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RESEARCH ARTICLE

Application of manure to no-till soils: phosphorus losses by sub-surface and surface pathways

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Abstract The acceleration of surface water eutrophication attributed to agricultural runoff has focused attention on manure management in no-till. We evaluated losses of phosphorus (P) in sub-surface and surface flow as a function of dairy manure application to no-till soils in north-central Pennsylvania. Monitoring of a perennial spring over 36 months revealed that dissolved reactive P (DRP) concentrations increased 3- to 28-fold above background levels whenever manure was broadcast to nearby field soils. A study conducted with 30-cm deep intact soil cores indicated that incorporation of manure by tillage lowered P loss in leachate relative to broadcast application, presumably due to the destruction of preferential flow pathways. More P was leached from a sandy loam than a clay loam soil, although differences between soils were not as great as differences between application methods. In contrast, rainfall simulations on 2-m^2 field runoff plots showed that total P (TP) losses in surface runoff differed significantly by soil but not by application method. Forms of P in surface runoff did change with application method, with DRP accounting for 87 and 24% of TP from broadcast and tilled treatments, respectively. Losses of TP in leachate from manured columns over 7 weeks (0.22–0.38 kg P ha^{-1}) were considerably lower than losses in surface runoff from manured plots subjected to a single simulated rainfall event (0.31–2.07 kg TP ha^{-1}). Results confirm the near-term benefits of incorporating manure by tillage to protect groundwater quality, but suggest that for surface water quality, avoiding soils prone to runoff is more important.

Keywords Phosphorus · Runoff · Leaching · No-till · Dairy manure

Abbreviations

DRP	Dissolved reactive P
DOP	Dissolved organic P
EDI	Effective depth of interaction
TDP	Total dissolved P
TP	Total P

Introduction

Freshwater eutrophication, the biological enrichment of surface waters accelerated by anthropogenic inputs of phosphorus (P), remains one of the most pervasive

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surface water quality problems in the US (Environmental Defense 2007). Surveys of water quality in the US have pointed to agriculture as a key source of P in watersheds where eutrophication is a concern (Carpenter et al. 1998; U.S. Geological Survey 1999). Nearly all states now require that certain categories of livestock agriculture, particularly concentrated animal feeding operations, develop nutrient management strategies that target P-based management toward fields identified as vulnerable to non-point source P pollution by site risk assessment indices (Sharpley et al. 2003).

Historically, the loss of P from agricultural lands was primarily attributed to erosion of P-rich soil particles (Daniel et al. 1994). Control of non-point source P pollution was addressed by implementing practices that decreased soil erosion and sediment-bound P losses (Sims and Kleinman 2005). A variety of studies have shown that no-till practices decrease both erosion and sediment-bound P losses relative to conventional tillage (McDowell and McGregor 1980; Sharpley and Smith 1994). As farming systems become more specialized and intensive, the control of dissolved P losses from agricultural soils receiving regular applications of livestock manure has been elevated as a water quality concern (Sharpley et al. 2005; U.S. Environmental Protection Agency 2004). Therefore, no-till practices that conserve soil have been re-examined in light of their effect on dissolved P losses in runoff. It is now well documented that no-till can exacerbate losses of dissolved P in surface runoff relative to conventional tillage (Mueller et al. 1984; Sharpley and Smith 1994).

Several related processes contribute to the potential for no-till soils to release dissolved P to surface runoff. First, surface application of fertilizers and manures to no-till soils promotes stratification of P with depth, with most P concentrated in the upper few centimeters (Guertal et al. 1991; Andraski et al. 2003; Butler and Coale 2005). Runoff interacts primarily with P in the surface soil. For instance, Sharpley (1985) determined the effective depth of interaction (EDI) between soil P and runoff water to be in the upper 0.1–3.7 cm. As P levels increase in the surface of no-till soils, so too does the potential for soil P release to surface runoff (Vadas et al. 2005).

The second major process leading to the enrichment of surface runoff with P is the direct contribution of manure P to runoff water, referred to as “rapid incidental transfer” by Preedy et al. (2001). Manures contain high concentrations of P that is readily released to water (Kleinman et al. 2005a). When manures are broadcast to the soil surface as in no-till, there is minimal interaction between applied manure P and soil particles that tend to react with P to form relatively insoluble complexes. Consequently, P in surface applied manure is readily available to runoff water (Vadas et al. 2004). Over time, P in surface applied manure is translocated into the soil via leaching (e.g., infiltrating manure water and rain water) and bioturbation (e.g., earthworm action) (Chardon et al. 2007; Vadas et al. 2007). In fact, several studies have reported an increase in the population and activity of earthworms under reduced compared to conventional tillage practices, concomitant with an increase in food or energy supply (Trojan and Linden 1998; Shipitalo et al. 2000). When manure P is translocated from the surface, its availability to runoff water declines (Kleinman and Sharpley 2003). Thus, from the standpoint of dissolved P loss in surface runoff, tilling soils to which manure has been broadcast serves to dilute soil and manure P within the EDI and to promote the sorption of dissolved P with soil colloids that are relatively unsaturated with respect to P (Sharpley 1985, 2003).

