ORIGINAL ARTICLE

Effect of dairy manure slurry application in a no-till system on phosphorus runoff

Keisha N. Johnson · Peter J. A. Kleinman ·
Douglas B. Beegle · Herschel A. Elliott ·
Lou S. Saporito

Abstract Incorporation of manure slurry under reduced tillage conditions remains a challenge in the northeastern US. New technologies to directly incorporate slurry are available but their agronomic and environmental benefits have generally not been quantified. This study evaluated the effects of five manure slurry application methods on phosphorus (P) loss in runoff (broadcasting with and without incorporation by tillage, shallow disk injection, banded application and aeration, and pressurized injection) and a control (no manure). Research was conducted over a 2 year period in central Pennsylvania on a well-drained Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf) under corn (*Zea mays* L.) production. Approximately 72 h after dairy (*Bos Taurus*) slurry application ($56{,}000 \ l \ ha^{-1}$) to 10×13 m plots, a single rainfall simulation ($68 \ mm \ h^{-1}$) was conducted in triplicate on 10×2 m areas within the plots. Trends in total P losses in runoff ($kg \ ha^{-1}$) from plots varied between years and treatments. Aeration yielded lower losses than all other treatments in 2006 and was amongst the lowest in 2007 with losses statistically similar to shallow disk and pressure injection. Remarkably, few differences were apparent in losses of dissolved reactive P between treatments, reflecting high variability in runoff depths. Indeed, variability in runoff depths resulted in some unexpected trends, including high loads from the unamended control and modest loads from the tillage treatment. Results highlight tradeoffs in alternative manure slurry application practices but point to the potential to significantly lower runoff P losses from reduced tillage systems receiving manure slurry.

Keywords Phosphorus · Manure application · Surface runoff · No-till

Abbreviations

DRP	Dissolved reactive phosphorus
TP	Total phosphorus
WEP	Water extractable phosphorus
EDI	Effective depth of interaction
TS	Total solids

K. N. Johnson (✉) · D. B. Beegle
Department of Crop and Soil Sciences, Agricultural
Sciences and Industry Building, Pennsylvania State
University, University Park, PA 16802, USA
e-mail: knj107@psu.edu

P. J. A. Kleinman · L. S. Saporito
Pasture Systems and Watershed Management Research
Unit, USDA-ARS, 3702 Curtin Road, University Park,
PA 16802, USA

H. A. Elliott
Department of Agricultural and Biosystems Engineering,
Agricultural Engineering Building, Pennsylvania State
University, University Park, PA 16802, USA

Introduction

Runoff from manure amended agricultural fields is a major water quality concern due to phosphorus (P) in

manure and the potential for that P to enrich runoff and promote eutrophication of downstream water bodies (Ginting et al. 1998; Andraski et al. 2003). A growing body of research has highlighted the potential of manure application methods to differ in their effect on P in runoff (Mueller et al. 1984; Withers et al. 2001; Kleinman and Sharpley 2003; Gessel et al. 2004; Volf et al. 2007). In no-till and reduced-tillage systems, manure has traditionally been broadcast on the soil surface. Broadcasting manure without incorporating the manure into the soil results in high concentration of manure P at the soil surface, lower potential for P sorption to the soil, and stratification of P within the surface soil horizon (Buah et al. 2000; Borges and Mallarino 2003; Sharpley 2003; Schwab et al. 2006). Because the effective depth of interaction (EDI) between soil and runoff is generally less than 2 cm deep (Sharpley 1985), and because manure contains concentrations of water extractable P that are roughly three orders of magnitude greater than in surface soils (Kleinman et al. 2005), broadcast application of manure significantly increases the potential for P release to runoff water in no-till soils, especially dissolved P forms (Sharpley 2003).

Traditionally, manure incorporation has primarily been achieved via tillage following broadcasting of manure. Tillage lowers the availability of P to runoff by incorporating most of the manure on the soil surface, placing it beneath the EDI (Heathwaite and Dils 2000), and by diluting P-rich surface soil with subsoil that is generally lower in P and has a greater P buffer capacity (Sharpley 2003). The primary trade-off of manure incorporation by tillage with regard to P runoff is that erosion potential increases with tillage, as does the potential for particulate P losses. Furthermore, tillage runs counter to modern soil conservation programs stressing reduced forms of soil disturbance (Machado and Silva 2001).

A variety of methods exist to incorporate manure slurry into soil as alternatives to intensive forms of tillage, from slurry injection to mechanical aeration. These methods have the potential to lower P runoff, provide other environmental benefits (e.g., ammonia-N conservation), and can be integrated into modern reduced-tillage systems (Morken and Sakshaug 1998; Buah et al. 2000; Machado and Silva 2001). Manure slurry injection methods are widespread in some regions (e.g., Midwestern US) and offer the ability to directly incorporate slurry behind tillage implements such as chisels, disks and knives. However, traditional slurry injection systems have not been widely adopted in other regions (e.g., northeastern US), especially regions where soils are steep and stony where steel implements can be difficult to draw through soil and are readily damaged. In south-central Pennsylvania, Dou et al. (2001) found that less than 5% of 994 dairy farms injected manure slurry. Shallow injection systems are less susceptible to failure than deep injection systems in stony and steep soils due to relatively minimal contact between the implement and soil. Daverede et al. (2004) used a shallow disk injection system to incorporate swine slurry into a silt loam soil. Compared with broadcast slurry, disk injection lowered P loss in surface runoff from field plots by more than 90%.

