

Comissão 3.2 - Corretivos e fertilizantes

AVAILABLE CONTENT, SURFACE RUNOFF AND LEACHING OF PHOSPHORUS FORMS IN A TYPIC HAPLUDALF TREATED WITH ORGANIC AND MINERAL NUTRIENT SOURCES⁽¹⁾

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SUMMARY

The application of animal manure to soil can increase phosphorus availability to plants and enhance transfer of the nutrient solution drained from the soil surface or leached into the soil profile. The aim of this study was to evaluate the effect of successive applications of organic and mineral nutrient sources on the available content, surface runoff and leaching of P forms in a Typic Hapludalf in no-tillage systems. Experiment 1 was set up in 2004 in the experimental area of UFSM, in Santa Maria (RS, Brazil). The treatments consisted of: control (without nutrient application) and application of pig slurry (PS), pig deep-litter (PL), cattle slurry (CS), and mineral fertilizers (NPK). The rates were determined to meet the N crop requirements of no-tillage black oat and maize, grown in the 2010/2011 growing season. The soil solution was collected after each event (rain + runoff or leaching) and the soluble, particulate and total P contents were measured. In November 2008, soil was collected in 2 cm intervals to a depth of 20 cm, in 5 cm intervals to a depth of 40 cm, and in 10 cm intervals to a depth of 70 cm. The soil was dried and ground, and P determined after extraction by anion exchange resin (AER). In

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experiment 2, samples collected from the Typic Hapludalf near experiment 1 were incubated for 20, 35, 58, 73 and 123 days after applying the following treatments: soil, soil + PS, soil + PL, soil + CS and soil + NPK. Thereafter, the soil was sampled and P was analyzed by AER. The applications of nutrient sources over the years led to an increase in available P and its migration in the soil profile. This led to P transfer via surface runoff and leaching, with the largest transfer being observed in PS and PL treatments, in which most P was applied. The soil available P and P transfer via surface runoff were correlated with the amounts applied, regardless of the P source. However, P transfer by leaching was not correlated with the applied nutrient amount, but rather with the solution amount leached in the soil profile.

Index terms: organic waste, nutrient release, environmental contamination, no-tillage system.

RESUMO: *TEOR DISPONÍVEL, ESCOAMENTO SUPERFICIAL E PERCOLAÇÃO DE FORMAS DE FÓSFORO EM ARGISSOLO COM A ADIÇÃO DE FONTES ORGÂNICAS E MINERAL DE NUTRIENTES*

A aplicação de dejetos de animais no solo pode aumentar a disponibilidade de fósforo às plantas e potencializar a transferência do nutriente pela solução escoada ou percolada. Este trabalho objetivou avaliar o efeito de sucessivas aplicações de fontes orgânicas e mineral de nutrientes sobre o teor disponível, o escoamento superficial e a percolação de formas de P em um Argissolo Vermelho manejado sob sistema plantio direto. O experimento 1 foi desenvolvido em 2004 na área experimental do Departamento de Solos da Universidade Federal de Santa Maria, em Santa Maria, RS, sob plantio direto. Os tratamentos foram testemunha (sem aplicação de nutrientes), dejetos líquidos de suínos (DLS), cama sobreposta de suínos (CSS), dejetos líquidos de bovinos (DLB) e fertilizante mineral (NPK), sendo as doses determinadas para suprir a necessidade de N das culturas. Durante o ano agrícola de 2010/2011 (cultivo de aveia-preta e milho), após cada evento (chuva + escoamento ou percolação), foi coletada solução e determinaram-se os teores de P-solúvel, total e particulado. Em novembro de 2008, amostras de solo foram coletadas estratificadas de 2 em 2 cm, até 20 cm; de 5 em 5 cm, até 40 cm; e 10 em 10 cm, até 70 cm. O solo foi seco, moído e determinado o teor de P extraído pela resina trocadora de ânions (RTA). No experimento 2, os tratamentos foram solo; solo + DLS; solo + CSS; solo + DLB; e solo + NPK. Após 20, 35, 58, 73 e 123 dias de incubação, foram determinados os teores de P extraído por RTA. As aplicações de fontes de nutrientes ao longo dos anos proporcionaram incremento e migração de P-disponível no perfil do solo, refletindo em transferências de P por escoamento superficial e percolação, especialmente no solo com a aplicação de DLS e CSS, onde foi realizada a maior adição do nutriente. Os teores de P disponível no solo e as transferências de P por escoamento superficial correlacionam-se com as quantidades aplicadas, independentemente da fonte de P utilizada. Porém, a transferência de P por percolação não se correlacionou com a quantidade aplicada do nutriente, mas sim com a quantidade de solução percolada no perfil do solo.

Termos de indexação: resíduos orgânicos, liberação de nutrientes, contaminação ambiental, sistema plantio direto.

INTRODUCTION

More than 54 % of the swine production in Brazil is concentrated in the South of the country. The dairy industry of this region is responsible for around 32 % of the domestic milk production (Embrapa, 2012). These two activities generate large volumes of liquid or solid manure due to the high number of animals. Manure can be applied to the soil as nutrient source, for containing N, P and K, to annual crops or pasture, increasing nutrient cycling on the property, which may reduce costs in the purchase of industrialized fertilizers.

The rate of manure application to the soil is established based on its percentage of dry matter, on the nutrient concentration and on the efficiency index. This index refers to the total quantity of nutrients contained in the manure which may be transformed from the organic to the mineral form during the period of crop development (CQFS-RS/SC, 2004). However, frequent manure applications in the same area, especially on soils under no-tillage, may lead to accumulation of nutrients, including P, in surface soil layers (Ceretta et al., 2003; Adeli et al., 2008; Scherer et al., 2010; Guardini et al., 2012a,b; Lourenzi et al., 2013). That is because the P applied on the soil, derived

from manure or mineral fertilization, may be adsorbed with high binding energy to the functional groups in the mineral fraction of the topsoil. Furthermore, the addition of high P quantities to the soil, especially in areas treated with successive manure applications, may reduce the binding energy between the ion and the functional group involved, due to saturation of the adsorption sites. There is thus P accumulation in inorganic labile fractions, especially in the soil surface layers, but also in deeper layers (Gatiboni et al., 2008; Ceretta et al., 2010a; Guardini et al., 2012a; Lourenzi et al., 2013). Among the methods used for evaluating P availability in the soil is the anion exchange resin (AER) method (Bolland et al., 1996; Berwanger et al., 2008; Guardini et al., 2012b), used for determining P availability to plants (CQFS-RS/SC, 2004) and also as an indicator of the contamination potential in soils with sequential application of animal manure (Guardini et al., 2012b).

