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Nutrient losses from manure and fertilizer applications as impacted by time to first runoff event ☆

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Fertilization with manures results in lower nutrient runoff than inorganic fertilizers, especially if at least one week passes between fertilization and runoff.

Abstract

Nutrient losses to surface waters following fertilization contribute to eutrophication. This study was conducted to compare the impacts of fertilization with inorganic fertilizer, swine (*Sus scrofa* domesticus) manure or poultry (*Gallus domesticus*) litter on runoff water quality, and how the duration between application and the first runoff event affects resulting water quality. Fertilizers were applied at 35 kg P ha^{-1}, and the duration between application and the first runoff event varied between 1 and 29 days. Swine manure was the greatest risk to water quality 1 day after fertilization due to elevated phosphorus (8.4 mg P L^{-1}) and ammonium (10.3 mg NH_4-N L^{-1}) concentrations; however, this risk decreased rapidly. Phosphorus concentrations were 2.6 mg L^{-1} 29 days after fertilization with inorganic fertilizer. This research demonstrates that manures might be more environmentally sustainable than inorganic fertilizers, provided runoff events do not occur soon after application.

Keywords: Urea; Triple superphosphate; Swine manure; Poultry litter; Phosphorus; Nitrogen

1. Introduction

Phosphorus (P) and nitrogen (N) losses to surface waters from agricultural sources have been identified as a contributor to surface water quality degradation (Carpenter et al., 1998). For agriculture to remain sustainable, nutrient losses to surface water must be reduced. Recently, a national research effort was conducted in the United States to develop regional P indices to assist producers in making environmentally sound decisions with regard to manure application (Lemunyon and Gilbert, 1993; Sharpley et al., 1999). Application of manures to pasture or cropland in some areas within the United States has become a contentious topic. This is especially true in portions of the country where the catchment for a drinking water reservoir of a large city contains a large number of confined animal feeding operations (DeLaune et al., 2006).

Several factors have been shown to be important in controlling P losses from fields. Soil test P levels have been shown to be a factor controlling P losses if no fertilizers have been recently applied (DeLaune et al., 2004b; Schroeder et al., 2004b). Following the surface application of fertilizer or manure, the amount of soluble P applied can be the most important factor controlling P concentrations in runoff (DeLaune et al., 2004a; Smith et al., 2004a, b). Greater crop residue levels have also been shown to reduce P runoff concentrations (Torbert et al., 1999; Grande et al., 2005). Application of a

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fertilizer to drier soils has also been shown to aid in reducing P and N losses in runoff (Torbert et al., 1999).

The duration between fertilizer application and the first rainfall–runoff event has also been shown to be an important factor in controlling P losses. When an irrigation event occurred immediately after fertilizer application, the P concentrations in runoff were two times greater than when the first irrigation occurred as the water deficit reached 50 mm (Bush and Austin, 2001). Schroeder et al. (2004a) observed that as the time between poultry (*Gallus domesticus*) litter application and the first rainfall event increased, P concentrations in runoff decreased. Increasing the time between poultry litter application and the first runoff event was observed to decrease concentrations of soluble P, NH_4-N, and total N; however, no effect of rainfall timing was observed for NO_3-N (Sharpley, 1997). When rainfall simulations occurred in the Spring, dairy cattle (*Bos taurus*) manure applied in Spring produced greater P concentrations in runoff than manure applied in the Fall or no manure applications (Grande et al., 2005). However, contrary to most results, Edwards et al. (2000) found little effect of rainfall timing on P or N losses from plots fertilized with cattle manure, however manure was applied to pasture at fairly low rates, and there was 4 weeks between manure application and the first rainfall–runoff simulation.

Many studies have compared the impacts of fertilizer or manures on P or N in runoff (Sharpley, 1997; Torbert, 1999; Edwards et al., 2000; Bush and Austin, 2001; DeLaune et al., 2004a; Schroeder et al., 2004a; Smith et al., 2004a, b; Vadas et al., 2004; Grande et al., 2005). Relatively fewer studies have compared the impact of fertilizers on water quality with that of manures from different species (Gaudreau et al., 2002; Kleinmann et al., 2002; Daverede et al., 2004; DeLaune et al., 2004b; Tarkalson and Mikkelsen, 2004), or how the duration between application of different fertilizer sources and a runoff event will affect the concentrations of nutrients in runoff (DeLaune et al., 2004b; van Es et al., 2006). The objectives of this study were to identify the impact of the duration between fertilizer or manure application and first rainfall–runoff event on P and N concentrations in runoff, and to compare the effects of the fertilizer source on nutrient losses.