Other alternative slurry application systems, developed primarily for perennial forages, have shown promise in reduced tillage systems, but have been in limited use. Surface placement systems (e.g., banding, drag-shoes, sleigh-foot) apply slurry directly on the surface but beneath the vegetative cover of soil. Such systems represent a compromise between injection and broadcasting manure slurry and have been shown to significantly reduce ammonia losses relative to broadcasting in fields with vegetative cover (Bittman et al. 1999, 2005). Mechanical aeration has been used to improve infiltration of liquid manure slurry into the soil by creating elongated holes that provide preferential infiltration points for surface applied slurry as well as temporary storage for the slurry below the soil surface. Aeration systems have been shown to decrease surface compaction and bulk density (van Vliet et al. 2006), as well as to lower ammonia volatilization and reduce runoff volumes (Shah et al. 2004; Franklin et al. 2007).

Despite the prevalence of alternative manure slurry application methods, there has been little research documenting the specific effects of these systems on P loss in runoff and few studies have tested several methods side-by-side. The objective of this study was therefore to quantify differences of P loss in runoff from reduced tillage corn related to five methods of dairy manure slurry application. Methods used in this study include aeration with banded manure slurry, shallow disk and pressure injection, conventional broadcasting, and manure slurry incorporation by tillage.

Materials and methods

Experimental design and site characterization

A field study investigating alternative methods of applying dairy (*Bos Taurus*) manure slurry was conducted at the Pennsylvania State University Russell E. Larson Agricultural Research Center (Rock Springs, PA). The study was located on a well-drained Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf), with an average slope of 3–5%. The site consisted of four acres under no-till management for 7 years prior to the initiation of the study in 2006. The recent cropping history of the site included corn (*Zea mays* L.), soybeans (*Glycine max* L.) and oats (*Avena sativa* L.), with the entire area having a uniform cropping history and no history of manure slurry application. Average Mehlich-3 soil P at the site was 12 mg kg^{-1} and average pH was 6.4 (soil:water = 1:1). Long-term average annual precipitation is 950 mm, and annual average temperature is 9°C.

Eighteen field plots (10 × 13 m) were arranged in a randomized complete block design with replications blocked by field strip (Fig. 1). Five manure slurry application treatments were evaluated in triplicate. Treatments included:

Broadcasting manure slurry without incorporation

Manure slurry was broadcast with a six unit splash plate applicator, with plate located approximately 1 m above the soil surface. No tillage was conducted in association with this treatment.

Incorporation of broadcast manure slurry by chisel plowing

Broadcast manure slurry was incorporated within 2 h of application using a chisel plow (standard twist, 8–9 inch plow depth) and immediately followed by a culti-mulcher (harrow tines and corrugated roller) for seedbed preparation.

Shallow disk injection

Yetter 2986 series Avenger^{TM} injectors (Colchester, IL)[1] were used for shallow disk injection of the

---

[1] Mention of trade names does not imply endorsement by the USDA.

manure slurry, with a distance of 75 cm between injection units. Each shallow disk injection unit consisted of a 74 cm opening coulter paired with a drop tube to place manure slurry at a depth of approximately 12 cm in the opening made by the coulter. Behind the drop tube were two, inclined closing (sealing) coulters.

Pressure injection

The Moi A/S Direct Ground Injector (DGI)^{TM} (Moi, Norway) was used for pressurized injection of the manure slurry. The pressure injector consisted of four, 125-cm wide injection boxes that slid on 30-cm spaced skis over the soil surface. Manure slurry pulsed under high pressure (5–8 bars) through a 1-cm orifice in the bottom of each ski, and was injected approximately 6 cm into the soil.

Aeration with banded application

An Aerway SSD^{TM} (Holland Equipment Ltd, Norwich, ON, Canada) was used for the banded application of manure slurry with aeration. The aeration-infiltration unit consisted of gangs of rolling aeration tines with four 20 cm spikes per spindle spaced approximately 20 cm apart. Manure slurry was banded behind the tines and infiltrated to a depth of 8 cm into the soil.

No manure (control)

No manure application or tillage was conducted in association with this treatment.

In 2006 and 2007, manure slurry was obtained from a local dairy farm reception pit at near full capacity and mixed thoroughly prior to pumping. Slurry was pumped into a typical field scale manure slurry spreader (8,316 l capacity), equipped to accommodate different tool bars with the alternative application systems. The spreader was calibrated both years with each of the application systems prior to its use on field plots by weighing the manure applied over a measured distance. Slurry was applied to field plots at a rate of roughly 56,000 l ha^{-1}, confirmed by weighing the spreader before and after slurry application to each plot. Slurry was applied to replicate field plots on April 27, May 1 and May 8 in 2006 and on May 4,
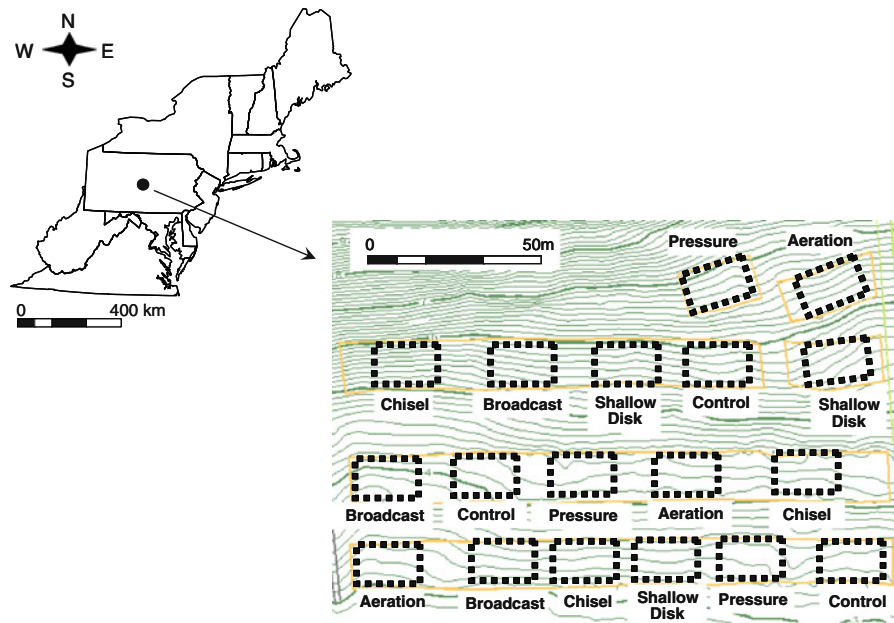
Fig. 1 Map of study site showing location of field site in Rock Springs, Pennsylvania and layout of field plots