While the effect of tillage and manure application methods on P in surface runoff has received considerable attention, comparatively limited research has examined the effect of these management practices on sub-surface P transport. In part, this is because surface runoff is typically the major pathway by which P is transported from soil to surface waters (Sims et al. 1998). However, a growing body of research has highlighted the importance of subsurface P transport in a range of physiographic settings (Sims et al. 1998; Chardon and van Faassen 1999). Leaching of P through soils is likely dominated by preferential flow via macropores (Jensen et al. 1998; Stamm et al. 1998, 2000), as opposed to piston-type flow through micropores of the soil matrix (Geohring et al. 2001; Akhtar et al. 2003). Indeed, no-till and grassland soils are the subject of the majority of studies reporting significant sub-surface transport of P (Sims et al. 1998; Chardon and van Faassen 1999). Old generalizations concerning P leaching only through coarse-textured soils have been replaced with numerous examples of subsurface P transport in finer textured soils with extensive macropore

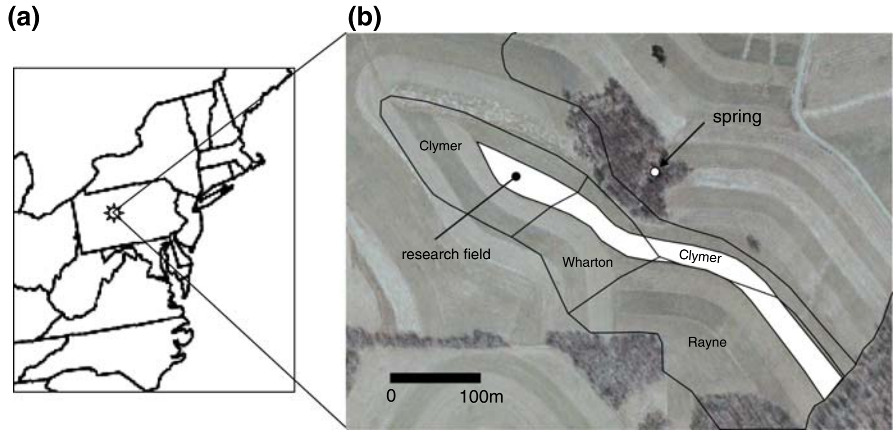

Fig. 1 Map of northeastern US showing location of research site within Allegheny Plateau of central Pennsylvania (**a**), as well as soil map units, field layout and location of spring that served as a groundwater sampling point (**b**). Runoff and leaching studies were conducted within the Clymer and Wharton soil portions of the *highlighted* field

networks (e.g., Djodjic et al. 1999; van Es et al. 2004). Therefore, tillage practices that disturb soil macropores may impede P leaching through soils. For instance, Shipitalo and Gibbs (2000) identified earthworm burrows as a primary conduit for swine slurry found in tile drain effluent. In that study, tilling the soil above the tile drain curtailed subsequent contamination of the tile drain when slurry was applied, presumably by destroying the continuity of the burrows between the surface soil and the tile drain.

Given the trade-offs in managing tillage and manure related to dissolved and sediment-bound P in surface runoff and leachate, we sought to examine differences in P transport related to P application method on contrasting, no-till soils. This study provides evidence of P leaching to groundwater following broadcast application of dairy manure to no-till field soils and quantifies the near-term effects of broadcasting or incorporating manure by tillage on P loss from two well-structured no-till soils via leaching and surface runoff.

Materials and methods

Site description

The study was conducted on a 172-ha dairy farm (100 head of milking cattle) located on the Eastern Allegheny Plateau and Mountains region (Major Land Resource Area 127) of Pennsylvania (Fig. 1). Average rainfall in the area is 110 cm and average monthly temperatures range from −5°C in January to 21°C in July. A typical crop rotation on the farm consists of 4 years of corn (*Zea mays* L.) followed by 4 years of alfalfa (*Medicago sativa*)—orchardgrass [*Dactylis* L. (Poaceae)] hay. All crops are no-till planted. The first year of corn is planted into a sod burned down the previous fall with a combination of glyphosate and 2,4-D. Succeeding years of corn are treated with a glyphosate, s-metolachlor, mesotrine and atrazine mix[1] Soils are occasionally chisel plowed to break up corn stalks in the year of hay establishment. During years of corn production, soils receive ~ 34 m^3 ha^{-1} liquid dairy manure by surface application with a broadcast spreader, resulting in a total P (TP) application rate of roughly 20–30 kg ha^{-1} (Table 1 for manure nutrient concentrations from this study). During years of alfalfa-grass production, soils receive ~ 19 m^3 ha^{-1} manure if it is available after all the corn fields on the farm have been amended. In addition to dairy manure, 250–287 kg ha^{-1} starter fertilizer (% N–P_2O_5–K_2O = 29.2–0–18.2) is applied at corn planting.

A 1.3 ha strip-cropped field in the final (fourth) year of corn production was selected for the study (Fig. 1). The field was dominated by Wharton clay loam (fine-loamy, mixed, active, mesic Aquic Hapludult) and Clymer sandy loam (coarse-loamy, siliceous, active, mesic Typic Hapludult) soils and was located at the summit position of a Rayne–Gilpin–Ernst catena, separated from a forested lot by another field of similar dimensions and soil

[1] Mention of trade names does not imply endorsement by USDA. Nor does it imply approval to exclude other products that may also be suitable.

