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Nutrient transfer by runoff under no tillage in a soil treated with successive applications of pig slurry

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ABSTRACT

High rates and successive applications of pig slurry can cause nutrient transfer by surface runoff. The aim of this study was to evaluate the importance of surface runoff in transferring nitrogen (N), phosphorus (P) and potassium (K) under a no tillage system and for successive applications of pig slurry. The research was carried out in the Agricultural Engineering Department of the Federal University of Santa Maria, Brazil, from 2002 to 2007 in a Typic Hapludalf soil. Pig slurry rates of 0, 20, 40 and 80 m^3 ha^{-1} were applied, scattered on the surface, before the sowing of each species in a cultivation sequence. On average 119, 238 and 475 kg ha^{-1} yr^{-1} of N; 102, 203 and 406 kg ha^{-1} yr^{-1} of P and 43, 87 and 173 kg ha^{-1} yr^{-1} of K were added, for rates of 20, 40 and 80 m^3 ha^{-1} of pig slurry, respectively. Samples of water runoff from the soil surface were collected during the entire period and the minerals, N, P and K were determined. Successive applications of pig slurry decreased surface runoff. In relative terms, the K losses were higher than N and P. As regards total nutrients applied through pig slurry, losses through surface runoff were of 2.74, 1.61 and 1.37% of mineral N; 6.29, 5.01 and 3.51% of available P and 17.16, 9.01 and 11.14% of [illegible] ry on a [illegible] uence: [illegible] losses of P are positively related to the quantities of P added through pig slurry. Applications of pig slurry along the years decrease the surface runoff.

1. Introduction

In the southern region of Brazil, swine breeding mainly occurs on small farms. Since 1990s, the number of swine farms has increased, elevating the risk of excess manure application. Most producers apply high rates of manure on the same areas, as a way of disposal of excess manure production, unaware of the real nutritional needs of the cultivated plants and of possible soil and water pollution.

In countries such as the United States, France and Canada, where swine breeding is practiced in an intensive manner, application of pig slurry on land has caused soil and water contamination. This has led to changes in environmental legislation to enhance protection of the environment (Jongbloed et al., 1999). In Brazil, the State Environmental Protection Foundation in the State of Rio Grande do Sul, in the Southern region of Brazil (FEPAM, 2004), established that the application of pig slurry has to be based on soil analysis and plant nutrient demand. However, these guidelines do not provide information regarding the maximum rate at which manure becomes a contaminant for soil and water. In the European Union (EU) Nitrate Directive, it is stipulated that the maximum amount of manure N that can be applied on a vulnerable zone is limited to 170 kg ha^{-1} yr^{-1} (Bergström and Kirchmann, 2006). In 2001, almost 40% of the total EU land area was designated (or scheduled to be designated) as nitrate vulnerable. Most countries also restrict manure application during parts of the year, for example in the Netherlands, where manure cannot be applied from September 15th to February 1st (Bergström and Kirchmann, 2006).

Due to the predominance of no tillage system in more than 80% of total cropland in southern Brazil (Amado et al., 2006), pig slurry are applied predominantly in the soil surface, which can increase nutrient loss by runoff. This is due to continuous applications of pig slurry increase the amount of nutrients, such as nitrogen (N), phosphorus (P) and potassium (K), on the soil surface, exceeding crop nutrient requirements (Adeli et al., 2003) and increasing their

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potential transfer by surface runoff (Smith et al., 2001a; Gessel et al., 2004; Basso et al., 2005; Vadas et al., 2007; Ceretta et al., 2010).

Approximately 60% of N contained in manure is found in the ammonium N form (mineral form), which is quickly and easily transformed into nitrate in the soil (Diez et al., 2001; Payet et al., 2009). Most of the P of pig slurry is in an inorganic form (Cassol et al., 2001), the main form of nutrient accumulation in the soil (Hooda et al., 2001). The long-term application of manure to soils has been shown to decrease P sorption (Siddique and Robinson, 2003; Berwanger et al., 2008) because P, in general, is absorbed by the most avid sites (Barrow et al., 1998). The remainder – the left-over P – is retained in lower energy fractions which can be more bio-available and easily transferred by water. The K in the manure is found predominantly in the mineral form (Kayser and Isselstein, 2005), which is soluble and, therefore, more easily transferred by surface runoff.

The application of pig slurry on the soil surface and the evaluation of nutrient transfer in surface runoff have been the subject of many studies (Young and Mutchler, 1976; Steenhuis et al., 1981; Edwards and Daniel, 1993; Withers et al., 2000; Pote et al., 2001; Davede et al., 2004; Kleinman et al., 2009), also in the southern region of Brazil (Basso et al., 2005; Ceretta et al., 2005). In this region, Ceretta et al. (2005) conducted a study with application of 0, 20, 40 and 80 $m^3 ha^{-1}$ of pig slurry over a period of two years in Alfisol soil under no tillage system. These authors mention that losses of N and P by surface runoff are related to the amounts of nutrients applied with manure and the interval between application and first runoff. However, it has been demonstrated that there is high variability in the amount of nutrients transferred via surface runoff depending on precipitation, and edaphic and agronomic factors (Daverede et al., 2003; Hart et al., 2004). The knowledge of N and P nutrient transfer is important to estimate the eutrophication potential of waters, which decreases the oxygen level and the diversity of aquatic species (Correll, 1998; Smith et al., 2001b, 2007).

The aim of this study was to evaluate the importance of surface runoff in transferring nitrogen, phosphorus and potassium under a no tillage system and for successive applications of pig slurry.

2. Materials and methods

2.1. Site description, treatment and evaluations

The experiment was carried out in the experimental area of the Agricultural Engineering Department of the Federal University of Santa Maria (RS), Brazil (latitude S29°43′; longitude W53°42′), in a Typic Hapludalf soil (Soil Survey Staff, 1999), with sandy loam surface texture and on a 4% slope. The area had been kept under a no tillage system for the eight years prior to the year 2000, when the experiment began. In March 2000 the area was sampled in the layer of 0–10 cm. The results of the analyses were clay 170 $g kg^{-1}$, silt 300 $g kg^{-1}$, sand 530 $g kg^{-1}$, pH-H_2O 4.7, soil organic matter 16 $g dm^{-3}$, Al 0.8 $cmol_c dm^{-3}$ (extracted by KCl 1 $mol L^{-1}$), Ca 2.7 $cmol_c dm^{-3}$ (extracted by KCl 1 $mol L^{-1}$), Mg 1.1 $cmol_c dm^{-3}$ (extracted by KCl 1 $mol L^{-1}$), P (extracted by Mehlich 1; HCl 0.05 $mol L^{-1}$ + H_2SO_4 0.0125 $mol L^{-1}$) 15.0 $mg dm^{-3}$ and 96 $mg dm^{-3}$ of K (extracted by Mehlich 1). The evaluations included in this paper were conducted from 2002 to 2007.

Since May 2002 the experimental field has been managed under the following crop sequence: black oats (*Avena strigosa* Schreb.), pearl millet (*Pennisetum americanum L.*), and black beans (*Phaseolus vulgaris L.*) in 2002; black oats/common vetch (*Vicia sativa L.*) and maize in 2002/2003 and 2003/2004; black oats, black beans and sunnhemp (*Crotalaria juncea L.*) in 2005/2006 and black oats and maize 2006/2007. Maize and black beans are grown during spring and summer as cash crops. Moreover, common vetch and black oats are grown during the winter while sunnhemp and pearl are grown during the spring as cover crops. All produced stubble was left on soil surface.