May 7 and May 14 in 2007. On each of these dates, a manure slurry sample was collected from the spreader for laboratory analysis. All manure slurry application equipment covered a width of approximately 4-m per pass, requiring three passes to complete application to each field plot. In 2007, 112 kg N ha^{-1} as ammonium nitrate was applied to the no-manure slurry control plot; no additional fertilization was applied to the fields in 2006. Corn was planted approximately 3 weeks after manure slurry was applied, using the same no-till planter for all plots in 2006 and 2007.

Rainfall simulations

A rainfall simulation experiment was conducted to assess nutrient and sediment losses in runoff approximately 72 h following manure slurry application. Artificial rainfall was applied using a rotating boom simulator developed for the Water Erosion Prediction Protocol (WEPP) on 10×2 m temporary runoff plots located within the 10 by 13 m experimental plot. Runoff plots were established immediately following the application of manure slurry. Each plot consisted of galvanized metal borders inserted approximately 7.5 cm into the soil (extending approximately 7.5 cm above the soil) and a steel

gutter located at the bottom end of the plot (Sharpley and Kleinman 2003).

The rainfall simulator consisted of a trailer mounted manifold with 10 radiating booms (7.6 m in length). Each boom houses TeeJet 2HH-SS50WSQ (Spraying Systems Co., Wheaton, IL) nozzles positioned at various distances from the trailer. A total of 15 nozzles were employed. When rotating at 4 rpm at approximately 2.5 m above the soil surface, the nozzles deliver rainfall with a coefficient of uniformity > 0.85. Rainfall was measured with four rain gauges per plot. Forty minutes of rainfall was applied to each plot resulting in a depth of 45 mm of rainfall. Average rainfall intensity was 68 mm h^{-1} for both years. This 1-h rainfall intensity has a return period between 25 and 50 years for central PA (Aron et al. 1986). Water used in the simulations was obtained from a local irrigation source with mean dissolved P concentration of 0.050 mg l^{-1}.

Soil moisture was measured before and after each rainfall event by capacitance sensor (Theta Probe, Delta T Devices, Cambridge, UK) at six locations within each runoff plot. Runoff flow during each event was measured continuously, and a 2 l sample of runoff water was obtained every 5 min, beginning 2.5 min after runoff initiation, until the 40 min rainfall event

was terminated. A 30-ml sub-sample of runoff was filtered (0.45 μm) immediately after the rainfall simulation. Filtered and unfiltered runoff samples were stored at 4°C until analysis.

Estimating water extractable P within the effective depth of interaction

To provide insight into processes controlling manure P loss in runoff, we measured water extractable P (WEP) in the surface 1 cm of the treated soil zone 24 h after manure slurry application. Each manure slurry application treatment was carried out as per the description above at a site adjacent to the runoff study area. Samples containing manure slurry and soil were obtained 24-h after manure slurry application by inserting a 1.0 by 0.2 m metal frame perpendicular to the line of manure slurry application. All material within the frame was collected to a depth of 1-cm below the soil surface. Three replicates were obtained per manure application treatment.

In other studies evaluating broadcast manure slurries only, WEP has been expressed simply as a concentration in the manure slurry (e.g., Kleinman et al. 2007). However, due to the spatially discrete way in which the different methods applied manure slurry to the soil surface, it was necessary to represent the total amount of WEP potentially exposed to runoff (kg WEP ha^{-1} of soil and manure), not simply the concentration of WEP in manure slurry (mg WEP kg^{-1} or mg WEP l^{-1}). By sampling the upper 1 cm of treated soil only, we attempted to isolate the zone most likely representing the source of P to runoff water, i.e., the EDI.

Laboratory analysis

Runoff

Dissolved P in runoff was determined on filtered samples by the colorimetric method of Murphy and Riley (1962), modified such that $\lambda = 712$ nm. Total P was measured on unfiltered samples following alkaline persulfate digestion by the method of Patton and Kryskalla (2003). Total solids and volatile solids were determined by gravimetric analysis, comparing the initial and final weight of crucibles after evaporating 150 ml of runoff water at 80°C.