Table 1 Properties of dairy manures used in study

Experiment	Collection date	Dry matter (%)	Total N (g kg^{-1}, dry weight basis)	Total P (g kg^{-1}, dry weight basis)	Water extractable P 200:1 (solution: solid) (g kg^{-1}, dry weight basis)
Runoff study	June 2002	10.5	37.8	8.6	NA
Lysimeter study	Febuary 2004	12.6	36	4.8	3.2

distribution. The finer-textured Wharton was located within a broad swale bisecting the field. Within the forest, approximately 80-m downslope of the experimental field, was a spring that had formerly served as a source of drinking water for the farm house. A concrete box surrounded the spring, which remained unfrozen over the entire period of the study. There was no apparent overland flow connection between the spring and the fields located upslope, and the near constant temperature indicated that it derived its water from subsurface sources.

Phosphorus leaching studies

Groundwater monitoring

The improved spring located downslope of the experimental field was periodically sampled from May 2001 to May 2004, to monitor dissolved P in emerging groundwater. Approximately 500 ml of water was obtained in a plastic sampling container and stored at 4°C until analyzed. During the monitoring period, the date and location of broadcast manure application to fields surrounding the improved spring were recorded for all fields surrounding the forest.

Column leaching experiments

To assess P leaching related to manure application method, 18 intact soil columns were collected from the experimental field: 12 of Clymer soil; six of Wharton soils by the method of Kleinman et al. (2005b). A 30 × 50-cm (internal diameter × depth) PVC cylinder was pushed into the soil by a 2-Mg drop weight. To prevent surface compaction, the drop weight was not allowed to contact the soil surface and no visual evidence of compaction was observed following cylinder insertion into the soil. Columns were removed by excavating the soil adjacent to the submerged cylinder and then tilting the cylinder to cleanly break contact between the soil column and the underlying subsoil.

To prepare columns for leaching experiments, columns were inverted and washed sand poured into the voids created by the separation of the peds at the column bottom Fig. 2). A layer of nylon drain fabric was placed over the sand as a retainer, followed by a 30-cm diameter PVC disk, perforated with roughly 60, 0.2-cm perforations. The disk, in turn, was held in place by a PVC cap sealed to the cylinder with silicone. With cap in place, the columns were returned to their original upright position. To allow drainage, a hole was drilled into the cap and fitted with a 1-cm PVC nipple that could be inserted into a plastic collection container. This design ensured that drainage did not become reductive during the leaching experiments. Soil columns were transported to a greenhouse where they were subjected to leaching experiments.

Columns were irrigated with deionized water (2.0 cm) once per week for 14 weeks: seven before manure application; seven after application of dairy manure. The irrigation rate corresponds roughly to average weekly rainfall depths at the study site (2.1 cm). Leachate was collected 24-h after the columns were irrigated.

Two manure application methods were simulated, broadcasting by hand and incorporation (to 10 cm) using a three-tined garden claw. Two manure application rates were evaluated, fixed on the basis of TP. A manure application rate of 30 kg TP ha^{-1}, roughly equivalent to the average rate applied to corn each year on the farm, was evaluated on six of the 12 Clymer soil columns and all six Wharton soil columns. In addition, manure was applied at a rate of 100 kg TP ha^{-1} to the remaining six Clymer soil columns. Treatment combinations (soil × application method × application rate) were replicated on three columns.