First pig slurry rates of 0, 20, 40 and 80 $m^3 ha^{-1}$ were applied on a total area of 12 m^2 (4 m × 3 m) in May 2000. The annual applications of manure and crops are shown in Table 1. After the harvest of grain, in summer crops, or flowering, in winter crops, the plants were desiccated and, under cultural residues, pig slurry was applied for the next crop. The pig slurry was scattered on the soil surface one day before the sowing of each species, without incorporating it into the soil. During the years of 2002 to 2007 twelve applications of manure were carried out, which, added to the six applications applied before 2002, since 2000, result in a total of eighteen pig slurry applications.

A random block experimental design with four replications was used. In each plot, metallic scaffolding was installed (0.75 m × 0.50 m). The metal structure was inserted into the soil to a depth of 5 cm. The surface runoff was conducted with a hard-wired collecting gutter connected to a hose, which was connected to a collecting container (20 L), where the surface runoff was stored (Ceretta et al., 2005). After each rainfall event, with sufficient runoff volume for analysis, the stored runoff volume was removed from collectors, its volume was measured and a sample (±300 mL) was taken to the laboratory for analysis. The amounts of surface runoff volume collected in each rainfall event, in the five crops evaluated, are presented in Fig. 1.

2.2. Nutrient analysis

The mineral N concentrations were determined using unfiltered samples of surface runoff and 20 mL of the sample collected in the field was distilled and then 0.2 g of MgO was added. The ammonium concentration (NH_4^+–N) was determined in a Kjeldahl half-micron vapor distiller, the distilled material being collected in boric acid and the entitlement of the extract carried out with diluted H_2SO_4 (Tedesco et al., 1995). In another sample 0.2 g of Devarda's alloy was added for the determination of the NO_3^-–N concentration (Tedesco et al., 1995).

The concentrations of P and K were determined using unfiltered samples of surface runoff. Fifty milligrams of the collected field solution samples of each experimental unit, with material in suspension, were placed in 100 mL snap-cap bottles, and then, 1 mL of HCl 0.11 $mol L^{-1}$ (PA) (extracting solution) was added. The samples were agitated for 10 min intermittently and then left to rest for 16 h. Afterwards, 5 mL of the extract was removed and the P content was determined by the Murphy and Riley (1962) method and the K by flame spectrometry (B262 Micronal).

For total N determination in the samples of pig slurry, the liquid and pasty fractions were separated. This procedure is necessary to calculate the proportions of both sample fractions to be weighed to assess the levels of N originally present in pig slurry, avoiding unrepresentative sampling. Approximately 50 g of manure were centrifuged for 20 min at 1500 g, obtaining two fractions. Then 0.2 g of pasty fraction was collected in a digestion pipe of 50 mL and a proportional amount of liquid added, thus reconstituting the two fractions originally present in the manure. Afterwards, 2 mL of concentrated sulfuric acid, 2 mL of 30% hydrogen peroxide, and 0.7 g of a digestion mixture (Na_2SO_4 + $CuSO_4 \cdot 5H_2O$) were added (Tedesco et al., 1995). Then 10 mL of the sample was distilled in a drag distiller of half-micron vapor Kjeldahl, with the addition of 5 mL of NaOH 10 N. The distilled fraction was collected in indicator boric acid and titled with H_2SO_4 0.05 N.

For total P and K analysis, pig slurry was dried in a laboratory drying oven with air temperature at 65 °C, until constant mass was obtained. Afterwards, 0.2 g of dried pig slurry were weighed and put in a distillation pipe of 50 mL and 2 mL of concentrated sulfuric acid, 1 mL of 30% hydrogen peroxide, and 0.7 g of a digestion

Table 1
Characteristics of the pig slurry applied before the sowing of each culture of the sequence.

Pig slurry characteristics	Nutrient applied before each culture											
Dry matter %	Third agricultural year (2002/2003)											
	Black oat 0.47 Application (kg ha^{-1})				Maize 6.68 Application (kg ha^{-1})				Black bean 4.82 Application (kg ha^{-1})			
	%	20	40	80	%	20	40	80	%	20	40	80
Total-N[a]	0.11	22.0	44.0	88.0	0.75	150.0	300.0	600.0	0.22	44.0	88.0	176.0
Total phosphorus[b]	2.12	2.0	4.0	8.0	1.19	15.9	31.8	63.6	2.95	28.4	56.8	113.6
Total potassium[b]	0.41	0.4	0.8	1.6	0.72	9.6	19.2	38.5	1.50	14.5	28.9	57.8
Dry matter %	Fourth agricultural year (2003/2004)											
	Black oat + common Vetch 2.37 Application (kg ha^{-1})				Maize 2.07 Application (kg ha^{-1})							
	%	20	40	80	%	20	40	80				
Total-N[a]	0.28	56.0	112.0	224.0	0.40	80.0	160.0	320.0				
Total phosphorus[b)]	3.41	16.2	32.3	64.6	3.33	13.8	27.6	55.2				
Total potassium[b]	2.90	13.7	27.5	55.0	4.58	19.0	38.0	76.0				
Dry matter %	Fifth agricultural year (2004/2005)											
	Black oat + common vetch 1.0 Application (kg ha^{-1})				Maize 7.2 Application (kg ha^{-1})							
	%	20	40	80	%	20	40	80				
N-total[a]	0.06	12.0	24.0	48.0	0.37	74.0	148.0	296.0				
Total phosphorus[b]	4.22	8.4	16.8	33.6	5.58	80.3	160.6	321.2				
Total potassium[b]	10.13	20.3	40.5	81.0	1.27	18.3	36.6	73.2				
Dry substance %	Sixth agricultural year (2005/2006)											
	Black oat 6.8 Application (kg ha^{-1})				Black bean 8.9 Application (kg ha^{-1})				Sunnhemp 12.14 Application (kg ha$^{-1)}$			
	%	20	40	80	%	20	40	80	%	20	40	80
N-total[a]	0.30	60.0	120.0	240.0	0.12	24.0	48.0	96.0	0.10	20.0	40.0	80.0
Total phosphorus[b]	2.95	40.1	80.2	160.4	4.43	60.2	120.5	241.0	4.79	116.3	232.6	465.2
Total potassium[b]	0.91	12.4	24.8	49.6	2.44	33.2	66.4	132.8	1.01	24.5	49.0	98.0
Dry matter %	Seventh agricultural year (2006/2007)											
	Black oat 9.94 Application (kg ha^{-1})				Maize 1.91 Application (kg ha^{-1})							
	%	20	40	80	%	20	40	80				
N-total[a]	0.10	20.0	40.0	80.0	0.16	32.0	64.0	128.0				
Total phosphorus[b]	5.37	106.7	213.5	427.0	5.18	19.8	39.6	79.2				
Total potassium[b]	1.85	36.8	73.6	147.2	3.56	13.6	27.2	54.4				

[a] Analyses and calculations on a humid weight base.
[b] Analyses and calculations on a dry weight base.

mixture ($Na_2SO_4 + CuSO_4{\cdot}5H_2O$) were added (Tedesco et al., 1995). At the end of the digestion process, the phosphorus content was determined by the Murphy and Riley (1962) method and the K by flame spectrometry (B262 Micronal). The dry matter content and the total amounts of N, P and K applied via pig slurry are presented in Table 1.