Soil

Mehlich-3 soil P was determined by shaking 1 g soil with 10 ml of Mehlich 3 solution (0.2N CH$_3$COOH, 0.25N NH$_4$NO$_3$, 0.015N NH$_4$F, 0.013N HNO$_3$, and 0.001N EDTA) for 5 min, filtering through a Whatman No. 2 (Mehlich 1984). Water extractable P was measured by mixing 1 g of soil with 25 ml of distilled water, shaken end-over-end for 1 h, filtering the supernatant through a Whatman No. 1 paper filter. Phosphorus in Mehlich-3 and water extracts was determined colorimetrically by modified method of Murphy and Riley (1962). Soil pH was measured in a 1:1 soil to water mixture (Eckert and Sims 1995).

Manure slurry

Liquid manure slurry obtained on the three application dates was analyzed for pH, total solids content, and total N, P and K. Manure slurry pH was measured in a 1:2 manure slurry ratio (Wolf et al. 2005). Total solids content of the manure slurry was determined by drying manure slurry at 105°C, overnight. Total N (TN) was determined by Elementar Vario Max CN Analyzer[2] (combustion, chromatographic separation and thermal conductivity detection of N). Total P and K were determined by EPA Method 3051 using a microwave digestor (US Environmental Protection Agency 1986) with P and K in digests determined by inductively coupled plasma atomic emission spectroscopy. Water extractable P, expressed on a dry weight equivalent basis, was determined by mixing 1 g of manure slurry (as is) with 100 ml of distilled water, shaken end-over-end for 1 h, centrifuged, filtered through a Whatman No. 1 filter paper, and supernatant was analyzed colorimetrically (Kleinman et al. 2007).

Mixed soil and manure slurry samples

Surface soil and manure slurry mixtures sampled in 2007 to represent the EDI were air dried, weighed and analyzed for water extractable and total P. Water extractable P was determined by the method of Kleinman et al. (2007) as described above for manure slurry. Total P in soil and manure slurry mixture was

---

[2] Mention of trade names does not imply recommendation or endorsement by USDA-ARS.

Table 1 Properties of dairy manure used in study

Analyte	2006	2007
pH	6.89	7.62
Solids (%)	9.65	7.06
Total nitrogen (g kg^{-1})[†]	40.9	50.1
Total P (g kg^{-1})	5.37	6.83
Water Extractable P (g kg^{-1})	NA[‡]	1.5

[†] Total nitrogen and P expressed on a dry weight equivalent basis

[‡] Not available

analyzed by a modified semimicro-Kjeldahl procedure (Bremner 1996) (see Table 1).

Statistical analysis

Data were analyzed by SAS's PROC UNIVARIATE to confirm assumption of normality and equal variance distribution. In the case of DRP concentration (mg l^{-1}) in runoff, logarithmic transformation was needed to achieve a normal distribution for statistical analysis, and then back-transformed for discussion in text. An analysis of variance (ANOVA) in PROC MIXED (SAS Institute 2000) was used to analyze runoff interval data using flow weighted averages so that a single concentration was used to represent flow from a plot. Associations between P in runoff and soil and manure slurry variables were analyzed by least squares regression. For variables that could not be transformed to achieve a normal distribution, i.e., DRP and total P loss (kg ha^{-1}), differences among treatments were evaluated using a non-parametric Friedman two-way analysis of variance by ranks and multiple comparison procedures as described by Ipe (1987). For parametric statistics, statistical significance an α of 0.05 was used, whereas for non-parametric statistics, an α of 0.10 was employed.

Results and discussion

Phosphorus losses (kg ha^{-1}) in runoff from field plots across all treatments were considerably lower in 2006 than in 2007 (Table 2), corresponding with differences in runoff depth that were likely driven by antecedent moisture. Runoff depths, calculated by dividing runoff volumes by plot area, were very low in 2006, averaging 1.5 mm compared to 10.4 mm in 2007. Antecedent

soil moisture averaged 0.16 m^3 m^{-3} in 2006 (well below an estimated field capacity of 0.29 m^3 m^{-3}), and 0.24 m^3 m^{-3} in 2007. In 2006 only 1.5 mm of rainfall was recorded at the site during the week before the rainfall simulation experiments, whereas in 2007, 33.5 mm of rainfall was recorded for the same period. Compared with other rainfall simulation studies, runoff depths in 2006 were low; Daverede et al. (2003) reported 8.6 mm runoff and Srinivasan et al. (2007) reported 6.7 mm runoff.

Phosphorus concentrations in runoff varied widely, from 0.06 to 1.83 mg dissolved P l^{-1} and 0.16–2.81 mg total P l^{-1} in 2006 and from 0.03 to 2.46 mg dissolved P l^{-1} and 0.76–3.4 mg total P l^{-1} in 2007. These concentrations fell within the lower range of P concentrations reported in other studies involving manure slurry application despite the low soil P levels at the study site (e.g., Daverede et al. 2003, 2004; Vadas et al. 2005). Dissolved P contributed from 4 to 92% of TP in runoff over the 2 years, reflecting broad differences in sources of P (i.e., soil vs. manure slurry) available to runoff water from each treatment (Table 2). Erosion, as represented by total solids content in runoff, was also low, ranging from 0.02 to 381 kg ha^{-1} with concentrations of 0.41–4.08 mg l^{-1}.

Effect of manure slurry application methods on runoff P

Along with differences in antecedent soil moisture and runoff depths, trends in P losses between treatments were highly variable over the 2 years although the lowest TP losses were consistently associated with the banded aeration treatment (Table 2).