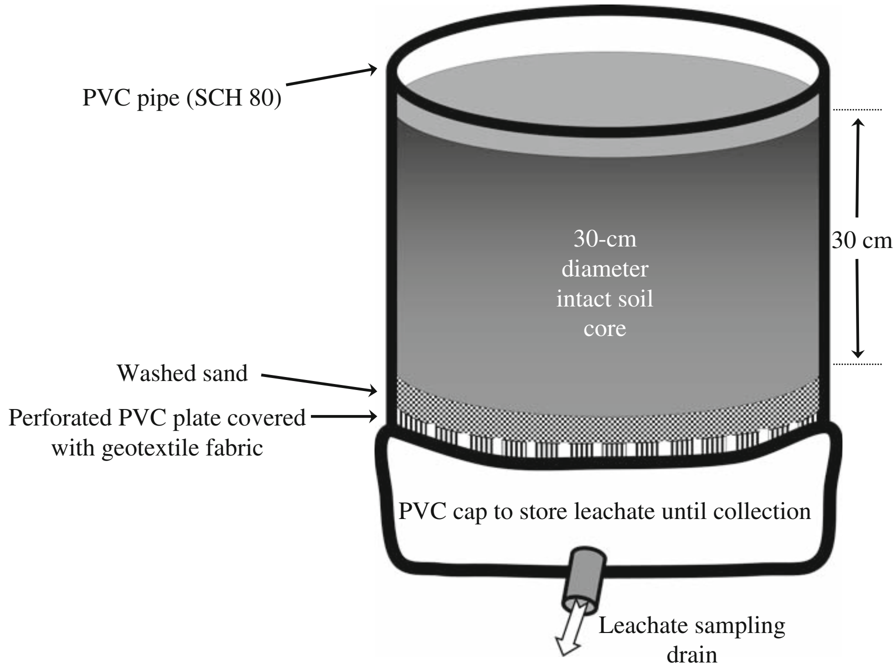

Fig. 2 Soil column design used in leaching study

Surface runoff experiments

Rainfall simulation experiments were conducted to compare losses of P in runoff related to manure application method on the Clymer and Wharton soils. A total of eight runoff plots, each consisting of two pairs of abutting 1 × 2 m plots, were installed in the two soils. Rainfall-runoff experiments were carried out following a modified protocol of the National Phosphorus Research Project (2007) and are described in greater detail by Garcia et al. (2008). Briefly, rainfall was delivered at ~75 mm h^{-1} until 30 min of runoff was collected. Rainfall simulations were conducted on soils before and after manure application. The first rainfall simulation was conducted on unamended soils on June 18, 2002. A single, composite runoff sample was obtained for each event, and both filtered (0.45 μm) and unfiltered sub-samples were obtained. At this point, soil samples (2-cm diameter) were collected from 0–2, 4–6, 14–16 cm depths adjacent to each plot. After the first rainfall simulation, manure was broadcast by hand to all plots at a rate of 30 kg TP ha^{-1}. Manure was from the same source as that used in the leaching experiment, but was collected at a different date so the two manures differed somewhat their properties (Table 1). A hand-operated rototiller was used to incorporate manure (~20-cm mixing depth) into half of the plots so that two manure application treatments, surface applied and incorporated, were evaluated. The final rainfall simulation was conducted on all plots (broadcast and incorporated) on June 25, 2002, 24 h after manure had been incorporated.

Laboratory analyses

All soils were air dried, sieved (2-mm) and analyzed for Mehlich-3 P by shaking 2.5 g of soil with 25 ml of Mehlich-3 solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.013 M HNO_3 + 0.001 M EDTA) for 5 min (Mehlich 1984). Phosphorus in the Mehlich-3 extracts was measured colorimetrically by a modified method of Murphy and Riley (1962), with a spectrophotometer wavelength of 712 nm.

Manure was analyzed for TP by modified semi-micro-Kjeldahl procedure (Bremner 1996). One g dry-weight equivalent fresh manure was shaken with 200 ml of distilled water on an end-over-end shaker for 60 min. The mixture was then centrifuged (about 2,900*g* for 20 min to facilitate filtration) and filtered through a Whatman No. 1 filter paper. Filtrate P was determined colorimetrically. Dry matter content of all

Table 2 Properties of Clymer and Wharton soils prior to rainfall simulation studies and manure

Soil	Sample depth (cm)	Sample no.	Mehlich-3 P (mg kg^{-1})	pH	Particle size distribution (%)		
					Sand	Silt	Clay
Clymer	0–2	8	134	6.7	58	24	18
	4–6	8	129	6.8			
	14–16	8	95	6.8			
Wharton	0–2	8	62	6.7	39	28	33
	4–6	8	53	6.9			
	14–16	8	46	7.0			

manures was determined gravimetrically after oven-drying manures at 70°C for 48 h.

Dissolved reactive P (DRP) was determined on 0.45-µm filtered runoff and leachate water by the colorimetric method described for soil extracts. Unfiltered water samples were digested by modified semimicro-Kjeldahl procedure and P determined by colorimetry to quantify TP. In addition, for column leachate only, filtered samples were subjected to the semimicro-Kjeldahl digestion to quantify total dissolved P (TDP). The difference between TDP and DRP, sometimes termed dissolved unreactive P, was assumed to represent dissolved organic P (DOP). Runoff water was also analyzed for total solids content by evaporating 200 ml of unfiltered runoff water in an oven at 70°C and weighing the remaining material.

Statistical analyses

Data were evaluated for normality to confirm the use of parametric statistics. Treatment effects (manure application rate and method, soil type) were evaluated by Student's *t*-test or by general linear model using Tukey's test to compare individual means. Associations between variables were evaluated with Pearson's correlation analysis. Treatment differences discussed in the text were significant at $P \leq 0.05$. All analyses were performed using SAS's statistical software, version 9.1 (SAS Institute Inc. 2002).

Results and discussion

Soil properties

The two soils included in the study differed in a variety of properties that would be expected to affect their susceptibility to environmental P losses (Table 2). The Wharton soil occurred in a swale that bisected the research field, and had a slightly steeper slope gradient (7.5%) than did the adjacent Clymer soil (5.3%). Permeability of the finer textured Wharton clay loam (33% clay) was expected to be lower than the Clymer sandy loam (18% clay), contributing to greater potential for surface runoff and erosion and lesser source of groundwater recharge (Hillel 1998). In contrast, Mehlich-3 P in the Clymer soil was roughly twice that found in the Wharton soil, with Mehlich-3 P of the Wharton and Clymer soils rating "optimum" and "high", respectively, from an agronomic stand point (Beegle 2007). Soils also exhibited evidence of P stratification within the surface horizon as a result of the recent history of no-till management and surface application of manure: Mehlich-3 P at a 15-cm depth was roughly 25% lower than at the soil surface (Table 2).

Phosphorus losses to groundwater

Phosphorus in spring water

Although P losses to groundwater are often not considered of environmental importance unless soils are coarse textured or subject to artificial drainage (Sims et al. 1998), monitoring of the spring below the experimental field revealed significant spikes in DRP concentration of emerging groundwater after manure was applied to the fields upslope of the spring (Fig. 3). Application of manure to these fields was followed by an average fourfold increase in DRP concentrations in spring water relative to background concentrations, despite considerable variability in background DRP concentrations before manure was applied (coefficient of variation = 0.54), and after manure was applied (coefficient of variation = 0.75).