Phosphorus accumulation in soils with sequential application of manure may intensify nutrient transfer via runoff from the soil surface (Smith et al., 2001; Gessel et al., 2004; Basso et al., 2005; Vadas et al., 2007; Ceretta et al., 2010b), causing eutrophication of surface waters adjacent to the areas treated with organic residues (Correll, 1998; Smith et al., 2007). Moreover, P may be partially leached by the solution into the soil profile, especially in profiles with sandy texture and low organic matter and oxide contents (Kleinman et al., 2009; Sorensen & Rubaek, 2012), leading to contamination of the water table, making the water unsuitable for human consumption.

The P transfer via surface runoff and leaching occurs in soluble and particulate forms. According to Haygarth & Sharpley (2000), soluble P (or dissolved P) is obtained in a filtered solution at $<0.45 \mu\text{m}$, and particulate P is obtained by the difference between the total P of the non-filtered sample and the soluble P (filtered at $<0.45 \mu\text{m}$). Phosphorus transfer by the runoff and leached solution has been addressed in studies in traditional swine-raising countries around the world and in Brazil (Withers et al., 2000; Pote et al., 2001; Daverede et al., 2004; Basso et al., 2005; Ceretta et al., 2005; Kleinman et al., 2009; Ceretta et al., 2010b; Giroto et al., 2013). The P quantities transferred are especially dependent on the quantity of the nutrient applied to the soil; on the soil P content; and on the frequency and volume of rainwater, as well as on the characteristics of the soil and the crop system (Daverede et al., 2004; Hart et al., 2004; Ceretta et al., 2010b). Thus, regional field experiments should investigate soils with sequential application of organic and mineral P sources.

The aim of this study was to evaluate the effect of successive applications of organic and mineral nutrient sources on the available content, surface runoff and leaching of P forms in a Typic Hapludalf under no-tillage management.

MATERIAL AND METHODS

Experiment 1 - Surface runoff and leaching of P in soil treated with nutrient sources

The experiment was set up in 2004 in the experimental area of the Soil Department of the Universidade Federal de Santa Maria, in the region of the central geological depression in the State of Rio Grande do Sul (RS), Brazil (latitude $29^{\circ} 41' 25''$ S and longitude $53^{\circ} 48' 42''$ W), in a Typic Hapludalf (Soil Survey Staff, 1999) under no-tillage management. The climate in the region is humid subtropical, type Cfa 2 (Kottek et al., 2006), with a mean annual temperature of 19.2°C and average rainfall of 1,708 mm (Maluf, 2000).

The treatments consisted of a control (without nutrient application), pig slurry (PS), pig deep-litter (PL), cattle slurry (CS), and mineral fertilizer (NPK). The applied PS came from anaerobic lagoons/slurry ponds of swine-production farms near UFSM, and was composed of feces, urine, feed remains, and wash water of the facilities. The PL came from the swine-raising sector of UFSM, and consisted of residues from rice-cleaning operations, feces, urine, and feed remains. The CS came from anaerobic lagoons/slurry ponds of the cattle-raising sector of UFSM, and was composed of feces, urine, feed remains, and wash water of the facilities. The rates of the organic and mineral sources were determined to meet the N crop requirements, following the recommendation established by the CQFS-RS/SC (2004). The experiment was arranged in a randomized block design with four replications and 25 m^2 plots.

The crop succession used from the time of setting up the experiment was black oat (*Avena strigosa* Schreb.) /maize (*Zea mays* L.). The treatments were applied on an annual basis, always before planting the maize. As of 2010, the option was made to perform two applications, prior to both crop successions. The option was made for this practice so as to better represent the applications made by producers under field conditions. The quantities of N applied prior to crop planting were 30 and 105 kg ha^{-1} N (using urea as N source) for black oat (in 2010) and maize, respectively. For P and K, the quantities applied were calculated according to the rate applied and the content in the manure and, for the NPK treatment, 13.1 and 26.2 kg ha^{-1} P were applied (using triple superphosphate as P source) and 16.7 and 58.3 kg ha^{-1} of K were applied (using potassium chloride as K source), which corresponded to 30 and $60 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ and 20 and $70 \text{ kg ha}^{-1} \text{ K}_2\text{O}$ for black oat (in 2010) and maize, respectively. Thus, from the beginning of the experiment until the 2010/2011 growing season, the total applied nutrient amounts consisted of 1060 kg ha^{-1} N, 393 kg ha^{-1} P and 352 kg ha^{-1} K via PS; 1594 kg ha^{-1} N, 748 kg ha^{-1} P and 1684 kg ha^{-1} K via PL; 1599 kg ha^{-1} N, 288 kg ha^{-1} P and 549 kg ha^{-1} K via CS; and 800 kg ha^{-1} N, 223 kg ha^{-1} P and 333 kg ha^{-1} K via mineral fertilization.

In June 2008, channels were dug to collect the soil surface runoff and lysimeters were installed to capture the solution leached in the soil profile, as described in detail by Basso et al. (2005) and Ceretta et al. (2005). The lysimeters were installed at a soil depth of 70 cm, corresponding to the upper limit of the Bt horizon. In this study, results of the cultivation period of black oat and maize in the 2010/2011 growing season are presented. The characteristics of the manure applied prior to crop planting are shown in table 1. After each event (rain + runoff and/or leaching), the solution was collected and measured, and an aliquot was set aside for later analysis. In the solution collected, the P forms were evaluated, determining the total P contents (total P) by acid digestion, the soluble P contents (soluble P) being determined after filtering the solution through a 0.45 μm membrane, and the particulate P contents (particulate P) being obtained by the difference between total P and soluble P, according to the method described by Haygarth & Sharpley (2000). The P contents in the solutions were determined by colorimetry (Murphy & Riley, 1962).