Control (no manure)

As expected, average losses of P in runoff (kg ha^{-1}) from the control were among the lowest observed of the different treatments (Table 2); however, these losses did not differ significantly from most of the other treatments, reflecting high variability in P loss, either associated with the control (e.g., 2006 when the relative standard deviation of total P was 91%) or with the other treatments (e.g., 2007 when the relative standard deviation of total P was 136% for broadcast manure). In the case of the control, this variability was in large part associated with variability in runoff depth. Indeed, runoff depths from the control plots

Table 2 Means and standard deviations (SD) for depth, flow weighted concentrations and loads for total phosphorus (TP), dissolved reactive phosphorus (DRP) and total solids (TS) in runoff

Tillage treatment	N	Runoff depth (SD) (mm)†	Concentration (mg l⁻¹)			Load (kg ha⁻¹)		
			Phosphorus		Solids	Phosphorus		Solids
			DRP (SD)	TP (SD)	TS (SD)	DRP (SD)	TP (SD)	TS (SD)
2006								
Control	2	2.34 (2.52) a‡	0.056 (0.04) b	0.46 (0.13) b	1.47 (0.74) a	0.0021 (0.0028) ab	0.011 (0.01) c	25.1 (19.7) a
Broadcast	3	0.52 (0.57) ab	1.83 (0.68) a	2.81 (0.81) a	1.79 (0.44) a	0.008 (0.008) ab	0.013 (0.01) c	10.0 (12.35) a
Broadcast incorporation	3	0.33 (0.37) b	0.16 (0.18) b	1.45 (1.18) ab	3.94 (1.44) a	0.00019 (0.00006) b	0.008 (0.012) c	15.7 (21.6) a
Banded aeration	3	<0.0001 b	0.055 (0.0) b	0.16 (0.0) b	2.31 (0.0) a	<0.0001 bc	<0.0001 d	0.02 (0.04) a
Shallow disk injection	3	1.97(1.44) ab	0.34 (0.18) b	0.85 (0.17) ab	2.54 (0.99) a	0.008 (0.009) a	0.016 (0.011) ab	60.6 (46.7) a
Pressurized injection	3	3.53 (2.48) a	0.17 (0.25) b	0.95 (0.17) ab	1.34 (0.49) a	0.009 (0.014) a	0.036 (0.03) a	48.3 (35.5) a
2007								
Control	3	23.1 (1.05) a	0.03 (0.03) c	0.76 (0.09) c	1.66 (0.64) a	0.0060 (0.006) a	0.172 (0.005) a	381 (139) a
Broadcast	3	19.6 (24.6) ab	2.46 (0.90) a	3.4 (1.28) a	0.44 (0.34) c	0.44 (0.59) a	0.88 (1.2) a	97 (137) bc
Broadcast incorporation	3	7.43 (6.11) ab	0.10 (0.16) c	1.67 (0.28) a	4.08 (1.2) a	0.0051 (0.007) a	0.14 (0.12) ab	353 (380) a
Banded aeration	3	1.06 (1.67) b	1.84 (0.50) ab	2.85 (0.42) a	0.41 (0.05) c	0.034 (0.04) a	0.036 (0.05) c	4.33 (6.99) c
Shallow disk injection	3	6.72 (10.42) ab	0.46 (0.41) bc	0.78 (0.09) bc	0.85 (0.16) ab	0.015 (0.017) a	0.053 (0.08) cd	63.9 (102) bc
Pressurized injection	2	4.22 (2.04) ab	0.74 (0.13) bc	1.59 (0.27) a	0.72 (0.21) ab	0.030 (0.01) a	0.045 (0.04) bc	28.45 (6.02) c

† Depth was determined by dividing runoff volume by plot area

‡ Different letters within columns indicate significant differences between treatments using an analysis of variance and Tukey's mean separation $P < 0.05$ for concentrations (mg l⁻¹) and non-parametric Freidman two-way analysis of variance by ranks and multiple comparison as described by Ipe (1987) for loads (kg ha⁻¹) $P < 0.10$

included some of the highest depths observed across all treatments in both years (Table 2). These greater depths increased runoff P loads, even though concentrations (mg l^{-1}) of P in the runoff water from the control plots tended to be low.

Average concentrations of P in runoff from the control plots tended to be low, as would be expected given the absence of an applied manure P source with this treatment (Table 2). Again due to variability, runoff DRP concentrations from the control only differed from the two treatments with the highest DRP concentrations in runoff, i.e., those treatments in which manure was applied to the soil surface: broadcast manure (2006, 2007) and banded aeration (2007 only). Total P concentrations in runoff, which reflect both dissolved and particulate forms of P, were significantly lower than all treatments but shallow disk injection in 2007 when conditions were wet and runoff depths were relatively high, yet only significantly lower than broadcast manure in 2006, when conditions were dry.

Broadcast manure slurry without incorporation

Due to high variability in runoff properties within treatments, differences in P losses (kg ha^{-1}) between the broadcast manure slurry treatment and the other treatments varied over the two study years. For both years, total P losses associated with broadcast manure slurry were statistically similar to the control and incorporation by chisel plow. As described above, the absence of a significant difference in total P losses between control and broadcast manure slurry treatment largely reflects the high variability in runoff depths within treatments. However, it is likely that additional processes complicated findings related to the other treatments, including detachment and erosion of soil-bound P, floating of manure flocs and desorption of P from soils.

Broadcasting the manure slurry clearly increased DRP concentrations (mg l^{-1}) in runoff relative to the other treatments. In 2006, runoff DRP concentrations were greatest from the broadcast treatment, while in 2007 they were similar to the banded aeration treatment, which also left a large quantity of manure exposed on the soil surface. The high concentrations of DRP in runoff from the broadcast slurry plots reflect the large WEP content of the manure slurry and its availability to runoff (e.g., Kleinman et al.

