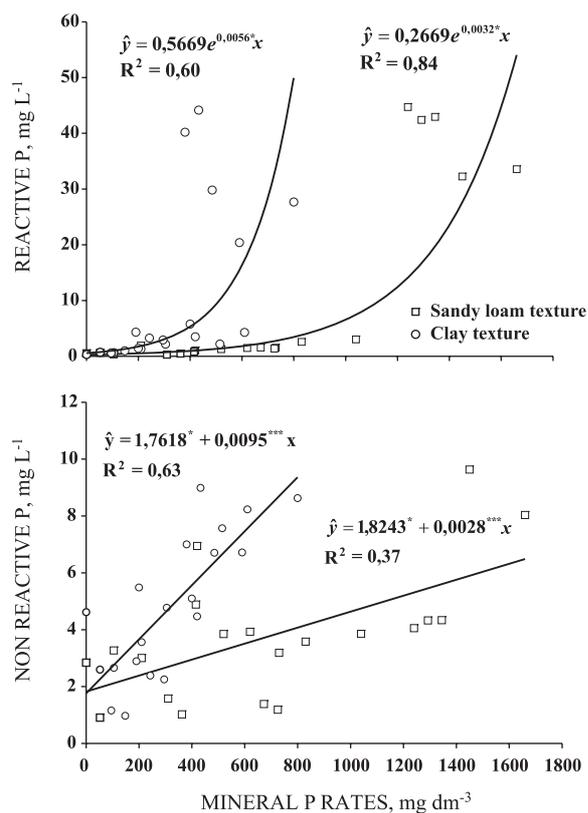


Figure 8. Concentration of reactive P (Pi) and non-reactive P (Po) in the leachates according to the rate of total mineral P applied in the first ring (0–10 cm), calculated by the sum of mineral prefertilization and poultry litter application, presuming that 61 % of the total of this material is in the inorganic form, in samples of two Latosols with sandy loam and clay texture. *, *: significant at 5 and 0.1 %, respectively.**

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