In November 2008, four years after setting up the experiment, the soil was sampled (layers 0-2, 2-4, 4-6, 6-8, 8-10, 10-12, 12-14, 14-16, 16-18, 18-20, 20-25, 25-30, 30-35, 35-40, 40-50, 50-60, and 60-70 cm). The soil was air-dried, ground by hand with a clod breaker, sieved (2 mm), and stored. The available P contents were extracted by Anion Exchange Resin (AER) (Rheinheimer et al., 2003) and P contents determined by colorimetry (Murphy & Riley, 1962). The data were subjected to analysis of variance and, when significant, the mean values were compared by the Scott-Knott test at 5 % probability.

Experiment 2 - Available P content in soil treated with nutrient sources

In October 2010, soil samples were collected in the 0-10 cm layer, near the area of experiment 1. The soil has the following properties: 58 g kg⁻¹ of clay; 94 g kg⁻¹ of silt; 848 g kg⁻¹ of sand; 19 g kg⁻¹ of organic matter;

pH (H₂O) of 4.9; SMP Index of 6.1; 20.3 mg kg⁻¹ P and 60 mg kg⁻¹ K (extracted by Mehlich-1); 7.3 mg kg⁻¹ N-NH₄⁺; 7.5 mg kg⁻¹ N-NO₃⁻; 814.4 mg kg⁻¹ total N; 0.03 cmol_c dm⁻³ Al³⁺; 0.8 cmol_c dm⁻³ Ca²⁺ and 0.3 cmol_c dm⁻³ Mg²⁺ (extracted from KCl 1 mol L⁻¹); 3.7 cmol_c kg⁻¹ H+Al; 1.3 cmol_c kg⁻¹ of effective Cation Exchange Capacity (CEC_{effective}); 5.0 cmol_c kg⁻¹ CEC at pH 7.0; Al³⁺ saturation of 2.0 % and base saturation of 25.4 %.

The soil was sieved (4 mm) and the moisture content adjusted to 80 % field capacity, determined in a disturbed sample on a suction table (0.01 MPa) (Reinert & Reichert, 2006). Subsequently, 133.4 g of soil was added to an acrylic container with a capacity of 110 mL, which corresponded to the experimental units. Then, the soil in each container was subjected to two compactations (to ensure homogenous density) and, thus, the final volume per container was 100 mL. In this way, the same soil density found in the field was obtained (1.2 kg dm⁻³). Then, the treatments PS, PL, CS and NPK were applied to the soil surface. In addition, there was a control treatment without nutrient application. Each nutrient source applied to maize contained 90 kg ha⁻¹ N (CQFS-RS/SC, 2004). The characteristics of the manure used are shown in table 1. The quantity of P added was 35.6 kg ha⁻¹ for PS; 42.6 kg ha⁻¹ for PL; 21.1 kg ha⁻¹ for CS and 40.0 kg ha⁻¹ with mineral fertilization. In mineral fertilization, the source was triple superphosphate. The containers were placed in 1,500 mL bottles/flasks to avoid excessive moisture loss. The bottles/flasks were stored in an incubation chamber at a constant temperature of 25±1 °C. Every three days, the bottles/flasks containing the experimental units were opened for 15 min in a ventilated area to avoid gas saturation inside. Moisture was monitored daily and, when necessary, distilled water was added to maintain field capacity at 80 %. A randomized complete block design was used, in a 5 × 6 factorial arrangement (treatments × time of evaluation), with four replications.

Soil samples were collected at the beginning of the experiment (time 0) and 20, 35, 58, 73 and 123 days

Table 1. Chemical characteristics of the organic sources used in the experiments

Nutrient source	Characteristic of the nutrient source								
	pH	MS	N-NH ₄ ⁺	N-NO ₃ ⁻	Total N	Total P	Total K	C	C/N
	Black oat 2010								
PS ⁽¹⁾	8.04	4.62	0.133	0.008	0.36	0.13	0.03	4.14	11.50
PL ⁽²⁾	7.15	66.22	0.015	0.094	1.00	0.49	0.54	35.67	35.67
CS ⁽³⁾	7.92	3.66	0.066	0.005	0.20	0.03	0.04	1.84	9.2
	Maize 2010/2011 and incubation								
PS	7.84	0.91	0.057	0.014	0.16	0.13	0.13	1.98	7.92
PL	7.81	56.31	0.003	0.028	0.80	0.40	1.47	27.38	33.2
CS	7.33	5.97	0.052	0.005	0.18	0.04	0.16	2.90	16.11

⁽¹⁾ Pig slurry; ⁽²⁾ Pig deep litter; ⁽³⁾ Cattle slurry.

after the beginning of incubation, equivalent to the phenological stages of maize: sowing; V3 - definition of yield potential; V7-V8 - definition of the number of kernel rows; V10 - definition of ear size and R1 - definition of kernel density and phenological maturity. The sampled soil was separated into two portions. The first portion was subjected to P analysis by AER (Rheinheimer et al., 2003) and the second was used for moisture determination (Tedesco et al., 1995). The data were subjected to analysis of variance and, when significant, the least significant difference (LSD) was obtained by the Tukey test at 5 % probability.

RESULTS AND DISCUSSION

Available P in the soil

The application of organic nutrient sources and mineral fertilizer led to an increase in the available P contents in the soil, especially in the surface layers (Table 2). The greatest increases were observed in the treatment with PL application at a depth of 25 cm, while in the treatments PS, CS and NPK, the increases were significant to a depth of 14, 18 and 4 cm, respectively (Table 2). One of the factors explaining this differentiated behavior is the total P quantity applied in each treatment from the beginning of the experiment (i.e., 393, 748, 288, and 223 kg ha⁻¹ P with the application of PS, PL, CS and NPK,

respectively), since the available P contents in the 0-10 cm layer were significantly correlated with the applied P quantities (Table 4). In relative terms, correlation was seen between the quantity of P applied and the available content of the nutrient because, as there was an increase of 36 % in the quantity of P applied with the use of PS in relation to CS and an increase of 90 % from the PL in relation to the PS, the increases in the available P contents were 39 and 93 %, respectively. Similar behavior was observed in the experiment with soil incubation, where the greatest available P contents were observed in the soil that received the treatment with the greatest addition of P (PL) (Figure 1).