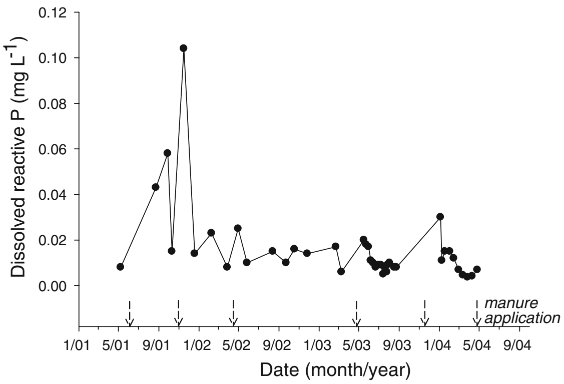

Fig. 3 Concentrations of dissolved reactive P (*DRP*) in spring water and timing of manure applications to upslope fields

Following a manure application event in late 2001, DRP concentrations reached 0.10 mg l^{-1}, an approximate 28-fold increase over the previous sample obtained before manure application. In contrast, an April application in 2003 resulted in only a threefold increase in DRP concentration above the previous sample. Variability was also observed in the duration that DRP concentrations remained elevated after manure, although the infrequent nature of spring water sampling likely contributed to some of the observed variability. Other sources of variability include nature and timing of precipitation events relative to manure application, antecedent soil moisture and crop management conditions at time of manure application, and differences in leaching susceptibility of soils receiving manure (Sims et al. 1998; Kleinman et al. 2003; van Es et al. 2004).

The apparent rapid response of DRP in spring water samples to manure application suggests the existence of preferential flow pathways that connect the surface soils to which the manure was applied with the groundwater. Fields upslope of the groundwater spring were in no-till production during the study period, which would sustain continuous macropores within the regolith, approximately 120–170 cm for Clymer and Wharton soils. Fractures within the underlying sedimentary bedrock favor high saturated conductivities that could enable the rapid transfer of DRP to the groundwater seep (Gburek and Folmar 1999). Although P enrichment of shallow groundwater has been observed (Sims 1998; Vadas et al. 2007), studies documenting elevated DRP concentrations below the vadose zone remain relatively rare, particularly with regard to agricultural sources of P (Nolan and Stoner 2000). Even so, concentrations in the current study fell within the range reported by Burkart et al. (2004) who surveyed 103 groundwater wells in unconsolidated geologic strata of Iowa agricultural watersheds. They observed concentrations of TDP of up to 1.0 mg l^{-1}, with mean values ranging from 0.07 to 0.21 mg l^{-1}.

Phosphorus leaching from soil columns

Given the fluctuations in DRP concentrations of water samples obtained from the spring, we expected field soils to transmit significant concentrations of manure P in leachate. Concentrations of P in leachate from the soil columns were higher than in water samples obtained from the spring, consistent with the dilution of DRP away from the manure source in groundwater samples (Table 3). Surprisingly, DRP represented a relatively minor fraction of TP in soil column leachate, averaging 25% of TP before manure application and 37% after manure application. Dissolved organic P contributions to TP in leachate were comparable to DRP, such that TDP in leachate (DRP + DOP) was equivalent to 51% of TP before application and 63% of TP after manure was applied. Thus, nearly half of TP in leachate from the soil columns was in sediment-bound form, even after manure application. Findings of sediment-bound P transport in subsurface flow have been reported elsewhere (e.g., Sharpley and Syers 1979; Dils and Heathwaite 1999). In studies of well-structured soils amended with liquid cattle manure, Schelde et al. (2006) observed that up to 80% of P in tile drain effluent was associated with sediment, while Toor et al. (2004) observed that over 70% of leachate P from soil columns amended with dairy slurry was in sediment-bound form. Clearly, such substantial contributions of sediment-bound P confirm the importance of bypass flow via macropores as a dominant transport mechanism of P transport in such soils.

Despite considerable variability in flow between soil columns (coefficient of variation = 0.29), P losses (kg ha^{-1}), which reflect leachate volumes, and P concentrations (mg l^{-1}) were strongly correlated ($r = 0.92$–0.97 for DRP, TDP and TP). Therefore, the temporal trends in P losses depicted in Fig. 4 were similar for P concentrations. Both concentrations and losses of P in leachate increased

Table 3 Average leachate depth and flow weighted phosphorus concentrations from Clymer and Wharton soil columns

Soil	Manure application (kg TP ha^{-1})		Leaching period (weeks)	N	Leachate depth (cm)	Dissolved fraction (<0.45 μm) mg l^{-1}		Total P (mg l^{-1})
	Rate	Method				DRP	DOP	
Clymer	0	Pre-application	7	12	7.02 (1.60)[a]	0.04 (0.04)	0.04 (0.02)	0.17 (0.12)
Clymer	30	Broadcast	7	3	8.81 (2.87)	0.08 (0.02)	0.05 (0.0)	0.25 (0.13)
Clymer	30	Incorporated	7	3	10.72 (1.35)	0.17 (0.15)	0.04 (0.02)	0.17 (0.21)
Clymer	100	Broadcast	7	3	9.48 (2.63)	0.21 (0.04)	0.17 (0.07)	0.5 (0.15)
Clymer	100	Incorporated	7	3	11.3 (0.33)	0.05 (0.37)	0.05 (0.01)	0.18 (0.07)
Wharton	0	Pre-application	7	6	7.11 (1.37)	0.03 (0.01)	0.05 (0.01)	0.15 (0.13)
Wharton	30	Broadcast	7	3	7.77 (3.6)	0.06 (0.04)	0.05 (0.03)	0.29 (0.18)
Wharton	30	Incorporated	7	3	7.47 (4.6)	0.02 (0.01)	0.05 (0.04)	0.12 (0.03)