The amount of inorganic P in the manure was determined with the use of anion exchanging resins. The extraction process was carried out in 11 mL glass test tubes, using 0.2 g of manure dry fraction, adding a resin anion exchanging in 2.5 cm × 3.0 cm blades, saturated in bicarbonate (Cassol et al., 2001) and 10 mL of de-ionized water. The suspension was agitated for 16 h in an end-over-end agitator at 27 rpm. The P restrained in the blades was recovered with 20 mL of HCl 0.5 mol L^{-1} and the P content was determined by the Murphy and Riley (1962) method in an aliquot of 3 mL of extract.

Total N determination in the soil was carried out in a layer of 0–10 cm. Samples were collected after eighteen pig slurry applications and dried in a laboratory drying oven with air temperature at 65 °C, until constant mass was obtained. Afterwards, 0.5 g of dried soil was weighed and put in a distillation pipe of 50 mL and 2 mL of concentrated sulfuric acid, 1 mL of 30% hydrogen peroxide, and 0.7 g of a digestion mixture ($Na_2SO_4 + CuSO_4{\cdot}5H_2O$) were added (Tedesco et al., 1995). Then, to determine total N, the same methodology mentioned above was used to determine total N in pig slurry. Soil samples were extracted by Mehlich 1 (Tedesco et al., 1995), and the extracts were analyzed for the determination of P and K. At the end of the extraction process, the P was determined by the Murphy and Riley (1962) method and the potassium by flame spectrometry (B262 Micronal).

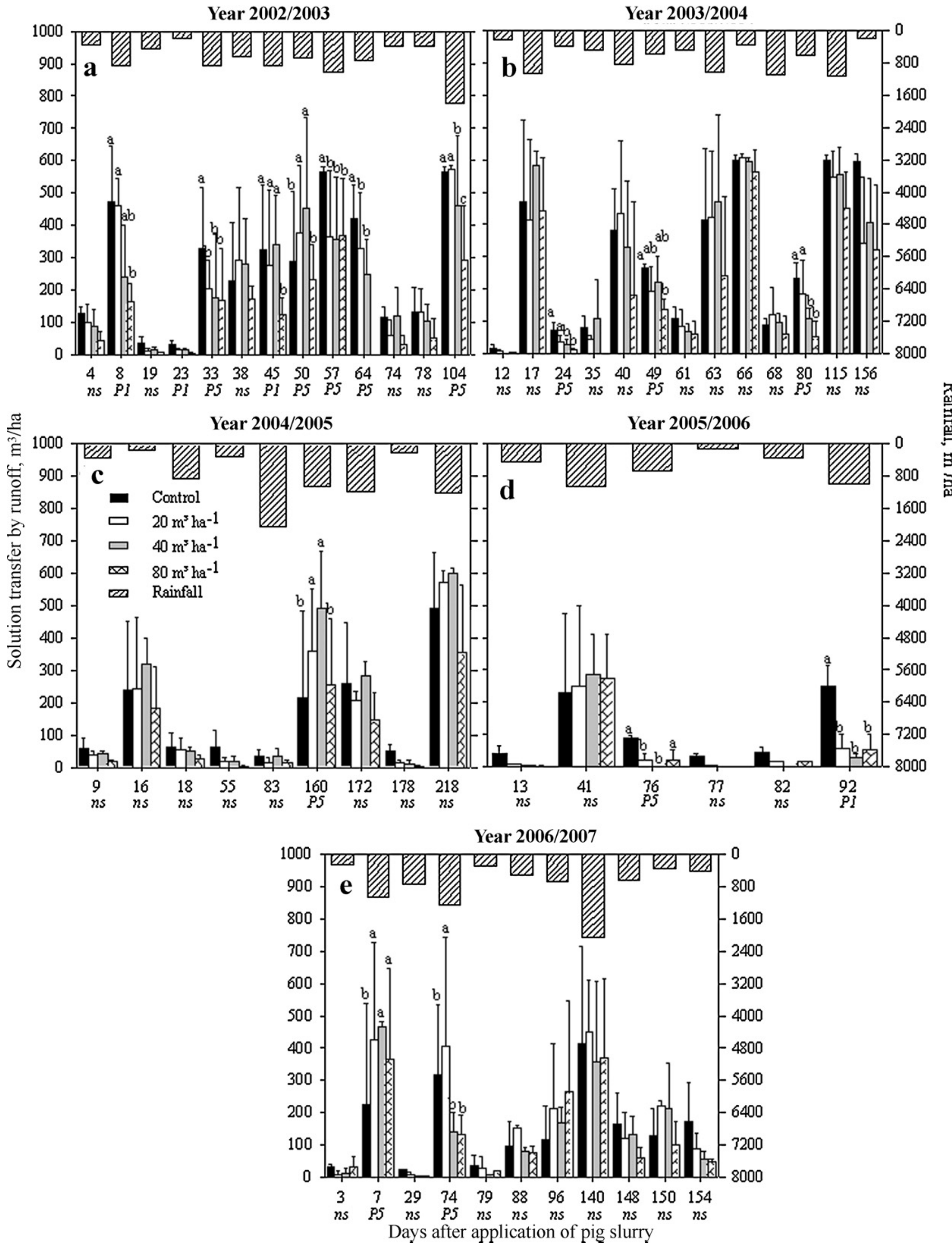

Fig. 1. Solution transfer by surface runoff in the cultures of black bean (2002/2003) (a), maize (2003/2004) (b), maize (2004/2005) (c), black bean (2005/2006) (d) and maize (2006/2007) (e), in area under successive applications of pig slurry and no tillage (bars indicate standard errors). Significance levels were obtained through (are from) ANOVA testing for differences between treatment means. Letters designate differences between treatment means identified by Tukey–Kramer multiple comparison tests, while n.s. denotes statistical similarity amongst means.

2.3. Statistical treatment of the data

Analysis of variance (ANOVA) was performed to determine treatment effects on runoff, and nitrate, P and K losses in runoff. Differences between treatment effects were determined using the Tukey–Kramer test. Treatment means were compared using the least square difference (LSD) with a significance level of $P < 0.05$. Linear regression analysis was used to test the significance of time trends in nitrate, P, K and runoff at $P < 0.05$. Pearson statistical tests were performed to test correlations between different runoff and nitrate, P and K. All statistical analyses were performed using SISVAR (Ferreira, 2008).

3. Results and discussion

3.1. Surface runoff volume and loss of mineral nitrogen

There was good correlation between runoff volume and rainfall (Fig. 2). However, the larger volume of solution transferred by runoff, in general, was variable depending on the rainfall that occurred in each solution collected (Fig. 1). The greatest runoff was observed in the year 2002/2003, when the rainfall was 56% higher than the average rainfall of the five years of evaluation. Generally, runoff decreased with increased slurry rate (Table 2). This probably occurred because increased rate of pig slurry resulted in higher dry matter yield by plants, resulting in higher input of residues in the soil surface which protected the soil leading to reduced runoff, as observed by Andraski et al. (2003). In addition, the application of pig slurry can increase the level of organic matter in soil, increasing the water infiltration in soil.