In addition, the form in which P is found in the manure and the management system adopted also contributes to greater accumulations of available P in the soil surface layers. That is because P is predominantly found in inorganic form in the manure, readily available to plants. This may be seen in figure 1, where the greatest available P contents were observed in the first days of soil incubation, which indicates that a large part of the P present in the manure is found in the inorganic form, which is the predominant form of accumulation in soils treated with manure (Chardon et al., 2007; Gatiboni et al., 2008; Ceretta et al., 2010a; Guardini et al., 2012a; Lourenzi et al., 2013). Furthermore, the absence of tilling in the no-tillage system favors P accumulation in the soil surface layers because, in the soil, the P

Table 2. Phosphorus contents extracted by anion exchange resin (AER) in layers of a Typic Hapludalf subjected to applications of nutrient sources under a no-tillage system in November 2008, four years after experimental setup

Layer	Control	PS ⁽²⁾	PL ⁽³⁾	CS ⁽⁴⁾	NPK ⁽⁵⁾
cm	P extracted by AER (mg kg ⁻¹)				
0-2	11.16 aC ⁽¹⁾	50.37 aB	125.31 aA	47.24 aB	17.54 aC
2-4	5.49 aD	46.79 aB	77.26 bA	32.86 bC	10.12 bD
4-6	4.36 aD	32.55 bB	57.20 cA	19.30 cC	5.86 cD
6-8	3.50 aD	21.44 cB	38.56 dA	12.74 dC	6.25 cD
8-10	1.50 aD	18.20 cB	30.32 eA	9.68 dC	4.63 cD
10-12	1.80 aB	19.34 cA	25.60 fA	8.87 dB	4.99 cB
12-14	2.60 aC	18.22 cB	25.20 fA	7.58 dC	4.14 cC
14-16	4.37 aB	16.66 cA	22.33 fA	5.74 eB	3.26 cB
16-18	2.94 aC	12.47 cB	20.01 fA	5.40 eC	4.11 cC
18-20	1.89 aB	5.75 dB	14.82 gA	4.34 eB	1.91 cB
20-25	1.81 aB	3.64 dB	10.55 gA	3.38 eB	0.86 cB
25-30	1.42 aA	4.01 dA	4.44 hA	1.06 eA	0.32 cA
30-35	0.60 aA	3.82 dA	5.44 hA	1.73 eA	1.78 cA
35-40	0.83 aA	3.44 dA	3.31 hA	1.46 eA	1.28 cA
40-50	0.57 aA	1.08 dA	0.98 hA	1.22 eA	0.92 cA
50-60	0.48 aA	0.64 dA	0.93 hA	0.95 eA	0.66 cA
60-70	0.39 aA	0.45 dA	0.68 hA	0.62 eA	0.44 cA

⁽¹⁾ Mean values followed by the same lower case letter in the column and upper case letter in the line do not differ from each other by the Scott-Knott test ($\alpha = 0.05$). ⁽²⁾ Pig slurry; ⁽³⁾ Pig deep litter; ⁽⁴⁾ Cattle slurry; ⁽⁵⁾ Mineral fertilization.

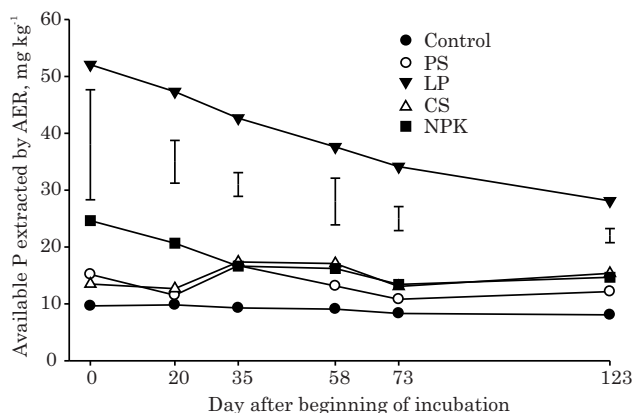


Figure 1. Phosphorus contents extracted by anion exchange resin (AER) in a Typic Hapludalf treated with nutrient sources and incubated for 123 days. The vertical bars represent the least significant difference between the mean values of each treatment (Tukey test at 5 %).

may be adsorbed to the surface of functional groups of reactive particles, normally forming inner sphere complexes (specific adsorption) (Barrow, 1999). As the adsorption sites of the soil reactive particles are finite and have different degrees of affinity for the phosphate ion (Rheinheimer et al., 2000), P is adsorbed initially at those sites that more strongly attract the phosphate ion (Barrow et al., 1998), which may decrease the available P contents in the soil over time, especially in soils with low P contents (Figure 1). However, the addition of high P quantities in the soil reduces the binding energy between phosphate and the reactive particles of the soil (Barrow et al., 1998), allowing P to remain soluble or retained with less binding energy, making it more easily available (Parfitt, 1989). Thus, P can migrate in the soil profile, leading to an increase in the available P content in the deeper soil layers (Table 2). These results are similar to those of Guardini et al. (2012b), who observed greater increases of P extracted by AER to a depth of 20 cm in a Typic Hapludalf under PL applications, in comparison to soil with a history of PS application.

In the 0-10 cm layer, used for diagnosis of soil fertility in a no-tillage system in the South of Brazil (CQFS-RS/SC, 2004), the available P contents observed were 5.2, 33.9, 65.7, 24.4 and 8.9 mg dm⁻³ for the treatments: no fertilization, application of PS, PL, CS and NPK, respectively. This represents an increase of 551, 1163, 368 and 71 % through the application of PS, PL, CS and NPK, respectively, in comparison to the available P contents in unfertilized soil. According to the criteria used by the CQFS-RS/SC (2004), the available P contents observed in the 0-10 cm soil layer are interpreted as low for the soil without application and with application of NPK; high for the soils with application of PS and CS; and very high for the soil with PL application. This shows that, especially for PL, using N contents for determining P rates might

not be the best criterion. The reason is that, after successive manure applications, there was an accumulation of available P in the surface layers and migration in the soil profile, intensifying P transfer via surface runoff (Bertol et al., 2010; Ceretta et al., 2010b; Brennan et al., 2011; Kang et al., 2011) and leaching (Basso et al., 2005; Girotto et al., 2013), which may cause eutrophication of surface and underground water bodies (Correll, 1998; Smith et al., 2007; Ceretta et al., 2010b; Hahn et al., 2012).