[a] Standard deviations presented in parentheses

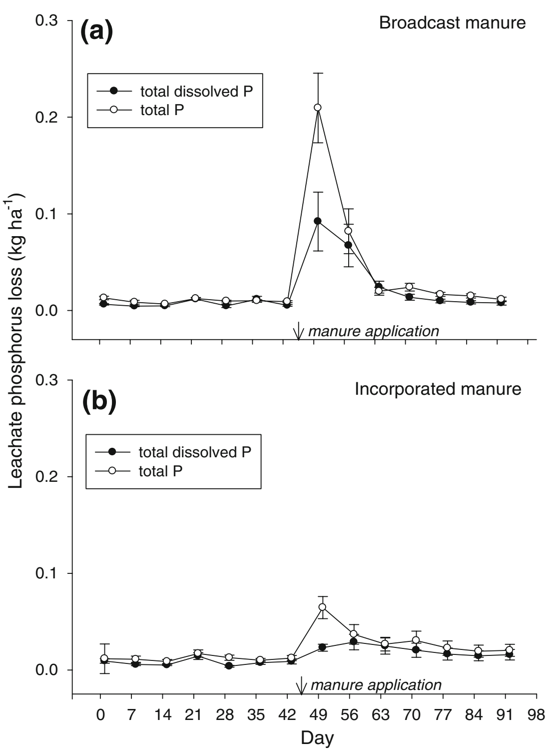

Fig. 4 Average losses and standard error of total dissolved P and total P in leachate collected from columns of Clymer and Wharton soils before and after dairy manure application by broadcasting (**a**) and incorporation with simulated tillage (**b**)

after manure was applied to the soil columns, identifying applied manure as a significant source of P in leachate. Total dissolved P and TP in leachate increased significantly with the first leaching events after manure application, but declined rapidly, stabilizing within three to four events. Such a flashy response of P in leachate to manure application is consistent with other studies (e.g., Geohring et al. 2001; van Es et al. 2004) as well as with the fluctuations in P observed in the spring water samples (Fig. 3). Notably, TDP and TP losses and concentrations remained significantly elevated above pre-manure levels for the duration of the experiment, revealing an enduring impact of manure P on column leachate P not apparent in spring water samples.

Phosphorus losses in leachate differed significantly between manure application methods (Fig. 4), with TDP and TP losses roughly 4.0 and 3.2 times greater, respectively, from the broadcast treatment in the first event after application than in corresponding leachate from the incorporated treatment. Results clearly support the hypothesis that tillage curtails P translocation from the soil surface to lower in the solum. Consistent with this, Geohring et al. (2001) observed that light disking of dairy slurry after broadcasting resulted in greater P transfers to tile drains than did moldboard plowing, attributing the differences to a greater degree of incorporation of the slurry with plowing than disking. The incorporation method used in the current study would represent a severe form of tillage, more akin to several tillage passes than light disking. Even so, both TDP and TP losses in leachate from the incorporated manure columns remained significantly elevated above pre-manure application levels for the duration of the leaching study (Fig. 4). Over the 7 week period after manure application, cumulative losses of TDP and TP in leachate from broadcast were 1.5 and 1.7 times greater, respectively, than from incorporated manure.

Manure application rate (30 vs. 100 kg TP ha^{-1}) and soil (Clymer vs. Wharton) interacted significantly with application method in affecting P leaching losses from manure, but the effect of these factors tended to be less than the effect of manure application method. Manure application rate differences in leachate P (both TDP and TP) from Clymer soil columns were statistically significant in the first two rainfall events after manure was applied (Fig. 5). Cumulative differences in leachate P loss over the 7 weeks after manure application were 1.3-fold for TDP and 1.1-fold for TP, with maximum differences in the second week after manure application (Fig. 5). In contrast, differences in leachate P related to the two soils did not become apparent until the second week after manure application (30 kg TP ha^{-1} rate only), but persisted for the remainder of the study (Fig. 6). Consequently, on a cumulative basis, leachate TDP losses from the Clymer soil were 2.3 times greater than from the Wharton soil and cumulative TP losses from the Clymer soil were 1.3 times greater than from the Wharton soil. The principal cause of the differences in

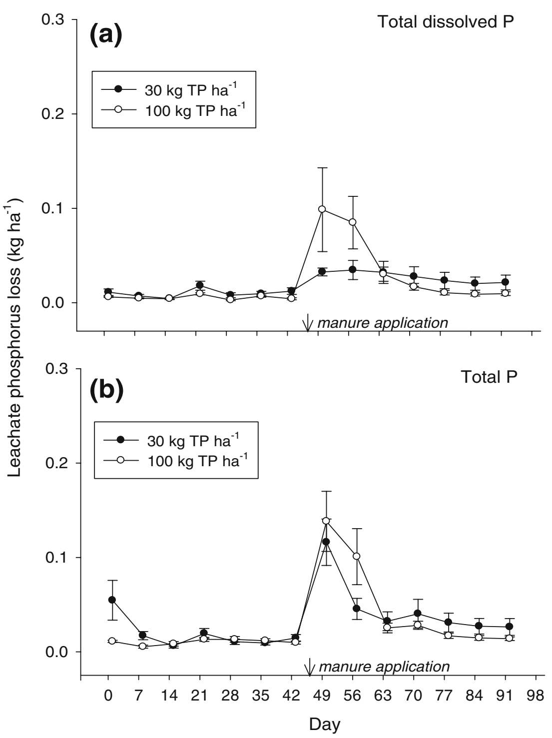

Fig. 5 Average losses and standard error of total dissolved P (**a**) and total P (**b**) in leachate from Clymer soil columns before and after dairy manure application at 30 and 100 kg TP ha^{-1}