2. Materials and methods

Fifteen main plots were built on an Octagon silt-loam soil (fine-loamy, mixed, mesic, Mollic Hapludalf) at the Throckmorton Purdue Agricultural Research Center, near Lafayette, IN (40° 18′ 00″ N, 86° 53′ 41″ W, 212 m asl). The area used for this study was cropped to tall fescue (*Festuca arundinacea* Shreb.), and would represent an area that would be used for hay production. Each plot consisted of four sub-plots measuring 0.75 m wide and 2 m long. Plots and sub-plots were hydrologically isolated from the surrounding soil by inserting 0.2 m wide 14 gauge galvanized sheet metal borders approximately 0.1 m into the soil.

A 4 × 5 factorial design was used for treatment allocation, with four fertilizer treatments, and five time treatments (i.e. time to first runoff event). For this study, fertilizer treatments were: (1) inorganic fertilizer; (2) poultry litter; (3) swine (*Sus scrofa* domesticus) manure; and (4) unfertilized control. Poultry litter (including feces, wood shavings and spilled feed) was collected from a commercial broiler operation near Starkeville, MS. Swine manure was collected from a finishing swine house using manure pits for waste disposal at the Purdue University Animal Farm, near West Lafayette, IN. Inorganic fertilizers used for this study were purchased in bags as triple superphosphate and urea.

Soluble P in fertilizers was analyzed using a 1:100 (fertilizer/reagent grade water) dilution, shaking for on an oscillating shaker for 2 h, vacuum filtered through 0.45 μm membrane filters, and acidified to pH 2 with HCl. Soluble P concentrations in filtered extracts were determined using an inductively coupled argon plasma–optical emission spectrometry (ICAP-OES; Optima 2000, Perkin Elmer, Shelton CT). Fertilizer total P was determined by digesting using Kjehldahl digestion procedures. Total P was analyzed using the ascorbic acid reduction procedures of Murphey and Riley (1962) on a Konelab Aqua20 (Thermo Electron Corp, Franklin, MA). Total N and total C content of fertilizers was analyzed on samples by combustion analysis (LECO CHN 2000; St. Joseph, MI).

Manures were surface applied at 35 kg P ha^{-1}, with the tall fescue in the plots approximately 7.5 cm tall. The P application rate chosen was close to agronomic requirements and lower than if applied for N requirement. There were three replications of each treatment and time combination. Inorganic fertilizer was surface applied as triple super phosphate at 35 kg P ha^{-1}, and urea was surface applied to the inorganic fertilizer plots at a rate of 100 kg N ha^{-1}. The N rate for inorganic fertilizer was based on estimations of N during the first year after application from the poultry litter treatment.

Rainfall simulations were carried out 1, 4, 8, 15 and 29 days after fertilization at an intensity of 100 mm h^{-1} for a duration sufficient to produce 30 min of continuous runoff. Eight discrete runoff samples were collected starting 2 min after continuous runoff was observed, and every 4 min after that. Discrete runoff samples were collected for no longer than 1 min in 250 mL HDPE bottles. Following collection, each bottle was weighed to obtain the runoff volume, a 20 mL sample was filtered (0.45 μm membrane filter) and acidified to pH 2 with concentrated HCl and frozen until analysis. Runoff volumes from each plot were calculated as:

$$V_t = \sum v_i \times t_i$$

where V_t is the total volume of runoff for the 30 min collection period, v_i is the volume of runoff collected during the 1 min of runoff collected during period i, and t_i is the total time, in minutes, of period i. Nutrient concentrations were flow weighted for each event based on their relative volume contribution to the total volume of runoff that occurred during the rainfall simulation from a given plot.

Soluble P was analyzed using ICP-OES within 4 weeks of sample collection. Concentrations of NH_4-N and NO_3-N in filtered (0.45 μm) water samples were analyzed colorimetrically using a Konelab Aqua20 (Thermo Electron Corp, Franklin, MA). NH_4-N concentrations were detected using method APHA 4500-NH_3 F, and NO_3-N concentrations were detected using method APHA 4500-NO_3 H (Clesceri et al., 1998).