P transfer via surface runoff

The transfer in the runoff solution was higher at the greatest rainfall events (Figure 2a,b), indicating a close correlation between these two factors, as also observed by Ceretta et al. (2010b). The greatest transfer in the runoff solution occurred in the treatment without nutrient application to black oat and maize, representing 55 and 43 % of the total rainfall volume, respectively (Table 3). Considering the two crops, the transfer in the runoff solution was on average 49 % of the total rainfall volume in the treatment without nutrient application and 31, 25, 31 and 21 % of the total rainfall volume in the treatments with application of PS, PL, CS and NPK, respectively. This probably occurred because of the greater addition of organic matter in the treatments that received nutrient applications, be it through the concentration of dry matter in the residues added or through the greater production of dry matter of crop residues on the soil (Ceretta et al., 2005; Adeli et al., 2008; Giacomini & Aita, 2008), which leads to an increase in the organic carbon contents in the soil (Lourenzi et al., 2011) and, consequently, improves the capacity of water infiltration in the profile, reducing the transfer of solution via surface runoff (Ceretta et al., 2010b).

The greatest concentrations of soluble P, particulate P and total P in the runoff solution were observed in the first rain events after applying the treatments to black oat (Figures 3a, 4a and 5a) and maize (Figures 3b, 4b and 5b). The reason was that a large part of the P present in the manure was in mineral form (Cassol et al., 2001) and, soon after application to the soil, this induced an increase in the inorganic forms available in the soil (Figure 1). In addition, as the crops have low nutrient demand at the beginning of their development and soil cover is incomplete since the plant canopy is undeveloped, the P applied becomes susceptible to transfer via surface runoff, especially in the first rain events after application (Ceretta et al., 2010b). Similar results were obtained by Smith et al. (2007), who observed greater concentrations of soluble P in the first rains after the application of manure and, according to the authors, the reaction of P added via manure with the soil particles or the formation of co-precipitates with metals, for example Cu, derived from the manure, reduces the P concentration in the solution of the subsequent events.

The greatest transfer of the P forms was observed in the treatments with the application of the greatest quantities of P (PS and PL) (Table 3), showing a close relationship between the quantities applied and P transfer via surface runoff (Table 4). This may be observed in total P, where the PS application led to greater P transfer in black oat, reaching values of 4.44 kg ha⁻¹, and the PL application led to greater P transfer in maize, with values of 6.21 kg ha⁻¹ P (Table 3). For soluble P, the greatest quantities transferred were observed in the soil with PL application, with transfer of 2.63 and 5.60 kg ha⁻¹, for black oat and maize, respectively, while for particulate P, the greatest transfer occurred in the soil with PS application, with values of 2.52 and 0.77 kg ha⁻¹ for black oat and maize, respectively (Table 3).

In addition, the quantities of soluble P and total P transferred via surface runoff were correlated with

the available P contents in the soil, but not with the volume of runoff solution (Table 4). These results are in agreement with the observations of Yu et al. (2006), who highlighted that P transfer via surface runoff is affected by the fertilization rate, by the quantity of labile P in the soil, and by topography, temperature, soil use, and rainfall (intensity and duration). Sweeney et al. (2012), for their part, observed correlation between the transfer of available P via surface runoff and the available P contents in the soil, which may also be one of the important factors in this study since the available P contents in soils with application of PS and PL were greater in comparison to the other treatments (Table 2).

In the period from 2008 to 2011, the mean transfer of soluble P, particulate P and total P were 4.5, 3.5 and 7.2 % of the total soil-applied P in PS; 6.8, 0.5 and 7.7 % of the total in PL; 10.4, 2.7 and 13 % of the total in CS;

Table 3. Total quantity of phosphorus applied, total rainfall and transfer of solution via runoff and leaching and transfer of soluble phosphorus, particulate phosphorus and total phosphorus in surface runoff and leaching from black oat and maize, in a Typic Hapludalf treated with nutrient sources

Treatment	P applied	Quantity transferred			Solution	Rainfall
		Soluble P	Particulate P	Total P		
		kg ha ⁻¹			m ³ ha ⁻¹	
Surface runoff from black oat - 2010						
Control	-	0.32 d ⁽¹⁾	0.22 c	0.54 d	3719 (55.2) ⁽³⁾ a	6738
PS ⁽⁴⁾	34.29	2.51 (6.39) ² a	2.52 (6.71) a	4.44 (11.37) a	2129 (31.6) b	6738
PL ⁽⁵⁾	26.56	2.63 (8.69) a	0.44 (0.83) b	3.26 (10.24) b	2012 (29.9) b	6738
CS ⁽⁶⁾	8.24	1.62 (15.78) b	0.67 (5.46) b	2.30 (21.36) c	2251 (33.4) b	6738
NPK ⁽⁷⁾	13.10	0.96 (4.88) c	0.26 (0.30) c	1.22 (5.19) d	1417 (21.0) c	6738
Leaching from black oat - 2010						
Control	-	0.017 b	0.047 c	0.064 c	744 (11.0) c	6738
PS	34.29	0.010 (0.00) b	0.044 (0.00) c	0.054 (0.00) c	682 (10.1) c	6738
PL	26.56	0.219 (0.76) a	0.126 (0.30) b	0.345 (1.06) a	1101 (16.3) b	6738
CS	8.24	0.022 (0.06) b	0.069 (0.27) c	0.091 (0.33) c	722 (10.7) c	6738
NPK	13.10	0.024 (0.05) b	0.158 (0.85) a	0.183 (0.91) b	1431 (21.2) a	6738
Surface runoff from maize - 2010/2011						
Control	-	0.58 c	0.43 b	1.01 d	1933 (42.8) a	4516
PS	106.95	3.39 (2.63) b	0.77 (0.32) a	4.17 (2.95) b	1419 (31.4) b	4516
PL	102.08	5.60 (4.92) a	0.61 (0.18) a	6.21 (5.09) a	912 (20.2) c	4516
CS	48.69	3.05 (5.07) b	0.23 (0.00) c	3.27 (4.64) c	1271 (28.1) b	4516
NPK	26.20	0.90 (1.22) c	0.13 (0.00) c	1.03 (0.08) d	986 (21.8) c	4516
Leaching from maize - 2010/2011						
Control	-	0.002 c	0.020 a	0.022 c	81 (1.8) c	4516
PS	106.95	0.004 (0.00) c	0.014 (0.00) a	0.018 (0.00) c	43 (1.0) c	4516
PL	102.08	0.193 (0.19) a	0.011 (0.00) b	0.205 (0.18) a	542 (12.0) a	4516
CS	48.69	0.022 (0.04) b	0.019 (0.00) a	0.041 (0.04) b	213 (4.7) b	4516
NPK	26.20	0.002 (0.00) c	0.004 (0.00) c	0.005 (0.00) d	190 (4.2) b	4516