The average water loss by runoff was 36, 30, 28 and 20% of rainfall during the five years of study, with doses of 0, 20, 40 and 80 m^3 ha^{-1} of pig slurry, respectively. These results are similar to those found by Bertol et al. (2008), who reported losses of water by runoff in soil under no tillage system varying from 24% to 30% of total precipitation, in the study conducted in different cropping systems under simulated rainfall in southern Brazil. In addition, these authors reported water losses by runoff are influenced by the type of management and soil cover.

The total N applied to the soil between 2002 and 2007 was 594, 1188 and 2376 kg ha^{-1}, corresponding to the pig slurry supply rates of 20, 40 and 80 m^3 ha^{-1}, respectively. In a previous survey on the same experimental site, Basso et al. (2004) determined that the N losses by volatilization amounted to an average of 23, 24 and 26%, for the rates of 20, 40 and 80 m^3 ha^{-1}, respectively. Considering the N losses by volatilization, the total N amounts effectively added to the soil, in the last five years, were 457, 903 and 1758 kg ha^{-1}.

As the current study spanned a period of five years (2002–2007), in an area where manure had been previously applied for two years, it was considered that the total amount of N applied in seven years could be transformed into mineral N in the soil. From total N applied in the soil by pig slurry (Tables 1 and 2) over the period of five years, the amounts of mineral N lost through surface runoff were of 16, 19 and 33 kg ha^{-1}, with an average of 3.3, 3.9 and 5.5 kg ha^{-1} yr^{-1}, corresponding to the pig slurry supply rates of 20, 40 and 80 m^3 ha^{-1}, respectively. These data also consider the amounts of mineral N lost from the control areas where manure was not applied. In five years, the amounts of mineral N lost through surface runoff in control plots was 46.69 kg ha^{-1}. The source of this N probably was N fixation by legumes such as *Vicia sativa L.*, *Crotalaria juncea L.*, *Phaseolus vulgaris L.* and the mineralization of soil organic matter.

The transfers of mineral N by surface runoff were only correlated with the rate of pig slurry applied in the fifth year of assessment (2006–2007) (Table 3). Moreover, the lost amount of mineral N in the treatments with successive application of pig slurry was correlated with runoff accumulated over the five years of evaluation. Corroborating with these results, other studies have demonstrated that the lost amount of total N and NO_3^-–N in runoff is directly affected by the amount of runoff volume (Borin et al., 2005). This result suggests that adoption of agricultural practices that can decrease runoff volume and increase infiltration may be the effective long-term strategy to reduce mineral N in farms with application of pig slurry. In addition, Randall and Mulla (2001) reported that the largest N losses in an agricultural field occurred after frequent precipitation events with above normal precipitation and when crops were not actively growing.

In addition, the transfers of mineral N by surface runoff can be considered small in comparison to the total amount of N added with pig slurry. This suggests that there can be other destinations for the N in the soil–plant system. In the same experiment, Basso et al. (2005) demonstrated that, from 2000 to 2002, the amount of mineral N lost through subsurface drainage was also small: the accumulated transfers were of 1.4, 0.7 and 2.1% on average, considering the amount of total N added, corresponding to the application of 20, 40 and 80 m^3 ha^{-1} of pig slurry, respectively. Part of the N applied by manure was absorbed and exported with the grains. Part of the N also accumulated in the soil. The total soil N contained in the layer 0–10 cm of soil was of 1.07 mg kg^{-1} in the control treatment and of 1.19, 1.24 and 1.59 mg kg^{-1} where pig slurry was applied.

Nitrate losses are important with respect to environmental pollution. The maximum limit for nitrate in water, for the water to be used for human consumption, has been fixed at 10 mg L^{-1} (CONAMA, 2005). This level is often exceeded in the surface runoff during the cultivation of some commercially important crop species. This is shown in Fig. 2 where NO_3^-–N concentrations were greater than 10 mg L^{-1} in the surface runoff during the cultivation of black beans and maize, for all the input rates. It is known that, generally, pig slurry, after its application, contains higher amounts of NH_4^+–N than of NO_3^-–N (Smith et al., 2007). As the NH_4^+–N of the pig slurry is quickly nitrified, even without its incorporation into the ground, 15–20 days after application, the nitrate can already be predominant (NO_3^-–N) (Aita et al., 2007).

The highest concentrations of NO_3^-–N recovered in the surface runoff in the black bean crop (2002/2003) resulted from the application of 80 m^3 ha^{-1} of pig slurry. For example, on the 74th day after the application of the pig slurry, the concentration of NO_3^-–N in the surface runoff was of 66.32 mg L^{-1} (Fig. 2a) and this certainly represents great potential for the eutrophication of surface waters, as reported by Smith et al. (2001b) and Smith et al. (2007). Based on these results, it can be inferred that the transfer of NO_3^-–N by surface runoff occurs with the highest rates of pig slurry. Therefore, applications of high rates of pig slurry in the same area must be avoided. Furthermore, it was observed that the use of manure with high levels of dry matter in the rainiest periods resulted in a higher loss of mineral N by surface runoff. An example of this occurred in the agricultural year 2002/2003, when the highest amounts of mineral N were lost in the surface runoff for a total of 33.3, 32.6 and 35.8 kg ha^{-1}, corresponding to the pig slurry rates of 20, 40 and 80 m^3 ha^{-1} (Table 2), as a result of the higher percentage of N in manure applied (Table 2) and the large volume of surface runoff (Fig. 1). It is interesting to notice that every year the volume of surface runoff diminished with increasing pig slurry rates.

3.2. Phosphorus transfer

Between 2002 and 2007, the total P applied to the soil was 508, 1016 and 2032 kg ha^{-1}, corresponding to the pig slurry rates of 20, 40 and 80 m^3 ha^{-1}. During this period, the losses of available P (HCl extracted by 0.11 mol L^{-1}) by surface runoff were, on average, 6.29, 5.01 and 3.51% of total P applied, which corresponds to 32, 51 and 71 kg ha^{-1} to the pig slurry rates of 20, 40 and 80 m^3 ha^{-1}, respectively (Table 2). On average, in the case of pig slurry addition to the soil, the P losses were 6.4, 10.2 and 14.4 kg ha^{-1} yr^{-1}, corresponding to the pig slurry input rates of 20, 40 and 80 m^3 ha^{-1}, whereas in the case of the control treatment, the average P loss was 2.4 kg ha^{-1} yr^{-1}. This shows that the P transfers were 2.7, 4.2 and 6.0 times higher where pig slurry was applied at the rates of 20, 40 and 80 m^3 ha^{-1} in comparison to the control treatment.