Soil samples were collected twice from the 0–2 cm profile from each plot, 4 days prior to fertilizer application and again immediately before rainfall simulations occurred. Samples were air dried, ground, and sieved (2.0 mm mesh). Extractable P, Al, and Fe were analyzed in soil samples using the Mehlich 3 extraction procedure (Mehlich, 1984). Briefly, soil was extracted with 0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.013 M HNO_3 + 0.001 M ethelenediamine tetraacetic acid, using a 1:10 extraction ratio, followed by filtration through Whatman #2 filter paper. The extracts were then analyzed using ICAP-OES for concentrations of P, Al and Fe. A P sorption ratio (PSR) for soils was calculated from the Mehlich 3 data as: (mmol P)/(mmol Al + mmol Fe), as per Maguire and Sims (2002).

Statistical analysis were performed using general linear model procedures in SAS v. 8.0, with means separated at $\alpha = 0.05$ using Fisher's protected least significant difference (SAS Institute, 1985). Temporal trends for mean nutrient concentrations were analyzed using curvilinear regression techniques from SigmaPlot v. 6.0 (SPSS, 2000).

3. Results and discussion

Selected properties of the fertilizer and manure used in this study are presented in Table 1. Soluble and total P values for swine manure are similar to those observed in other studies

Table 1
Selected properties of manure and fertilizer applied to plots for rainfall simulation studies

Manure property	Inorganic fertilizer[a]	Swine manure	Poultry litter
Soluble P, g kg^{-1}	135	1.28	2.59
Total P, g kg^{-1}	196	1.37	8.31
Total N, g kg^{-1}	468	6.5	45.6
Total C, g kg^{-1}	202	24.6	327
Soluble P/total P	0.69	0.93	0.31
N:P	3.0	4.7	5.5
C:P	1.3	14.0	39.4
Soluble P applied, kg ha^{-1}	24.0	32.7	10.9
Total P applied, kg ha^{-1}	35.0	35.0	35.0
Total N applied, kg ha^{-1}	100	166	192

[a] Soluble P and total P values for inorganic fertilizer were calculated for triple superphosphate. Total N and total C values for inorganic fertilizer were calculated for urea. The N:P and C:P ratios were calculated as the ratio of N or C to P from urea and triple superphosphate on an as-applied basis.

(Smith et al., 2004a, b; Vadas et al., 2004). Total P and N concentrations were greatest for the inorganic fertilizer, which was expected. The N:P ratios were greatest in the swine manure (4.7) and lowest in the inorganic fertilizer (2.4), resulting in more N being applied to plots from the manure treatments when applied at the same rate of P (i.e. 166 and 192 kg N ha^{-1} for pig and poultry, respectively). Rates of N application for the inorganic treatment were meant to be comparable to the amount of available N from the manure treatments. The C:P ratio of the inorganic fertilizer was approximately 1, while it was 14 for swine manure and 39 for poultry litter. Leytem et al. (2005) concluded that when applied at the same rate of P, manures that provide more C will stimulate microbial biomass activity, thereby sequestering greater amounts of P and reducing the soluble P content in surface soils.

3.1. Duration between application and rainfall

At 1 day after fertilizer application, mean soluble P concentrations in runoff were greatest for the swine manure fertilizer treatment, followed by the inorganic fertilizer, poultry litter and unfertilized control (Fig. 1A), reflecting the soluble P content of the fertilizers. As the duration between application and the first rainfall event increased, the mean soluble P concentrations from the swine manure treatment decreased, such that concentrations were similar to those observed for the unfertilized treatment on day 29. Mean soluble P concentrations from the inorganic fertilizer treatment were significantly greater than the poultry litter or unfertilized treatment at all time intervals, except at 8 days. Given the trends of decline shown in Fig. 1A, after 29 days, inorganic fertilizer may constitute a greater risk to water quality than fertilization with poultry litter or swine manure.

The reductions in P concentrations from the swine manure treatment followed a logarithmic decay ($R^2 = 0.95$, $P < 0.01$), which was consistent with responses observed by other researchers for poultry litter (Sharpley, 1997; Schroeder et al., 2004a). Similar relationships with time for soluble P were not observed for the other treatments. While these results are contrary to some studies on the subject, Edwards et al. (2000) did not observe a significant relationship between P concentrations and the duration between cattle manure application and runoff.