⁽¹⁾ Mean values followed by the same letters in the columns do not differ from each other by the Tukey test ($\alpha=0.05$). ⁽²⁾ The number in parentheses represents the percentage of phosphorus transferred in relation to the total applied, discounting the quantity transferred in the treatment without fertilization; ⁽³⁾ The number in parentheses represents the percentage of solution transferred in relation to the total rainfall in the period; ⁽⁴⁾ Pig slurry; ⁽⁵⁾ Pig deep litter; ⁽⁶⁾ Cattle slurry; ⁽⁷⁾ Mineral fertilization.

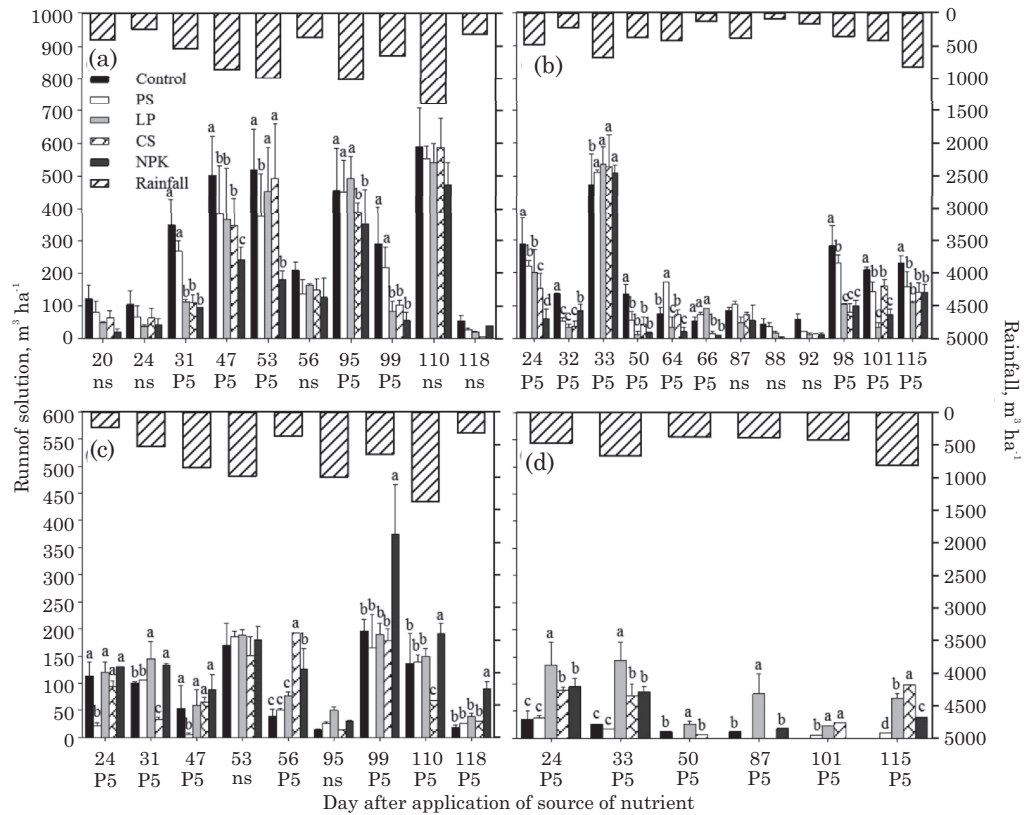


Figure 2. Volume of rainfall, runoff solution on the soil surface from black oat (a) and maize (b) and volume of the leached solution from black oat (c) and maize (d), in a Typic Hapludalf treated with nutrient sources. P5: significant at 5 % probability by the Scott-Knott test; ns: not significant at 5 % probability.

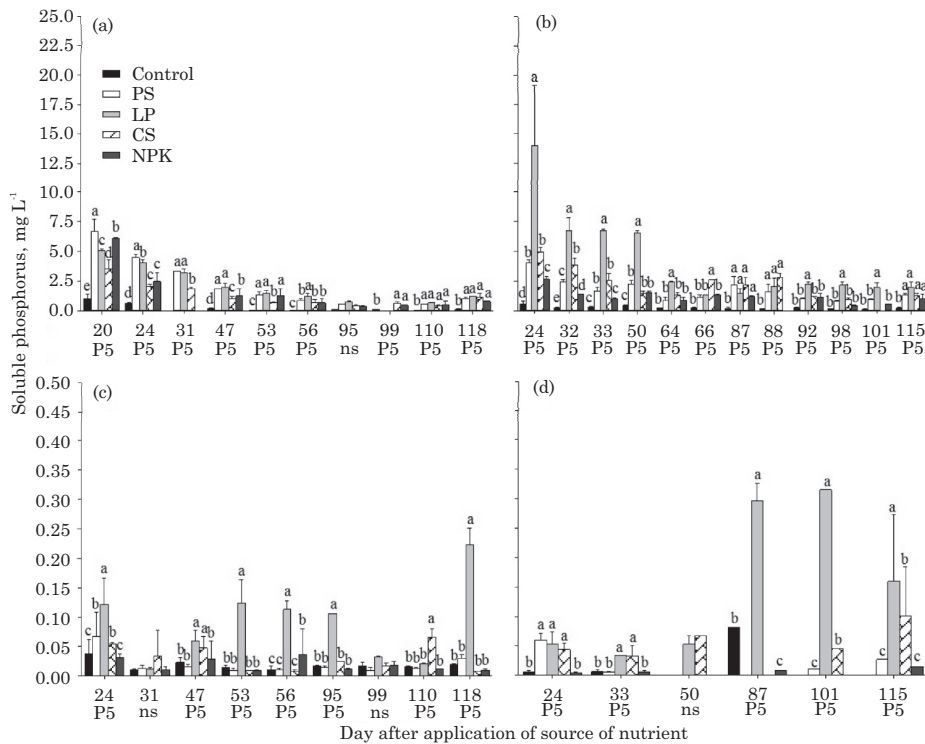


Figure 3. Soluble phosphorus content in the runoff solution on the soil surface from black oat (a) and maize (b); and in the leached solution from black oat (c) and maize (d), in a Typic Hapludalf treated with nutrient sources. P5: significant at 5 % probability by the Scott-Knott test; ns: not significant at 5 % probability.