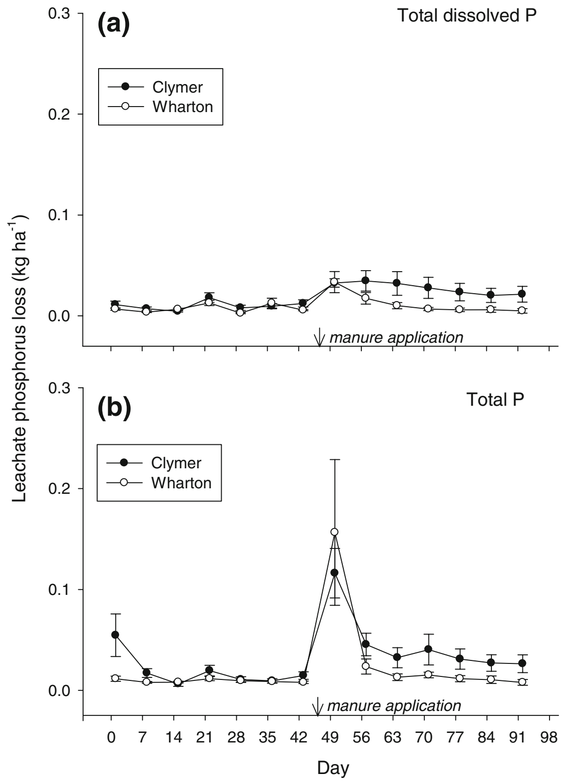

Fig. 6 Average losses and standard error of total dissolved P (**a**) and total P (**b**) in leachate from Clymer and Wharton soil columns before and after dairy manure application by broadcast and tillage incorporation methods (30 kg TP ha^{-1} only)

P leaching losses from the two soils was the volume of leachate (expressed as depth by factoring out area of soil column), which was significantly less from the finer-textured Wharton soil columns than from the Clymer soil columns (Table 3).

Phosphorus losses in surface runoff

Surface runoff results prior to manure application revealed significant differences between the two soils (Table 4). Without manure, losses of P were relatively low, with DRP accounting for 39% (Clymer) to 67% (Wharton) of TP in runoff. Losses of DRP and TP were significantly greater from the Wharton soil. As anticipated, surface runoff volumes (expressed as depths by factoring out the area of the runoff plot) were significantly greater from the finer textured Wharton soil than from the Clymer soil, corresponding to 57 and 21% of applied rainfall, respectively (Table 4).

Table 4 Average properties of runoff from plots established in Clymer and Wharton soils

Soil	Application method	Proportion of plots generating runoff	Runoff depth[a] (cm)	Runoff concentration			Runoff losses[c] (kg ha^{-1})		
				DRP (mg l^{-1})	Total P (mg l^{-1})	Total solids (g l^{-1})	DRP	Total P	Total solids
Clymer	Before manure	8/8	1.17 (0.71)[b]	0.28 (0.13)	0.81 (0.32)	0.19 (0.12)	0.04 (0.03)	0.10 (0.08)	24.4 (26.4)
Clymer	Broadcast manure	4/4	0.42 (0.31)	5.39 (3.12)	6.68 (1.86)	0.76 (0.29)	0.26 (0.33)	0.31 (0.31)	36.2 (39.1)
Clymer	Incorporated manure	3/4	0.72 (0.65)	3.38 (0.99)	6.84 (1.51)	0.19 (0.13)	0.32 (0.21)	0.61 (0.24)	69.2 (55.0)
Wharton	Before manure	8/8	2.67 (0.31)	0.74 (0.29)	1.69 (0.33)	0.14 (0.06)	0.20 (0.08)	0.32 (0.15)	35.9 (14.4)
Wharton	Broadcast manure	4/4	2.36 (0.26)	7.78 (0.44)	8.70 (1.48)	0.49 (0.38)	1.83 (0.18)	2.07 (0.54)	119.3 (87.2)
Wharton	Incorporated manure	4/4	2.08 (0.42)	0.94 (0.80)	7.45 (3.51)	0.82 (0.35)	0.18 (0.16)	1.64 (1.08)	166.3 (76.4)

[a] Runoff depth is determined from the volume of runoff divided by the area of the runoff plot

[b] Standard deviations are presented in parentheses. Data summarized previously in Garcia et al. (2008)

[c] Average losses calculated from all plots, including those from which no runoff was generated

Application of dairy manure (30 kg TP ha^{-1}) increased TP losses in runoff an average of fourfold. No significant differences in TP losses between broadcast and incorporated treatments were observed (Table 4). However, processes of P loss clearly differed between the two application methods. Rapid incidental transfers of readily soluble P in the applied dairy manure were likely the primary source of P in runoff from the broadcast treatment, whereas erosion of both soil and manure solids was most likely responsible for P losses from the tilled soils. Dissolved reactive P accounted for 81–89% of TP in runoff following broadcasting without incorporation, but only contributed 12–49% of TP in runoff from the tilled soil.