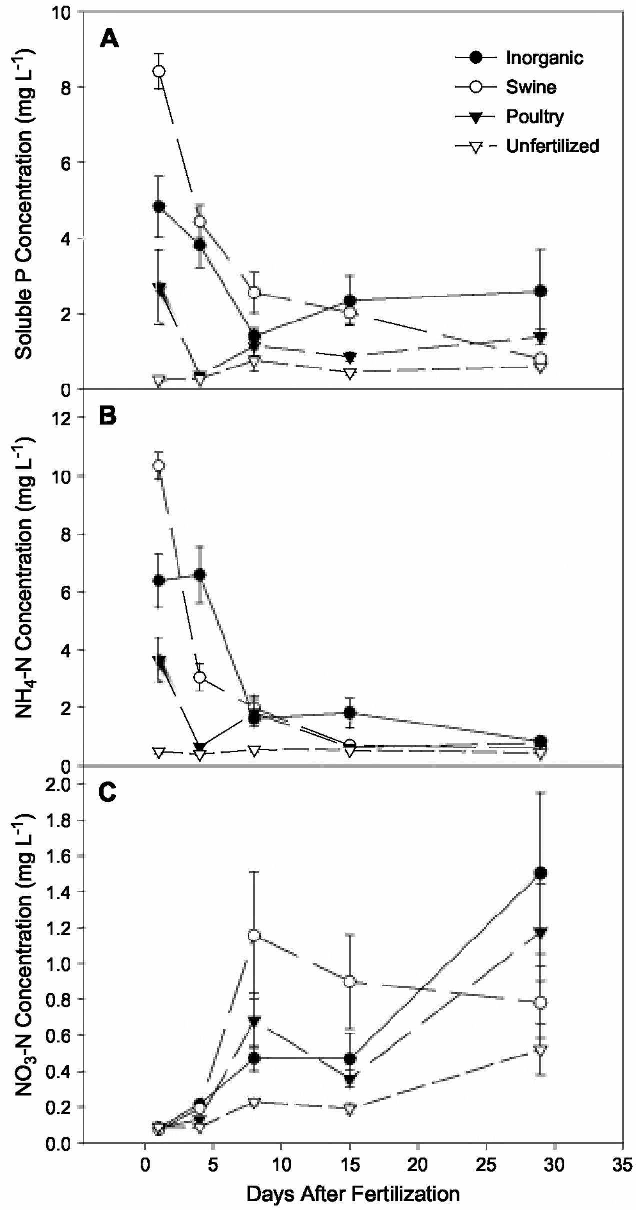

Fig. 1. Flow-weighted mean concentrations of (A) soluble P; (B) NH_4-N; and (C) NO_3-N in runoff from fertilizer treatments during rainfall simulations that occurred between 1 and 29 days after fertilizer application (vertical bars represent standard error).

Data from the current study concur with other studies using similar fertilizer sources where P concentrations were best correlated with the soluble P content of the manure (DeLaune et al., 2004a; Smith et al., 2004a, b). Observations made during the rainfall simulation that occurred 1 day after fertilizer application also indicate that when applied at the same P rate, the water soluble P/total P ratio of the fertilizer had a strong relationship with the P concentrations in runoff (Fig. 2). The curvilinear response indicates that when applied at 35 kg P ha^{-1}, a hypothetical fertilizer containing 100% of

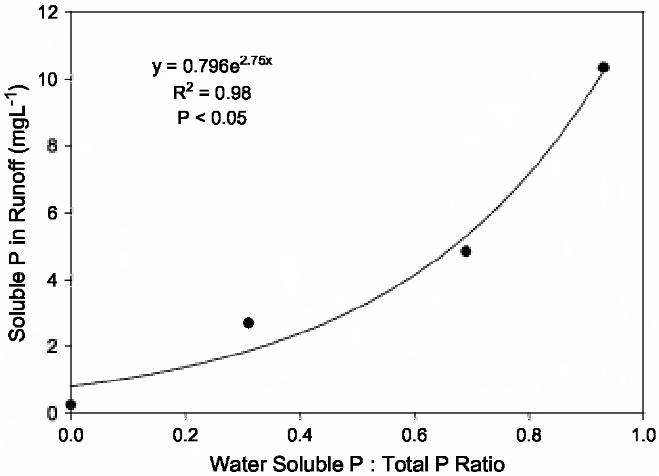

Fig. 2. Relationship between the soluble P concentrations in runoff water 1 day after fertilizer application and the water soluble P/total P ratio of the applied fertilizer.

the total P as water soluble P would result in runoff P concentrations near 12.5 mg L^{-1} 1 day after application.