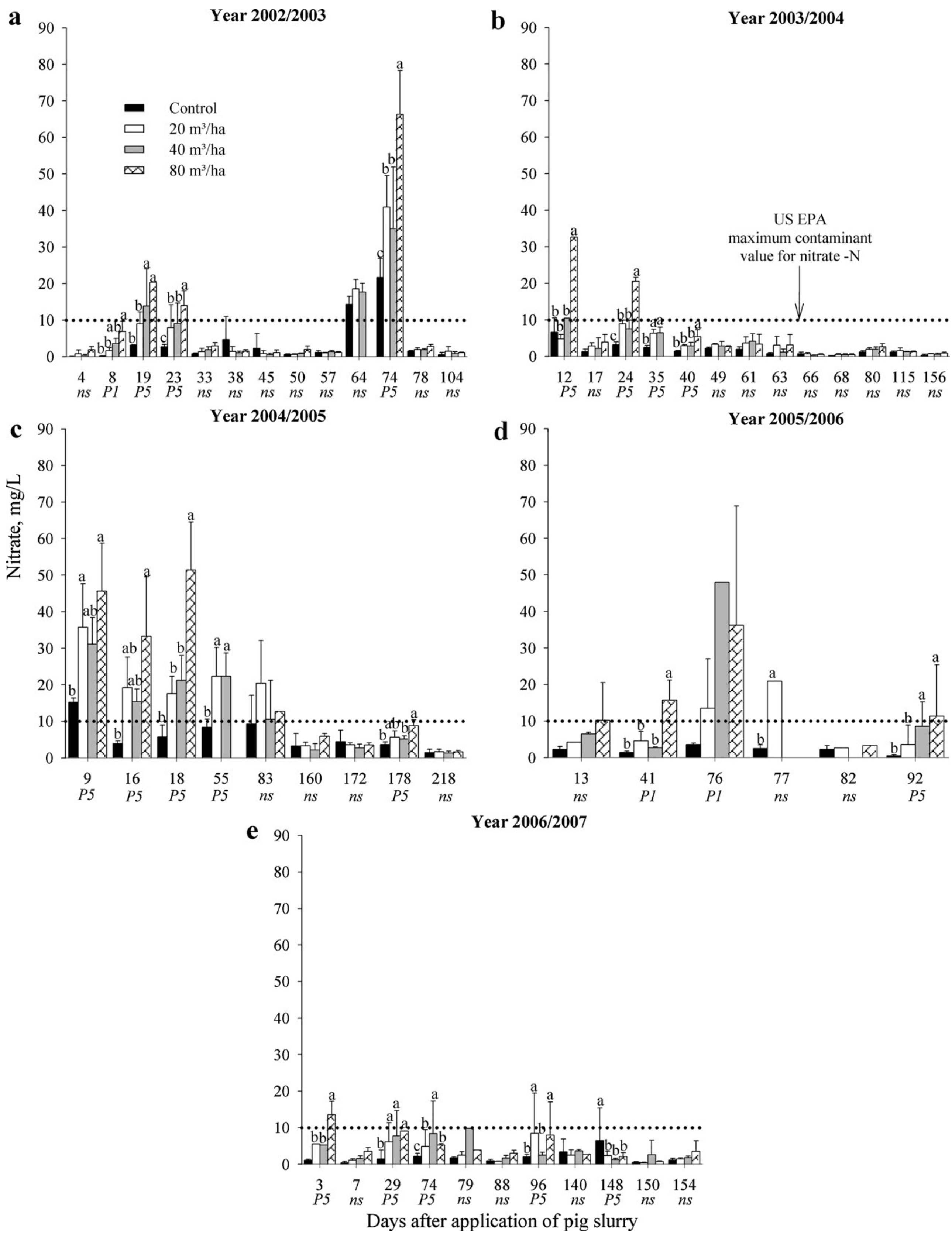

Fig. 2. Nitrate (NO_3^-–N) transfer by surface runoff in the cultures of black bean (2002/2003) (a), maize (2003/2004) (b), maize (2004/2005) (c), black beans (2005/2006) (d) and maize (2006/2007) (e), in area under successive applications of pig slurry and not tillage (bars indicate standard errors). Significance levels are from ANOVA testing for differences between treatment means. Letters designate differences between treatment means identified by Tukey–Kramer multiple comparison tests, while n.s. denotes statistical similarity amongst means.

Table 2
Applied amount of nutrients and losses through surface runoff for each pig slurry rate, in the agricultural years of 2002/2003, 2003/2004, 2004/2005, 2005/2006 and 2006/2007.

Pig slurry rate (m^3 ha^{-1})	Applied amount of nutrient			Precipitation (m^3 ha^{-1} yr^{-1})	Runoff (m^3 ha^{-1} yr^{-1})	Nutrient losses		
	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})			Mineral nitrogen[B] (kg ha^{-1})	Available phosphorus[C] (kg ha^{-1})	Available potassium[D] (kg ha^{-1}
Agricultural year 2002/2003								
00	–	–	–	25102	12163 (48.4) a[A]	28.73 ns	1.76 c	43.16 ns
20	216.0	46.3	24.5	25102	10217 (40.7)[E] ab	33.35 (2.42)[F]	6.21 (9.61)[G] bc	61.92 (76.57)[G]
40	432.0	92.6	49.0	25102	9260 (36.9) ab	32.58 (1.01)	11.14 (10.13) ab	54.88 (23.92)
80	864.0	185.2	98.0	25102	7140 (28.4) b	35.80 (0.94)	14.99 (7.14) a	92.83 (50.68)
Agricultural year 2003/2004								
00	–	–	–	13983	5654 (40.4) a	7.10 ns	5.91 b	16.58 b
20	136.0	30.0	32.7	13983	4696 (33.6) ab	9.93 (2.35)	9.88 (13.23) b	21.99 (16.54) b
40	272.0	59.9	65.4	13983	4532 (32.4) ab	10.24 (1.31)	12.06 (10.27) b	23.43 (10.47) b
80	544.0	119.8	131.0	13983	3649 (26.1) b	10.79 (0.78)	19.47 (11.32) a	36.35 (15.09) a
Agricultural year 2004/2005								
00	–	–	–	11241	2355 (21.0) ns	2.62 ns	2.12 b	7.70 ns
20	86.0	88.7	38.6	11241	2121 (18.9)	6.74 (5.41)	9.38 (8.18) ab	12.20 (11.66)
40	172.0	177.4	77.1	11241	2521 (22.4)	10.17 (4.99)	12.79 (6.01) a	16.13 (10.93)
80	344.0	354.8	154.2	11241	1361 (12.1)	11.35 (2.92)	15.30 (3.71) a	14.73 (4.56)
Agricultural year 2005/2006								
00	–	–	–	11427	2847 (24.9) a	4.14 ns	1.30 b	11.85 ns
20	104.0	216.6	70.1	11427	1684 (14.7) bc	5.13 (1.08)	7.34 (2.79) ab	15.20 (4.78)
40	208.0	433.2	140.2	11427	1705 (14.9) b	5.20 (0.58)	11.53 (2.36) a	19.70 (5.53)
80	416.0	866.4	280.4	11427	489 (4.3) c	5.74 (0.44)	7.27 (0.69) ab	10.53 (0.00)
Agricultural year 2006/2007								
00	–	–	–	18744	2545 (13.6) ns	5.10 ns	1.30 c	7.73 b
20	52.0	126.5	50.4	18744	2674 (14.3)	8.85 (8.15)	11.52 (8.08) bc	12.82 (10.10) ab
40	104.0	253.0	100.8	18744	1957 (10.4)	8.78 (4.02)	15.81 (5.74) ab	11.86 (4.10) ab
80	208.0	506.0	201.6	18744	1821 (9.7)	16.66 (6.39)	26.71 (5.02) a	28.98 (10.54) a
Average of five years								
00	–	–	–	16099	5113 (31.8)	9.54	2.48	17.40
20	118.8	101.6	43.3	16099	4278 (26.6)	12.80 (2.74)	8.87 (6.29)	24.83 (17.16)
40	237.6	203.2	86.6	16099	3995 (24.8)	13.37 (1.61)	12.67 (5.01)	25.20 (9.01)
80	475.2	406.4	173.2	16099	2892 (18.0)	16.07 (1.37)	16.75 (3.51)	36.68 (11.14)