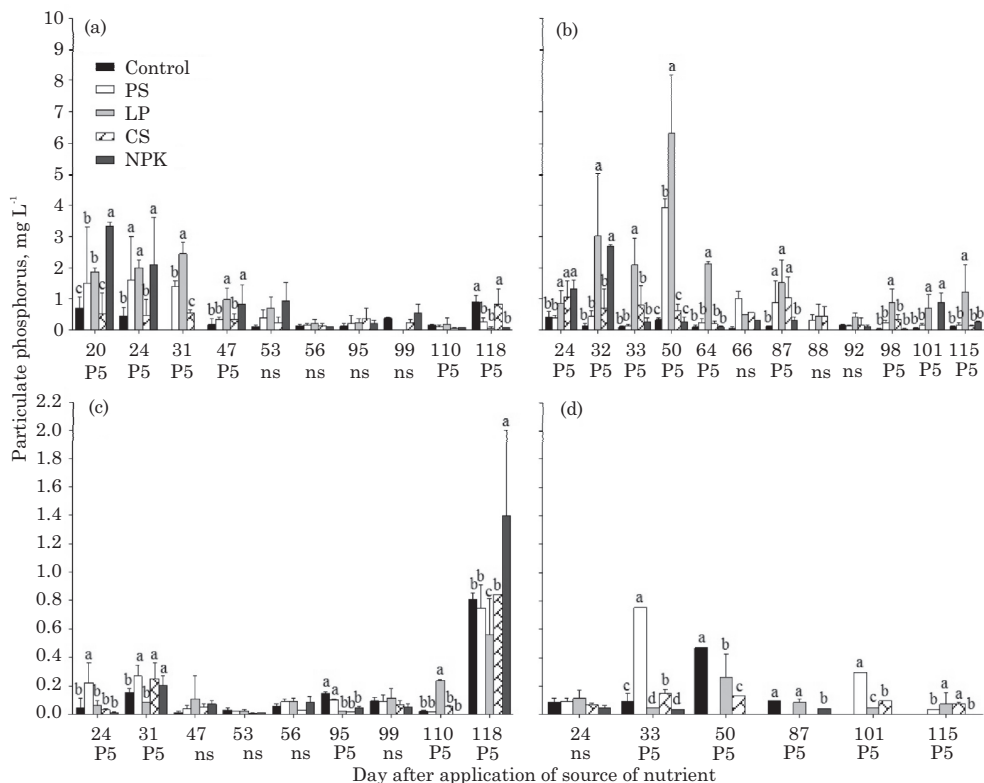


Figure 4. Particulate phosphorus content in the runoff solution on the soil surface from black oat (a) and maize (b); and in the leached solution from black oat (c) and maize (d), in a Typic Hapludalf treated with nutrient sources. P5: significant at 5 % probability by the Scott-Knott test; ns: not significant at 5 % probability.

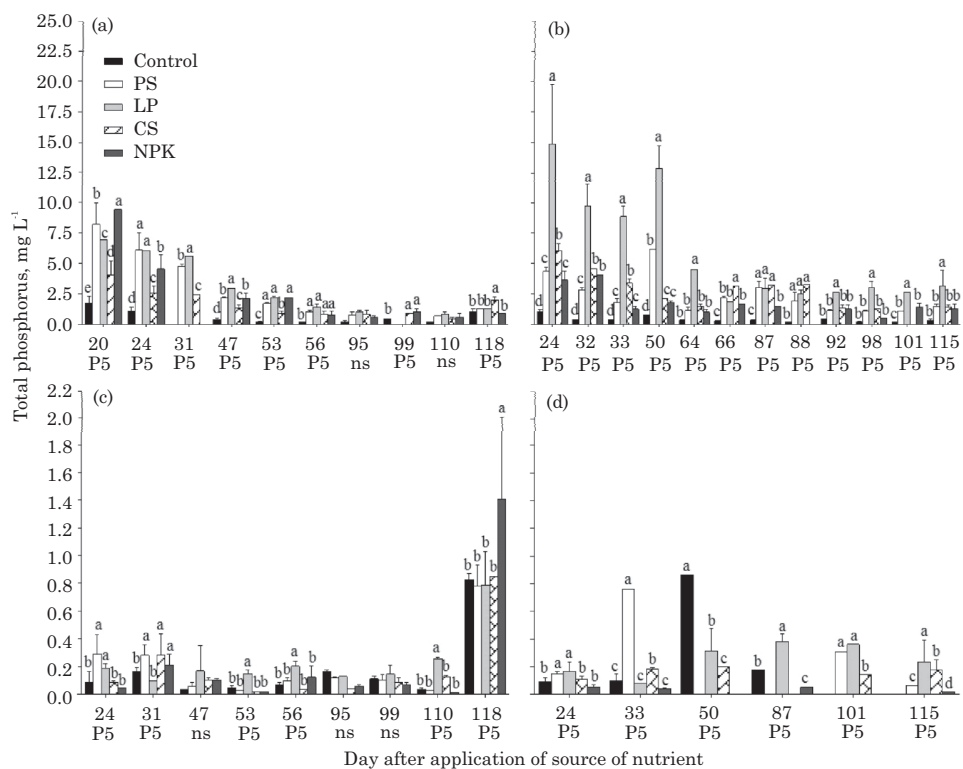


Figure 5. Total phosphorus content in the runoff solution on the soil surface from black oat (a) and maize (b); and in the leached solution from black oat (c) and maize (d), in a Typic Hapludalf treated with nutrient sources. P5: significant at 5 % probability by the Scott-Knott test; ns: not significant at 5 % probability.