During the initial rainfall simulation, swine manure was observed to the have greatest P concentrations in runoff, most likely because of the method of application and the high rate of soluble P application (Table 1). Swine manure was applied as a liquid, and as such, some of it adhered to the leaves of the forage, while the remaining portion adhered to the decaying thatch layer or infiltrated the soil. The dry fertilizers (inorganic fertilizer and poultry litter) were heavy enough to penetrate the aboveground biomass of the forage and come to rest on the thatch or soil surface layer. Rainfall on the swine manure treatments that washed the manure off the aboveground biomass, and transported it downslope via runoff. Rain falling on the other fertilizer sources would have had reduced kinetic energy after interception by the plant canopy and so the nutrients would have had a greater chance of interacting with soil particles or organic matter and being adsorbed out of solution prior to transport downslope. The poultry litter and inorganic fertilizer also contained larger particles than the swine manure, and as such would require a greater amount of energy than the swine manure to be transported downslope. Poultry litter applications were likely to have led to much lower P concentrations in runoff due to the lower soluble P levels applied, and potentially due to the high levels of C applied compared with other treatments (Leytem et al., 2005).

Mean NH_4-N concentrations in runoff for the swine manure were observed to follow the same trend as that observed for mean soluble P concentrations (Fig. 1B). Mean NH_4-N concentrations from the swine manure treatment also fit a logarithmic decay function ($R^2 = 0.97$, $P < 0.01$); however, as with the soluble P response, there was not a significant relationship between mean NH_4-N concentrations and time to first runoff event for the other treatments. Mean NH_4-N concentrations from the inorganic fertilizer treatment were greater in runoff that occurred 1 and 4 days after application than for the later events. Mean NH_4-N concentrations tended to be lower for the poultry litter application than other fertilizers during this study. Sharpley (1997) described a temporal trend of decreasing NH_4-N losses from poultry litter with increasing time to first runoff, which was not observed for the poultry litter treatment in this study, but was observed for the swine manure treatment.

Mean NO_3-N concentrations in runoff were initially very low for all treatments, and remained below the 10 mg L^{-1} drinking water standard at all times during this study (Fig. 1C). In contrast to soluble P and NH_4 concentrations, NO_3 concentrations generally increased as time between fertilizer application and runoff increased. Increases in mean NO_3-N concentrations were observed for the swine manure and poultry litter treatments from the rainfall simulation that occurred on day 8, which was observed to be the peak NO_3-N concentration for the swine manure treatment. This appeared to be the point at which sufficient organic N had been mineralized and nitrified to induce NO_3-N losses. It appears that after 29 days, most of the N that was mineralized from the swine manure had been taken up by plants, lost to leaching, or emitted as a gas (i.e. NH_3, N_2O, NO_2, or N_2), potentially from nitrification or denitrification (unpublished data). Relative to the unfertilized control, the only significant temporal trend that was observed for mean NO_3-N losses was a linear increase resulting from the inorganic fertilizer treatment ($R^2 = 0.96$, $P < 0.01$), suggesting that nitrification was still occurring in soils for this treatment. Increases in runoff NO_3 concentrations with time in the control treatment indicated mineralization of organic N was also occurring. There was no significant temporal trend for the poultry litter treatment, which concurs with results from other studies using poultry litter (Sharpley, 1997).

3.2. Temporal trends within a runoff event

Soluble P concentrations for discrete runoff water samples collected during rainfall simulations are presented in Fig. 3. Soluble P concentrations from the inorganic fertilizer treatment were observed to peak at the 10 min increment during the first two runoff events (Fig. 3A). This suggested that the fertilizer granules were releasing P to the water during the wetting process. Similar trends have been observed for discrete runoff samples taken from soils fertilized with poultry litter, and have been attributed to the physical breakdown of litter clumps during the rainfall simulation (Vadas et al., 2004). By day 8, this trend did not exist, likely due to dissolution of the fertilizer granules during this period.