[A] Significance levels are from ANOVA testing for differences between treatment means. Letters designate differences between treatment means identified by Tukey–Kramer multiple comparison tests in a column, while n.s. denotes statistical similarity amongst means.
[B] Nitrogen transferred in the mineral-N form.
[C] Phosphorus extracted by HCl 0.11 mol L^{-1}.
[D] Potassium extracted by HCl 0.11 mol L^{-1}.
[E] Numbers in parentheses represent the percentage of water losses by runoff surface in relation to rainfall in the period.
[F] The numbers in parentheses represent the percentages of nutrient losses relatively to the total applied deducted of the amount of losses where manure was not applied, considering a potential of loss volatilization of the mineral N by volatilization of 23, 24 and 26% for the rates of 20, 40 and 80 m^3 ha^{-1} of pig slurry, respectively in accordance to Basso et al. (2004) and deducting the value of the losses where manure was not applied.
[G] The numbers in parentheses represent the percentage of losses in relation to the P and K applied via manure, deducting the value of the losses where pig slurry was not applied.

The pig slurry rates also increase the losses of available P by surface runoff, demonstrating a great relationship between P losses by surface runoff and the quantities of P added to soil with applications of pig slurry, presented in Table 3. For example, when added 20 kg of P ha^{-1} at rates of 20 and 80 m^3 ha^{-1} of pig slurry, according to the equations presented in Table 3, the P losses by surface runoff were 9.86 and 20.4 kg ha^{-1}, respectively. Furthermore, it should be noted that P losses by surface runoff are not related to the runoff volume during each year.

For events occurring during the cultivations, the P losses by surface runoff were significant and, as observed for nitrate, the highest concentrations of P in runoff solution were observed within the first collections after the slurry application (Fig. 3). This was also reported by Ceretta et al. (2005), in the first two years of evaluating the experimental area with 80 m^3 ha^{-1} of pig slurry. Furthermore, the highest P transfers were observed with the application of the highest rates of pig slurry. However, part of the P added with the manure accumulated in soil, mainly in superficial layers. At 0–10 cm, where no manure was applied, the soil P (extracted by Mehlich 1) was 12.8 mg kg^{-1}. However, at rates of 20, 40 and 80 m^3 ha^{-1} of manure, the P levels were 122.0, 275.9 and 753.9 mg kg^{-1}, respectively. This shows that, the application of pig slurry over the years increases the levels of soil P, that cause the P transfer by surface runoff in soils that receiving repeated applications of pig slurry. This is justified by the fact that initially, the P is adsorbed in most avid sites, but as the manure has high

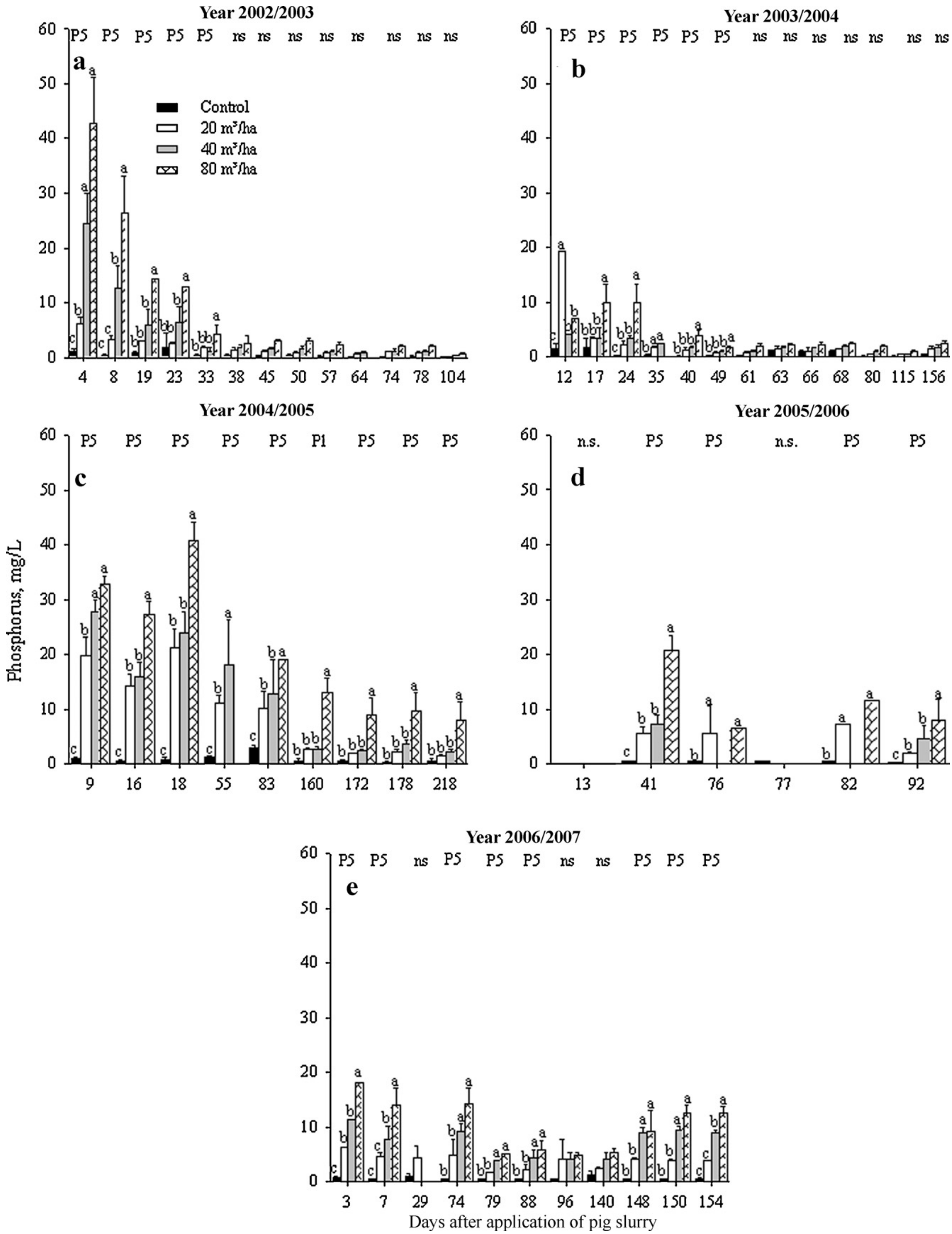

Fig. 3. Phosphorus extracted by HCl 0.11 mol L^{-1} transfer by surface runoff in the cultures of black bean (2002/2003) (a), maize (2003/2004) (b), maize (2004/2005) (c), black bean (2005/2006) (d) and maize (2006/2007) (e), in area under successive applications of pig slurry and no tillage (bars indicate standard errors). Significance levels are from ANOVA testing for differences between treatment means. Letters designate differences between treatment means identified by Tukey–Kramer multiple comparison tests, while n.s. denotes statistical similarity amongst means.

Table 3
Correlation equations relations runoff (Run_{off}), runoff cumulative ($Runoff_{cum}$), nitrogen mineral loss (N_{loss}), phosphorus available loss (P_{loss}), potassium available loss (K_{loss}), applied amount of nitrogen (N_{add}), applied amount of phosphorus (P_{add}), applied amount of potassium (K_{add}), (r^2: coefficient of determination; *p*:*p* value).