Table 4. Pearson's correlation coefficient (r) involving the P quantities applied, available P contents in the soil, transfer of solution, soluble P, particulate P and total P in surface runoff and leaching in a Typic Hapludalf treated with nutrient sources

Variable	P applied ⁽¹⁾ × P content in the soil		
	Black oat	Maize	Throughout the period of the experiment
Available P ⁽²⁾	0.69*	0.84*	0.81*
	P applied × P transfer via surface runoff		
Soluble P	0.85*	0.87*	0.89*
Particulate P	0.73*	0.57*	0.72*
Total P	0.86*	0.89*	0.93*
	P applied × P transfer through leaching		
Soluble P	ns	0.55*	0.49*
Particulate P	ns	ns	ns
Total P	ns	0.54*	ns
	Available P × P transfer via surface runoff		
Soluble P	0.86*	0.96*	0.95*
Particulate P	ns	ns	ns
Total P	0.67*	0.95	0.88*
	Available P × P transfer through leaching		
Soluble P	0.77*	0.87*	0.83*
Particulate P	ns	ns	ns
Total P	0.66*	0.86	0.77*
	Runoff solution × P transfer via surface runoff		
	Black oat	Maize	Year 2010/2011
Soluble P	ns	ns	ns
Particulate P	ns	ns	ns
Total P	ns	ns	ns
	Runoff solution × P transfer through leaching		
Soluble P	ns	0.91*	0.60*
Particulate P	0.86*	ns	0.86*
Total P	0.58*	0.90*	0.73*

⁽¹⁾ Quantity of P applied to the soil in the different treatments since the year 2004; ⁽²⁾ Available P content in the 0-10 cm soil layer; * significant at 5 % probability by the t test; ns: not significant.

and 3.0, 0.15 and 2.6 % of the total applied through NPK, respectively. These low values of P transferred via surface runoff in the different nutrient sources are similar to the results obtained by Bertol et al. (2010), who observed P transfer via surface runoff of less than 15 % of the total applied and suggested that the P remains accumulated in the soil surface layer, as verified in the present study (Table 2) and in other studies (Adeli et al, 2008; Scherer et al., 2010; Ceretta et al., 2010a; Guardini et al., 2012a). Nevertheless, after successive manure applications, there is a tendency for saturation of adsorption sites of the reactive particles of the soil. Thus, the added P will remain in the soil solution or it will be adsorbed to sites of lesser affinity and thus be more susceptible to migration in the profile (Lourenzi et al., 2013) or to transfer by the runoff solution on the soil surface (Smith et al., 2001; Ceretta et al., 2010b).

P transfer through leaching

The transfer of the leached solution was greater during black oat growth, with various events

exhibiting volumes greater than 100 m³ ha⁻¹ (Figure 2c) while, for maize, similar values were observed only in two events, in the soil with PL application (Figure 2d). However, the volumes of leached solution are not closely correlated with the rainfall volumes, as may be seen in the comparison of events that occurred after 95 and 99 days after application of the treatments in the oat crop (Figure 2c). A similar behavior was observed by Giroto et al. (2013) in a study evaluating the transfer of solution and nutrients by leaching in soil subjected to applications of 0, 20, 40 and 80 m³ ha⁻¹ PS. During the period of evaluation, the transfer of leached solution was, on average, 6.4 % of the total rainfall in the treatment without nutrient application and 5.6, 14.1, 7.7 and 12.7 % of the total rainfall in the treatments with application of PS, PL, CS and NPK, respectively. These results show the tendency to greater leaching where nutrients were applied. This may be attributed to the lower volume transferred by surface runoff in these treatments (Table 3), as a result of greater production and deposition of crop

dry matter on the soil surface, as observed by Ceretta et al. (2010b), which improves water infiltration in the soil.

The greatest concentrations of P forms in the leached solution, especially soluble P and total P, were observed, in most events, in the soil with PL application to black oat and maize (Figures 3c, 3d, 5c and 5d). In addition, the greatest transfer of soluble P and total P was observed in the soil with PL application (0.219 and 0.345 kg ha⁻¹ for black oat and 0.193 and 0.205 kg ha⁻¹ for maize, respectively) (Table 3), showing a close correlation with the available P contents in the soil (Table 4). On average, transfer of soluble P through leaching was 0.00, 0.48, 0.05 and 0.02 % of the total applied with PS, PL, CS and NPK, respectively, and, for total P, transfer through leaching was 0.00, 0.62, 0.18 and 0.45 % of the total applied with PS, PL, CS and NPK, respectively. For particulate P, the greatest transfer was observed with the application of NPK to black oat (0.158 kg ha⁻¹ or 0.85 % of the total applied) (Table 3).

Low values of P transferred by leaching in the different forms were also reported by Basso et al. (2005), who did not observe an expressive effect of PS application on the P concentration in the leached solution, and indicated that the surface nutrient applications favor P adsorption and accumulation in the soil surface layers. Nevertheless, with successive nutrient applications, saturation may occur at the adsorption sites of inorganic particles of the soil surface layers, promoting P migration in the soil profile (Table 2), which is in agreement with the data obtained by Lourenzi et al. (2013) in a Typic Hapludalf after 19 PS applications. For their part, Giroto et al. (2013), in a study performed with the application of 0, 20, 40 and 80 m³ ha⁻¹ PS, also emphasize that the P quantities applied in manure and the increase in the available content of the nutrient in the soil are the main factors that contribute to P transfer through leaching. Thus, the results obtained in this study show that the transfer of P forms through leaching were closely correlated to the P quantities applied, the P contents available in the soil, and the volume of leached solution (Table 4).

CONCLUSIONS

1. The applications of nutrient sources over the years led to an increase and migration of available P in the soil profile. This was reflected in P transfer via surface runoff and leaching, especially in the soil with the application of pig slurry and pig deep litter, where the amount of P applied was highest.

2. The available P contents in the soil and the P transfer via surface runoff correlate with the quantities applied, regardless of the source of P used. However, P transfer by leaching did not correlate with

the quantity of the nutrient applied, but rather with the quantity of the leached solution in the soil profile.

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