Concentrations of soluble P in runoff from swine manure decreased rapidly during the first runoff event; however, little change in concentrations for discrete samples during the rainfall events were observed after this (Fig. 3B). This trend would suggest that the relatively high level of soluble P in the swine manure solution was steadily being removed during the first rainfall simulation, whereas because the manure had time to dry prior to subsequent rainfall simulations, P in the manure had time to become less soluble by reacting with soil particles or co-precipitating with metals (i.e. Ca, Mg or Fe) in manure. Additionally, there could be sufficient time

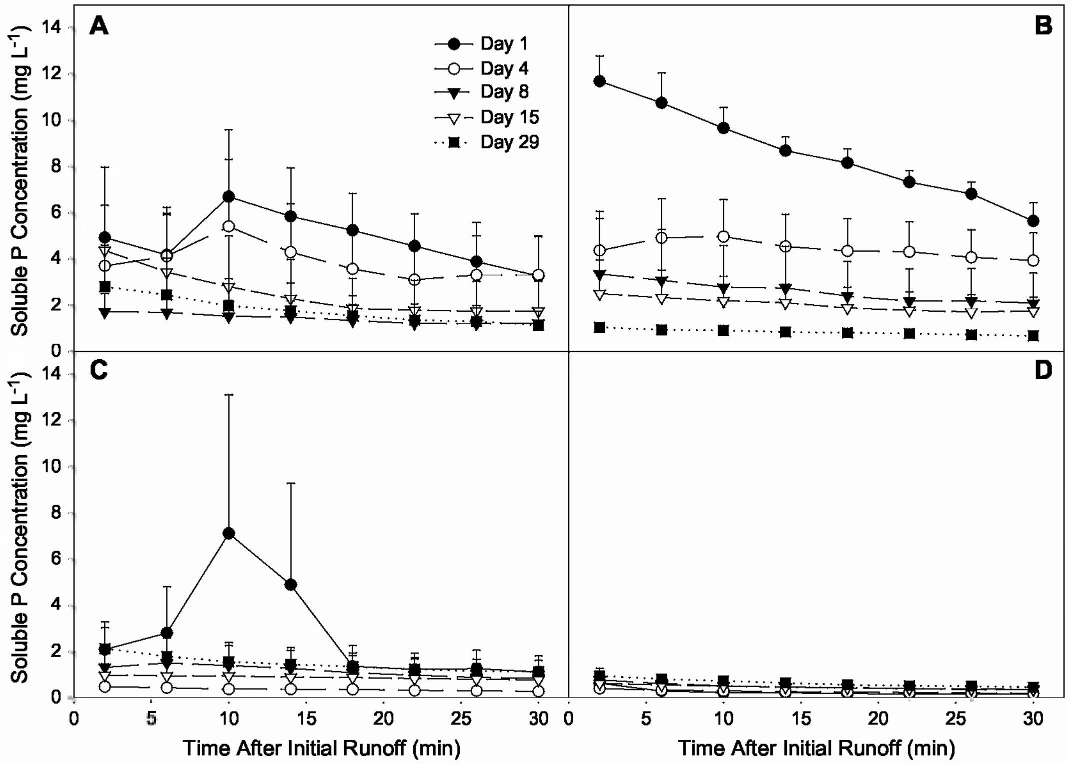

Fig. 3. Soluble P concentrations at specified times during runoff events 1, 4, 8, 15 and 29 days after fertilization with (A) inorganic fertilizer; (B) swine manure; (C) poultry litter; or (D) unfertilized (vertical bars represent standard error).

for microbial biomass to utilize available (i.e. soluble) P during this period.

As with the inorganic P treatment, soluble P from the poultry litter peaked during the 10 min time increment (Fig. 3C), suggesting release to the solution during wetting and breakdown of litter clumps (Vadas et al., 2004). This trend was not observed during the rainfall simulation that occurred 4 days after litter application, likely due to the physical breakdown of litter clumps by insects during the period between litter application and rainfall. At the time of litter application, darkling beetles (*Aliphitobius diaperinus* Panzer) were observed to be active in the litter. Analysis of discrete samples from rainfall simulations on the unfertilized plots indicate that P was lost at similar rates throughout the runoff collection period (Fig. 3D).