2002). For total P concentrations, differences between the broadcast treatment and treatments other than the control were not as apparent, reflecting the contribution of other sources of P to runoff (soil, manure). In 2006, total P concentrations in runoff associated with banded aeration were significantly lower than with broadcast application while in 2007, total P concentrations associated with shallow disk injection were significantly lower than with broadcast application. These inconsistent, but statistically significant, trends suggest that variability in performance of the applicators and site conditions can strongly influence the effect of manure application method on runoff P losses.

Manure slurry incorporation by chisel plowing

Total P losses in runoff following incorporation of broadcast manure slurry with chisel plowing differed between years. For both years there was no statistical difference in total P loss between the broadcast and chisel plowing treatments, although mean losses were up to 84% lower for the tillage treatment. In 2006, when runoff depths were low, incorporation by tillage yielded significantly lower total P losses than pressure injection and shallow disk treatments (77 and 50% respectively), with only the banded aeration treatment having lower losses (Table 2). The opposite was observed in 2007, where all other methods of incorporating manure slurry had significantly lower total P losses (>62%) compared to incorporation with plowing.

Aeration and banded manure slurry application

Total P losses from the aeration and banded manure slurry application treatment were consistently the lowest of all treatments (Table 2). In fact, average total P losses in runoff from the banded aeration treatment over both years were <4% of those observed from plots broadcast with manure slurry. These low losses can be attributed to the effect of aeration on rainfall infiltration into the soil. Other authors have also documented reductions in runoff P losses with the use of aeration on well drained soils. For instance, Franklin et al. (2007) also found that aerating well-drained grassland soils reduced dissolved P loss and runoff volumes by 35%. Elsewhere, van Vliet et al. (2006) also found that aeration before

manure slurry application significantly reduced dissolved and total P losses from grasslands relative to un-aerated control plots.

Although P losses from the banded aeration treatment were low, concentrations of P in runoff were amongst the highest in the study (Table 2). In 2007, dissolved P concentrations contributed to 64% of total P in runoff and were significantly higher than broadcasting manure slurry followed by incorporation and the control. This reflects large amount of exposed manure slurry and associated WEP. It is notable that these concentrations were only measured in runoff from a few plots; runoff was only generated from one of three replications in 2006 and two of three replications in 2007.

Shallow disk injector

Trends in total P losses associated with shallow disk injection were inconsistent between years. In 2006, total P losses were higher than all other treatments, including broadcasting manure slurry, except the pressure injector, which had the highest losses. In 2007, total P losses were significantly lower than the broadcast manure slurry treatment and even the control (Table 2). Results point to an important aspect of applicator performance. Even though the same shallow disk injection unit was used in both

years of the study, the performance of the shallow disk injector appeared to have been affected by the use of different manure slurry tankers with varying abilities to exert consistent hydraulic down pressure.

Pressurize injection

In 2006, losses of total P associated with pressure injection were among the highest of all treatments whereas in 2007 they were among the lowest. Concentrations of total P in runoff with pressure injection averaged 53–66% of runoff from broadcast manure slurry plots, pointing to good placement of manure P below the soil surface with pressure injection. It is notable that the pressure injector had a tendency to scrape crop residue from the soil surface and expose the soil to direct raindrop impact, although no increase in soil erosion was detected in comparison with other methods.

Runoff DRP and WEP within the effective depth of interaction

There was a strong positive linear relationship between DRP concentrations in runoff from the field plots with the quantity of WEP found in the samples (surface soil + manure slurry) that were collected to represent the EDI (Fig. 2). Although the EDI samples

Fig. 2 Relationships of dissolved reactive phosphorus (DRP) concentration in runoff (mg l^{-1}) with water extractable manure P (WEP) in the upper 1 cm of soil sampled in 2007 to represent the effective depth of interaction between soil and applied manure with runoff: **a** individual trends for 2006 and 2007 runoff simulations, **b** average trends for 2006 and 2007 runoff simulations
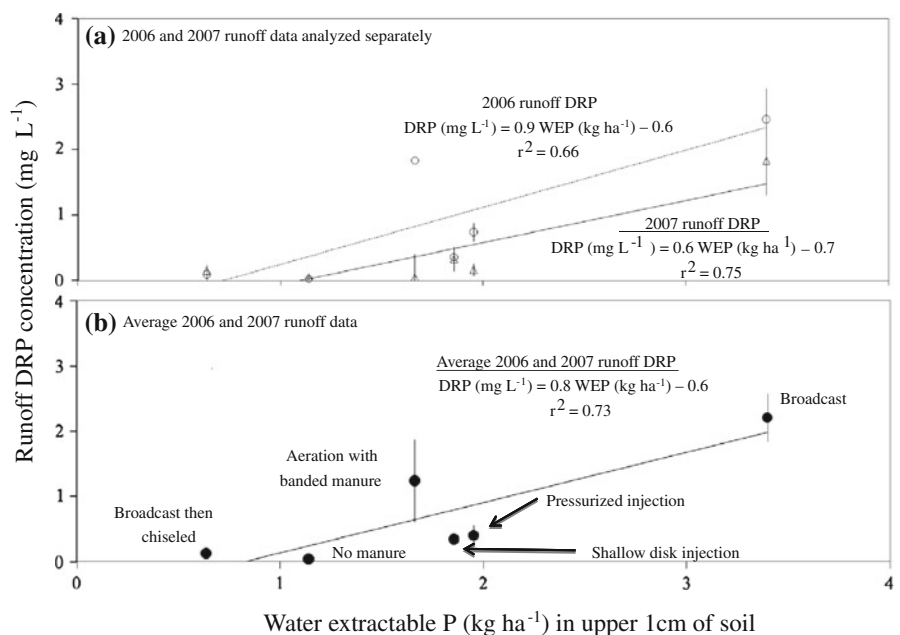
were only collected in 2007 and although they were collected from a separate site, when WEP from the EDI samples was related to DRP concentrations in 2006 and 2007 runoff samples from the field plots, the relationship was strong (r^2 ranged from 0.66 to 0.75), as it was when runoff data from the field plots for both years were averaged ($r^2 = 0.73$).