Runoff, and loss of N, P and K vs slurry rate

Agricultural year	Equation	r^2	*p*
2002/2003	$Runoff = 11{,}809 - 60.388^{*}$ SR	0.98	0.012^{**}
2003/2004	$Runoff = 17{,}256 - 83.664^{*}$ SR	0.97	0.016^{**}
2004/2005	$Runoff = 19{,}749 - 95.204^{*}$ SR	0.97	0.015^{**}
2005/2006	$Runoff = 22{,}374 - 122.168^{*}$ SR	0.96	0.020^{**}
2006/2007	$Runoff = 24{,}998 - 132.870^{*}$ SR	0.98	0.010^{**}
2002/2003	N_{loss}		Ns
2003/2004	N_{loss}		Ns
2004/2005	N_{loss}		Ns
2005/2006	N_{loss}		Ns
2006/2007	$N_{loss} = 51.5 + 0.377^{*}$ SR	0.92	0.039^{**}
2002/2003	$P_{loss} = 2.8 + 0.164^{*}$ SR	0.95	0.026^{**}
2003/2004	$P_{loss} = 8.8 + 0.330^{*}$ SR	0.99	0.004^{*}
2004/2005	$P_{loss} = 13.3 + 0.484^{*}$ SR	0.96	0.002^{**}
2005/2006	P_{loss}		Ns
2006/2007	$P_{loss} = 21.1 + 0.853^{*}$ SR	0.92	0.039^{**}
2002/2003	K_{loss}		Ns
2003/2004	K_{loss}		Ns
2004/2005	$K_{loss} = 69.0 + 0.899^{*}$ SR	0.93	0.034^{**}
2005/2006	$K_{loss} = 84.0 + 0.879^{*}$ SR	0.95	0.025^{**}
2006/2007	$K_{loss} = 90.4 + 1.136^{*}$ SR	0.95	0.024^{**}

Year nutrient loss vs year runoff

Pig SR $m^3\,ha^{-1}$	Equation	r^2	*p*
0	$N_{loss} = -3.5 + 0.002^{*}$ Runoff	0.96	0.004^{*}
20	$N_{loss} = -1.1 + 0.003^{*}$ Runoff	0.96	0.003^{*}
40	$N_{loss} = 0.1 + 0.003^{*}$ Runoff	0.93	0.009^{*}
80	$N_{loss} = 4.5 + 0.003^{*}$ Runoff	0.81	0.036^{**}
0	P_{loss}		Ns
20	P_{loss}		Ns
40	P_{loss}		Ns
80	P_{loss}		Ns
0	$K_{loss} = -0.7 + 0.004^{*}$ Runoff	0.98	0.001^{*}
20	$K_{loss} = -0.4 + 0.006^{*}$ Runoff	0.96	0.003^{*}
40	$K_{loss} = 4.2 + 0.005^{*}$ Runoff	0.93	0.007^{*}
80	$K_{loss} = 1.1 + 0.012^{*}$ Runoff	0.96	0.003^{*}

Cumulative nutrient loss vs cumulative runoff (multiple year)

Pig SR $m^3\,ha^{-1}$	Equation	r^2	*p*
0	$N_{loss} = 11.4 + 0.001^{*}\ Runoff_{cum}$	0.99	0.001^{*}
20	$N_{loss} = 4.0 + 0.003^{*}\ Runoff_{cum}$	0.99	0.001^{*}
40	$N_{loss} = 1.3 + 0.003^{*}\ Runoff_{cum}$	0.98	0.001^{*}
80	$N_{loss} = -10.7 + 0.005^{*}\ Runoff_{cum}$	0.91	0.011^{**}
0	$P_{loss} = -7.2 + 0.0001^{*}\ Runoff_{cum}$	0.96	0.003^{*}
20	$P_{loss} = -31.5 + 0.003^{*}\ Runoff_{cum}$	0.97	0.003^{*}
40	$P_{loss} = -37.5 + 0.004^{*}\ Runoff_{cum}$	0.94	0.006^{*}
80	$P_{loss} = -55.3 + 0.009^{*}\ Runoff_{cum}$	0.93	0.008^{*}
0	$K_{loss} = 1.8 + 0.003^{*}\ Runoff_{cum}$	0.99	0.001^{*}
20	$K_{loss} = 1.8 + 0.005^{*}\ Runoff_{cum}$	0.99	0.001^{*}
40	$K_{loss} = -10.9 + 0.007^{*}\ Runoff_{cum}$	0.98	0.001^{*}
80	$K_{loss} = 3.0 + 0.012^{*}\ Runoff_{cum}$	0.98	0.001^{*}

Year nutrient loss vs cumulative nutrient added (multi-year)

Pig SR $m^3\,ha^{-1}$	Equation	r^2	*p*
0	Not conditions for statistics		
20	$N_{loss} = 16.6 + 0.076^{*}\ N_{add}$	0.98	0.001^{*}
40	$N_{loss} = 13.1 + 0.043^{*}\ N_{add}$	0.98	0.001^{*}
80	$N_{loss} = 10.3 + 0.027^{*}\ N_{add}$	0.94	0.006^{*}
0	Not conditions for statistics		
20	$P_{loss} = 8.46 + 0.070^{*}\ P_{add}$	0.92	0.010^{**}
40	$P_{loss} = 13.1 + 0.049^{*}\ P_{add}$	0.93	0.006^{*}
80	$P_{loss} = 19.8 + 0.030^{*}\ P_{add}$	0.88	0.019^{**}
0	Not conditions for statistics		
20	$K_{loss} = 61.9 + 0.300^{*}\ K_{add}$	0.95	0.005^{*}
40	$K_{loss} = 54.1 + 0.176^{*}\ K_{add}$	0.95	0.004^{*}
80	$K_{loss} = 95.6 + 0.101^{*}\ K_{add}$	0.90	0.013^{**}

Ns, not significative; Runoff ($m^3\,ha^{-1}$ year).
* Statistically significant at 99% confidence level.
** Statistically significant at 95% confidence level; $Runoff_{cum}$ ($m^3\,ha^{-1}$, cumulative); N_{loss}, P_{loss}, K_{loss}, N_{add}, P_{add}, K_{add} ($kg\,ha^{-1}$); SR (slurry rate, $m^3\,ha^{-1}$).

amounts of P, occur the saturation of these sites and becomes adsorbed P in fractions with lower binding energy (Barrow et al., 1998), which may be bio-available and easily moved by surface runoff, immediately after application of pig slurry, as reported by Heathwaite et al. (2000), Toor et al. (2003), Davede et al. (2004) and Kleinman et al. (2009).

The P concentrations in the surface runoff were much greater than 0.15 $mg\,L^{-1}$ in the first samples (Fig. 3a–d), reaching the maximum concentration allowed for Class 3 Water (waters of class 3) (water that may be used for human consumption after adequate treatment) (CONAMA, 2005). This indicates that the successive application of manure increased P losses by runoff, causing contamination of water sources for human consumption, as well as increasing the risk of eutrophication of aquatic environments, as reported by Correll (1998) and Smith et al. (2001a).