In dairy manures, a high proportion of TP in the manure is readily water soluble. As reported above, water extractable P accounted for 66% of TP in the manure used in the leaching experiments (Table 1), identical to the proportion reported in the survey of Kleinman et al. (2005a) for dairy manures obtained from above-ground storage tanks. Notably, a considerable amount of manure dry matter was observed to erode from the broadcast treatment, accounting for the high total solids concentration in surface runoff from that treatment (Table 4). The light organic matter fraction of broadcast manure is readily floated by runoff and has been implicated as a source of sediment in other runoff studies of this type (McDowell and Sharpley 2002; Kleinman et al. 2004).

The absence of differences in TP losses between manure application methods corresponds with previous studies of manure incorporation by conventional (moldboard) tillage involving multiple runoff events over longer periods of observation. For instance, Mueller et al. (1984) repeated rainfall simulations on manured plots over a 2 year period. They observed similar losses of TP in runoff from no-till soils receiving broadcast dairy manure and soils in which the dairy manure was incorporated by conventional tillage. As in the current study, Mueller et al. (1984) observed losses of TP from the no-till soils that were predominantly in the form of DRP whereas DRP accounted for a minor fraction of TP losses from the conventionally tilled soils. In that study and elsewhere (e.g., Daverede et al. 2004), however, incorporation of manure by conservation tillage (chisel plowing), as opposed to conventional tillage, resulted in significant reductions in TP losses relative to broadcasting manure by limiting the erosion associated with conventional tillage. Such findings point to the potential to limit tillage impacts on sediment-bound P losses not evaluated in the current study, which simulated aggressive tillage.

Although manure application methods did not differ in their relative effect on TP losses in runoff, TP losses from the Wharton soil were three to seven times greater than those observed from the Clymer soil (Table 4). These differences derive primarily from greater runoff depths produced by the Wharton soil. In addition, manure incorporation did not significantly impact DRP in runoff from the Clymer soil, but did significantly lower DRP concentrations and losses from the Wharton soil. Differences in DRP trends between soils suggest a greater propensity for the fine-textured Wharton soil to adsorb soluble manure P, and may indicate better mixing of manure into the Wharton soil with the rototiller. Soil-specific differences clearly highlight the importance of edaphic variability in manure management and point to the potential for critical sources of runoff P to occur at scales finer than those typically managed by farmers. In this case, the Wharton soil occupied a 0.29-ha swale, representing only 22% of the total area of a small field, and was sufficiently small to be impractical to delineate as a separate management unit.

Conclusions

The fate of manure P in no-till soils is affected by a variety of factors. In the current study, application of manure to no-till soils clearly increased P losses in leachate and surface runoff relative to losses before manure was applied, regardless of application method and soil properties. The most acute risk of manure P loss by leaching and surface runoff was immediately after manure was applied, consistent with the concept of rapid incidental transfer that has been established with surface runoff. Although environmentally significant concentrations of TP were observed in leachate samples after manure application (>0.12 mg l^{-1}), TP losses in leachate from manured columns (0.22–0.38 kg P ha^{-1}) over 7 weeks were considerably lower than TP losses in surface runoff from manured plots subjected to a single simulated rainfall event (0.31–2.07 kg TP ha^{-1}). Even so, when normalized by the different depths of precipitation applied to the lysimeters and runoff plots, the first leaching event after manure application resulted in an average TP loss of 0.07 kg ha^{-1} cm^{-1} rainfall, compared with 0.17 kg ha^{-1} cm^{-1} rainfall in surface runoff.

This study points to the potential to manage manure P losses from no-till soils. Tilling soils that were broadcast with manure significantly lowered P losses in leachate relative to broadcasting manure, supporting the hypothesis that tillage destroys macropores that serve as the dominant pathway for subsurface P transport. However, tillage did not significantly lower the loss of TP in surface runoff, as tillage increased sediment-bound P loss in surface runoff relative to broadcasting, shifting the mechanism of P loss from rapid incidental transfer of soluble P in manure to erosion. Notably, the role of erosion in P transport would likely be even greater under natural conditions, as our surface runoff experiments favored rapid incidental transfers associated with the brief window of time after manure was applied. Tillage impacts would be expected to persist well beyond this brief period (Garcia et al. 2008).

This study also highlights the differential response of soils to manure application. Differences in manure P loss in leachate from the Clymer and Wharton soils were significant, although not as great as those induced by manure application method. In contrast, soil related differences in TP loss via surface runoff were not only significant when application method had no effect, but were also dramatic (threefold to sevenfold). Therefore, results of this study support the critical source area concept of managing manure application to soils by limiting application to soils, such as the Wharton, that are relatively prone to runoff. The difficulty in implementing such an approach is also illustrated by this study; such precision manure management may require that small, but environmentally significant, areas of field be treated as separate management units. In the case of the Wharton soil, manure application would have to be curtailed on a 130-m wide zone within the center of an already small (1.3 ha), strip cropped field.

While this study highlights trade-offs in P-based management related to incorporation of manure by tillage, it does not address the growing array of manure injection methods that increasingly represent an option for farmers in the region. Injection of manure would be expected to lower rapid incidental transfers to surface runoff while restricting tillage impacts to the zone of injection. At the same time, however, manure injection may also exacerbate nutrient leaching losses. Clearly, a systematic assessment of the trade-offs of alternative manure incorporation methods is needed to provide a complete perspective on the potential for optimizing manure management in no-till soils.

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