Treatment labels on averaged 2006 and 2007 DRP concentrations (Fig. 2b) do provide an indication of the extent to which individual manure application methods affected WEP within the EDI. The lowest WEP was associated with mixing of slurry with soil (chisel plowing), whereas banding of slurry and improving infiltration below the EDI (banded aeration), and injection of the manure, with some splatter on the soil surface (shallow disk and pressurized injectors) had intermediate WEP values.

These findings are consistent with the hypothesis that the relative placement of the manure slurry affects DRP in runoff over the short-term. Although relationships between runoff DRP and WEP of the EDI were strong, it is likely that an array of factors contributed to the variability in these relationships (e.g., Volf et al. 2007): antecedent moisture and hydrology; climatic conditions affecting drying of slurry; variability in performance of the applicators; and, variability in soil properties. In addition, estimation of WEP within the EDI clearly does not explain the effect of the individual methods on runoff hydrology or physical processes (e.g., detachment) controlling runoff P loss. Indeed, our estimates of WEP of the EDI explain relatively little of the variability in total P concentrations in runoff ($r^2 = 0.39$–0.53).

Conclusions

This study highlights tradeoffs in P loss and erosion from agricultural fields with alternative manure slurry application methods. Trends in total P losses varied between years and treatments. In 2006, dry conditions coupled with the well-drained soil used in this study resulted in little runoff across all treatments, with no statistically significant benefit from manure slurry incorporation to P losses, except for banded aeration where TP loss was significantly lower than broadcasting manure slurry. In 2007, when antecedent moisture and runoff volumes were relatively high,

both aeration and injection treatments significantly lowered P losses relative to broadcasting manure slurry (>94% reduction). Incorporation of manure slurry by chisel tillage lowered DRP concentrations but did not lower P losses in 2007 as erosion-related P losses increased after tillage.

Our research confirms that manure application methods that reduce WEP within the EDI lower DRP in runoff. Although we only sampled the EDI 1 year and samples could not be obtained from the same inference space used to measure runoff, this sampling explained much of the variability in DRP concentration over both years. A more refined sampling approach, one that distinguishes the manure and the soil contribution to WEP in the EDI, would likely have yielded greater insight into the specific processes controlling DRP release from amended soils to runoff water.

This study provides insight into the effect of manure application methods on runoff P over the short-term only, and possesses limitations when applied to long-term generalizations. For instance, the single rain event on freshly manured soil simulated in this study was insufficient to produce the sealing expected of exposed soil as seen in the relatively low runoff depths observed. The role of WEP in the applied manure would be expected to diminish over time. Even so, findings of this study provide valuable insight into the potential, and limitations, of using manure application methods in mitigating runoff P losses from agricultural soils.

References

Aron G, Wall DJ, White EL, Dunn CN, Kotz DM (1986) Field manual of Pennsylvania Department of Transportation: storm intensity-duration-frequency charts. Pennsylvania

State University, Pennsylvania Department of Transportation and Federal Highway Administration

Andraski TW, Bundy LG, Kilian KC (2003) Manure history and long-term tillage effects on soil properties and phosphorus losses in runoff. J Environ Qual 32:1782–1789

Bittman S, Kowalenko CG, Hunt DE, Schmidt O (1999) Surface-banding and broadcast dairy manure effects on tall fescue yield and nitrogen uptake. Agron J 91:826–833

Bittman S, van Vliet LJP, Kowalenko CG, McGinn S, Hunt DE, Bounaix F (2005) Surface-banding liquid manure over aeration slots: a new low-disturbance method for reducing ammonia emissions and improving yield of perennial grasses. Agron J 97:1304–1313

Borges R, Mallarino AP (2003) Broadcast and deep-band placement of phosphorus and potassium for soybean managed with ridge tillage. Soil Sci Soc Am J 67:1920–1927

Bremner JM (1996) Nitrogen—total. In: Sparks DL (ed) Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA, Madison, pp 1085–1121

Buah SSJ, Polito TA, Killorn R (2000) No-tillage soybean response to banded and broadcast and direct and residual fertilizer phosphorus and potassium applications. Agron J 92:657–662

Daverede IC, Kravchenko AN, Hoeft RG, Nafziger ED, Bullock DG, Warren JJ, Gonzini LC (2003) Phosphorus runoff: effect of tillage and soil phosphorus levels. J Environ Qual 32:1436–1444

Daverede IC, Kravchenko AN, Hoeft RG, Nafziger ED, Bullock DG, Warren JJ, Gonzini LC (2004) Phosphorus runoff from incorporated and surface applied liquid swine manure and phosphorus fertilizer. J Environ Qual 33:1535–1544

Dou Z, Galligan DT, Allshouse RD, Toth JD, Ramberg CF Jr, Ferguson JD (2001) Manure sampling for nutrient analysis: variability and sampling efficacy. J Environ Qual 30:1432–1437