3.3. Potassium transfer

Between 2002 and 2007, the total K applied to soil was 216, 432 and 864 $kg\,ha^{-1}$, corresponding to rates of 20, 40 and 80 $m^3\,ha^{-1}$ of manure. During this period, the losses of available K (extracted by 0.11 HCl 5.01 $mol\,L^{-1}$) surface runoff were, on average, 17.16, 9.01 and 11.14% of total K applied, which corresponds to 37, 39 and 96 $kg\,ha^{-1}$ at rates of 20, 40 and 80 $m^3\,ha^{-1}$ of manure, respectively (Table 2). On average, K losses in runoff were 7.4, 7.8 and 19.3 $kg\,ha^{-1}\,yr^{-1}$ for rates of 20, 40 and 80 $m^3\,ha^{-1}$, respectively. These results indicate that the increase of the amount of pig slurry added and K, increase the losses of K available by surface runoff. This becomes clear by analyzing Table 3, where relations between the amounts of K added and K losses in runoff are presented. For example, adding 50 kg of K ha^{-1} at rates of 20 and 80 $m^3\,ha^{-1}$ of pig slurry, according to the equations presented in Table 3, the K losses by surface runoff would be 76.9 and 100.6 $kg\,ha^{-1}$, respectively. Furthermore, the losses of K are related directly to the volume of surface runoff.

In relative terms, the K losses were higher than N and P. As regards total nutrients applied through pig slurry, losses through surface runoff were of 2.74, 1.61 and 1.37% of mineral N, 6.29, 5.01 and 3.51% of available P and 17.16, 9.01 and 11.14% of available K, for the three rates of applied pig slurry, respectively. This can be explained considering that most of the K in pig slurry is found in mineral form, as reported by Kayser and Isselstein (2005). This can also be explained by the high K concentration in the surface runoff in the first samples after the application to bean and maize crops (Fig. 4a–c and e). This demonstrates that, with regard to the K availability for (to) plant nutrition, the runoff losses of K are significant. Furthermore, the K accumulation in top soil layers was lower than the accumulation of P. The K content (extracted by Mehlich 1) in the 0–10 cm soil was 52.5 $mg\,kg^{-1}$ in the control treatment, and 62.8, 66.4 and 113.1 $mg\,kg^{-1}$ at rates of 20, 40 and 80 $m^3\,ha^{-1}$ of pig slurry, respectively. However, it should be noted that the amount

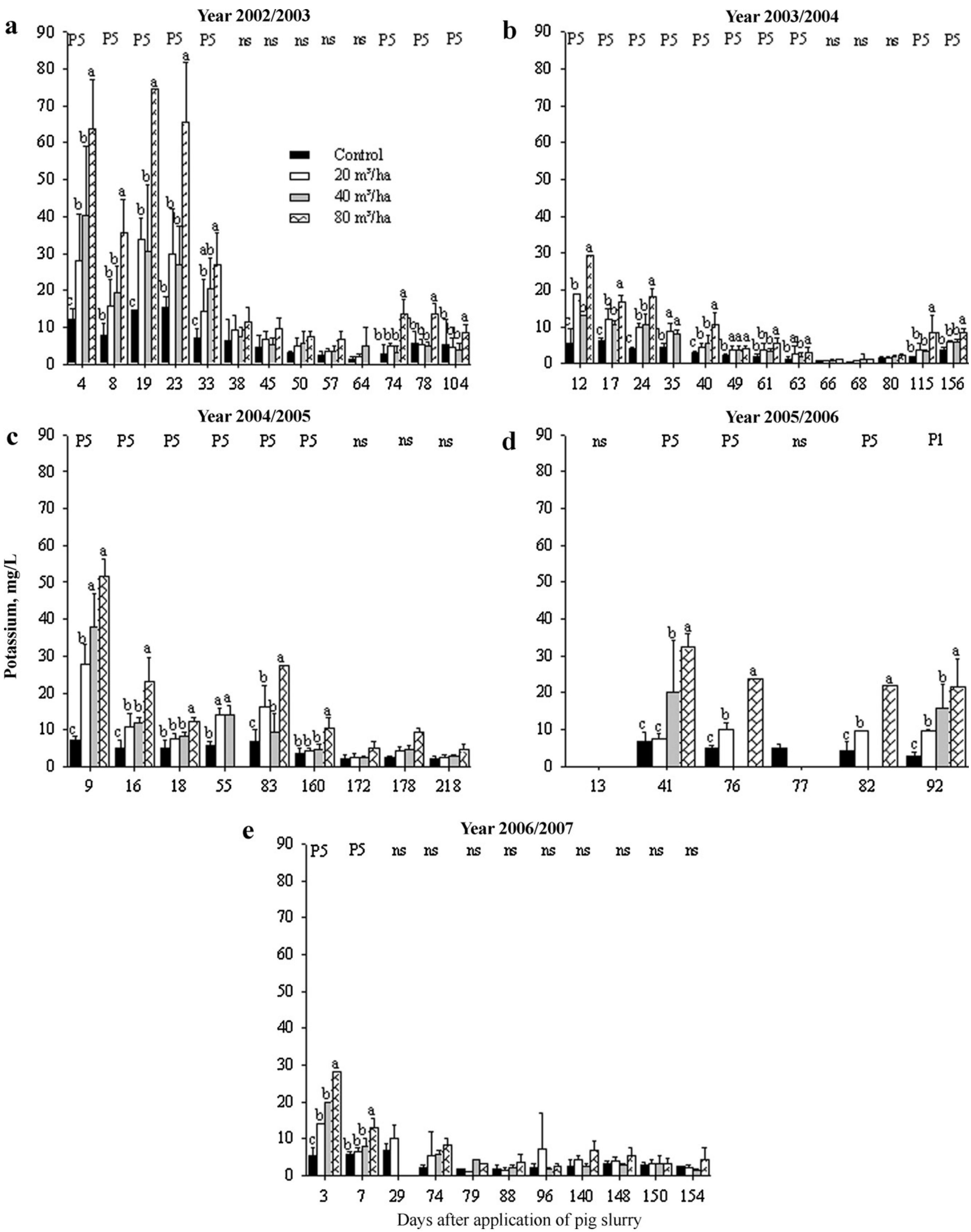

Fig. 4. Potassium extracted by HCl 0.11 mol L^{-1} transfer by surface runoff in the cultures of black bean (2002/2003) (a), maize (2003/2004) (b), maize (2004/2005) (c), black bean (2005/2006) (d) and maize (2006/2007) (e), in area under successive applications of pig slurry and no tillage (bars indicate standard errors). Significance levels are from ANOVA testing for differences between treatment means. Letters designate differences between treatment means identified by Tukey–Kramer multiple comparison tests, while n.s. denotes statistical similarity amongst means.

of K added to soil with the manure was lower than the amounts of P added.

These results indicate that special attention must be paid to the K added to soil by pig slurry, in order to be absorbed by plants. Even though K is applied in smaller amounts than N and P, its losses through surface runoff are higher. Additionally, in all the management systems, residues must be kept on the soil surface to increase infiltration of the solution and to diminish nutrient losses through surface runoff.

4. Conclusions

Repeated applications of pig slurry on a no tillage managed soil caused losses of nitrogen, phosphorus and potassium from the soil through surface runoff, in the sequence: potassium > phosphorus > nitrogen. The losses of N and K are positively related to the volume of surface runoff solution, whereas the losses of P are positively related to the quantities of P added through pig slurry. Applications of pig slurry along the years decrease the surface runoff.

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