Trends for NH_4-N concentrations in discrete runoff samples from rainfall simulations were similar to those observed for soluble P (Fig. 4). In the rainfall simulation 1 day after inorganic fertilizer application, the maximum release of NH_4-N to runoff water from granules of urea occurred between 10 and 18 min after runoff began (Fig. 4A). During the rainfall simulation that occurred 4 days after inorganic fertilizer application, the initial runoff samples (up to 10 min) contained the greatest NH_4-N concentrations. Urea granules are known to dissolve fairly rapidly, and within 4 days, all of the urea granules would have dissolved, releasing NH_4-N to the soil and/or the soil solution. Concentrations of NH_4-N from swine manure were very high in the first rainfall simulation, but steadily decreased throughout the runoff collection period, whereas concentrations remained relatively stable throughout subsequent rainfall simulations for this treatment (Fig. 4B), again indicating the water soluble component was depleted after the first event.

3.3. Impact of fertilizers on phosphorus in soils

One day after fertilization with inorganic fertilizer or poultry litter, the Mehlich 3 extractable P in the 0–2 cm soil profile was approximately 35 mg kg^{-1} greater than the samples taken from the unfertilized plots (Fig. 5). Mehlich 3 extractable P was approximately 12 mg kg^{-1} greater from the swine manure treatment than the unfertilized treatments 1 day after fertilization. This would support the observation of a portion of the swine manure adhering to above ground biomass, instead of reaching the soil. This would also support the hypothesis that P runoff from the swine manure treatment was greater than the other treatments 1 day after application due to swine manure ‘washing off’ the aboveground tall fescue biomass.

Reductions in Mehlich 3 P were observed between 1 and 4 days for soils samples collected from the inorganic fertilizer and poultry litter amended plots (Fig. 5). These observations are very similar to those made during another study, in which soil P levels decreased soon after a low soil test P soil was fertilized with poultry litter or inorganic fertilizer (Smith et al., 2005). Data from the current study indicate that decreases in Mehlich 3 extractable P occurred within 4 days following the application of inorganic fertilizer or poultry litter. This concurs with Smith et al. (2005) who found that soil P