Eckert D, Sims JT (1995) Recommended soil pH and lime requirement tests. In: Sims JT, Wolf A (eds) Recommended soil testing procedures for the Northeastern United States. Northeastern Reg. Publ. No. 493. University of Delaware, Newark, pp 16–21

Franklin DH, Cabrera ML, West LT, Calvert VH, Rema JA (2007) Aerating grasslands: effects on runoff and phosphorus losses from applied broiler litter. J Environ Qual 36:208–215

Gessel PD, Hansen NC, Moncrief JF, Schmitt MA (2004) Rate of fall-applied liquid swine manure: effects of runoff transport of sediment and phosphorus. J Environ Qual 33:1839–1844

Ginting D, Moncrief JF, Gupta SC, Evans SD (1998) Interaction between manure and tillage system on phosphorus uptake and runoff losses. J Environ Qual 27:1403–1410

Heathwaite AL, Dils RM (2000) Characterizing phosphorus loss in surface and subsurface hydrological pathways. Sci Total Environ 251(252):523–538

Ipe D (1987) Performing the Friedman test and the associated multiple comparison test using proc GLM. Proc Ann SAS Users Group Int Conf 12:1146–1148

Kleinman PJA, Sharpley AN (2003) Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. J Environ Qual 32:1072–1081

Kleinman PJA, Sharpley AN, Moyer BG, Elwinger GF (2002) Effect of mineral and manure phosphorus sources on runoff phosphorus. J Environ Qual 31:2026–2033

Kleinman PJA, Wolf AM, Sharpley AN, Beegle DB, Saporito LS (2005) Survey of water extractable phosphorus in manure. Soil Sci Soc Am J 67:701–708

Kleinman P, Sullivan D, Wolf A, Brandt R, Dou Z, Elliott H, Kovar J, Leytem A, Maguire R, Moore P, Saporito L, Sharpley A, Shober A, Sims T, Toth J, Toor G, Zhang H, Zhang T (2007) Selection of a water extractable phosphorus test for manure and biosolids as an indicator of runoff loss potential. J Environ Qual 36:1357–1367

Machado PLO, Silva CA (2001) Soil management under no-tillage systems in the tropics with special reference to Brazil. Nutr Cycl Agroecosyst 61:119–130

Mehlich A (1984) Mehlich-3 soil test extractant: a modification of Mehlich-2 extractant. Commun Soil Sci Plant Anal 15(12):1409–1416

Morken J, Sakshaug S (1998) Direct ground injection of livestock waste slurry to avoid ammonia emission. Nutr Cycl Ecosyst 51:59–63

Mueller DH, Wendt RC, Daniel TC (1984) Phosphorus losses as affected by tillage and manure application. Soil Sci Soc Am J 48:901–905

Murphy J, Riley J (1962) A modified single solution for the determination of phosphate in natural waters. Anal Chim Acta 27:31–36

Patton CJ, Kryskalla JR (2003) Methods of analysis by the US Geological Survey National Water Quality Laboratory: evaluation of alkaline persulfate digestion as an alternative to Kjeldahl digestion for the determination of total and dissolved nitrogen and phosphorus in water. Water Resources Investigations Rep. 03-4174, USGS, Branch of Information Services, Federal Center, Denver

SAS Institute (2000) SAS for Windows. version 8. SAS Inst, Cary

Schwab GJ, Whitney DA, Kilgore GL, Sweeney DW (2006) Tillage and phosphorus management effects on crop production in soils with phosphorus stratification. Agron J 98:430–435

Shah SB, Miller JL, Basden TJ (2004) Mechanical aeration and liquid dairy manure application impacts on grassland runoff water quality and yield. Trans ASAE 47(3):777–788

Sharpley AN (1985) Depth of surface soil-runoff interaction as affected by rainfall, soil slope, and management. Soil Sci Soc Am J 49:1010–1015

Sharpley AN (2003) Soil mixing to decrease surface stratification of phosphorus in manure. Soils J Environ Qual 32:1375–1384

Sharpley AN, Kleinman PJA (2003) Effect of rainfall simulator and plot scale on overland flow and phosphorus transport. J Environ Qual 32:2172–2179

Srinivasan MS, Kleinman PJA, Sharpley AN, Buob T, Gburek WJ (2007) Hydrology of small field plots used to study phosphorus runoff under simulated rainfall. J Envrion Qual 37:1833–1842

US Environmental Protection Agency (1986) Method 3051. Acid digestion of sediments, sludges and soils. Test methods for evaluating solid waste, vol 1A, 3rd edn. EPA/SW-846. National Technical Information Service, Springfield

Vadas PA, Haggard BE, Gburek WJ (2005) Predicting dissolved phosphorus in runoff from manured field-plots. J Environ Qual 34:1347–1353

van Vliet LJP, Bittmana S, Derksenb G, Kowalenkoa CG (2006) Aerating grassland before manure application reduces runoff nutrient loads in a high rainfall environment. J Environ Qual 35:903–911

Volf CA, Ontkean GR, Bennett DR, Chanasyk DS, Miller JJ (2007) Phosphorus losses in simulated runoff from manured soils of Alberta. J Environ Qual 36:730–741

Withers PJA, Clay SD, Breeze VG (2001) Phosphorus transfer in runoff following application of fertilizer, manure and sewage sludge. J Environ Qual 30:180–188

Wolf AM, Kleinman PJA, Sharpley AN, Beegle DB (2005) Development of a water extractable phosphorus test for manure: Inter-laboratory study. Soil Sci Soc Am J 69:695–700