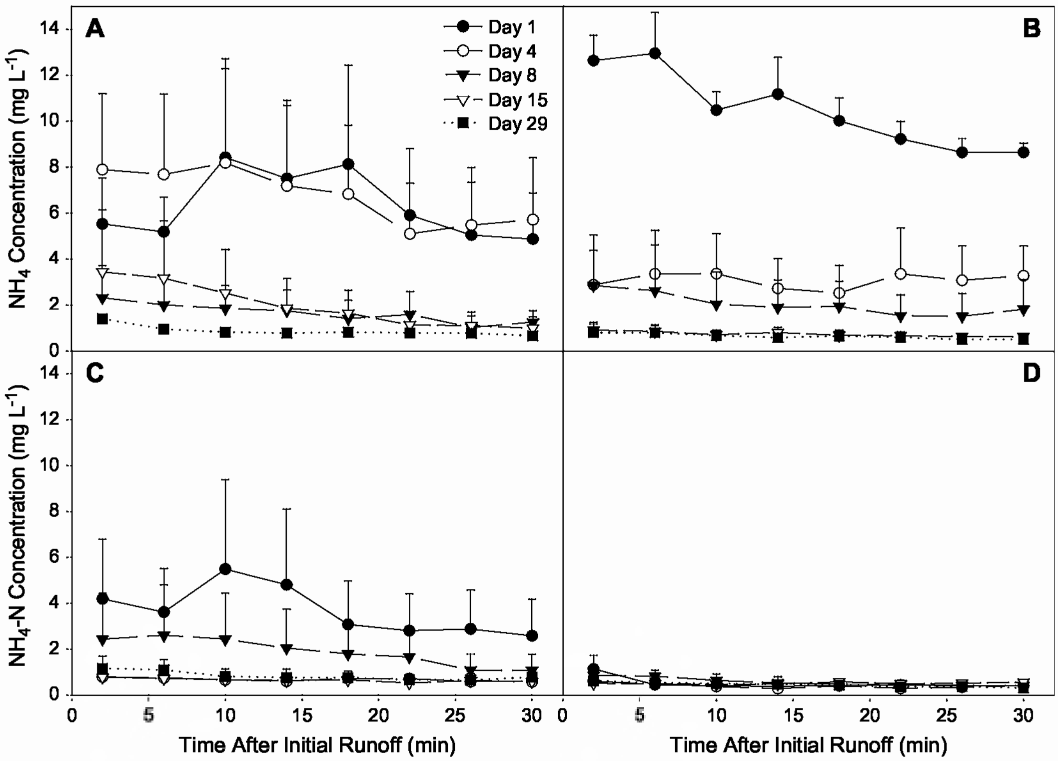

Fig. 4. Ammonium-N concentrations at specified times during runoff events 1, 4, 8, 15 and 29 days after fertilization with (A) inorganic fertilizer; (B) swine manure; (C) poultry litter; or (D) unfertilized (vertical bars represent standard error).

concentrations had decreased 15 days after fertilization. In the previous study, no samples were taken between 1 and 15 days. Data from the current study therefore indicate that transformation in extractable P may occur much sooner than reported by Smith et al. (2005). Similar to the previous study, there was no change in Mehlich 3 extractable P from the inorganic fertilizer or poultry litter treatment after the initial decrease at 4 days. There was also very little change in Mehlich 3 extractable P with time from the swine manure treatment.

Soil extractable P and the P sorption ratio (PSR; molar ratio of P to Al and Fe), did not accurately predict P runoff concentrations in this study. Other investigators have observed that the PSR can be a tool to predict P leaching and runoff (Maguire and Sims, 2002). The PSR values for soils in this study were all below 0.12, which is lower than the change-point of 0.20 beyond which PSR and P leaching were highly correlated (Maguire and Sims, 2002). There were no fertilizer applications to soils by Maguire and Sims (2002), whereas the fertilizer and manure applications in the current study resulted in increased P losses. In soils with no fertilizer application in the current study, the greatest PSR value observed was 0.053, approximately one-fourth the level at which PSR would be expected to have an impact on P concentrations in runoff.

4. Conclusions

When surface applied at the same rate to pastures, swine manure demonstrated the greatest risk to water quality 1 day after application relative to inorganic fertilizer and poultry litter. As the duration between swine manure application and the first runoff event increased, the risk of P and N losses to runoff water decreased. Inorganic fertilizer maintained a slightly elevated risk to water quality throughout the study period, particularly with respect to soluble P losses. The poultry litter used in this study, applied at 35 kg P ha^{-1} represented little risk to water quality, as soluble P and NH_4-N levels from this treatment were similar to those observed from unfertilized plots throughout the study. This was most likely due to the relatively lower levels of soluble P and the immobilization

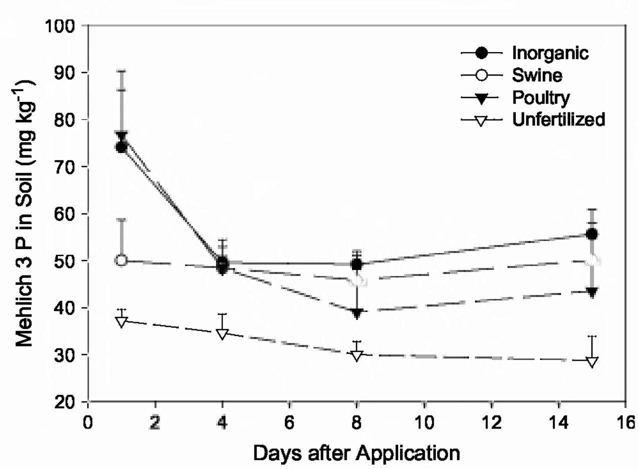

Fig. 5. Mehlich 3 extractable P concentrations by treatment from soil samples collected immediately prior to rainfall simulations (vertical bars represent standard error).

of soluble P through the stimulation of microbial biomass. NO_3-N losses were not observed to be a significant threat to water quality in this study. Provided there is more than 1 week between application and a rainfall–runoff event, swine manure and poultry litter applied at these rates may provide the agronomic benefits of supplying the crop with nutrients while minimizing the risks to water quality.

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