Management Practice Effects on Phosphorus Losses in Runoff in Corn Production Systems

L. G. Bundy,* T. W. Andraski, and J. M. Powell

ABSTRACT

Phosphorus losses in runoff from cropland can contribute to nonpoint-source pollution of surface waters. Management practices in corn (*Zea mays* L.) production systems may influence P losses. Field experiments with treatments including differing soil test P levels, tillage and manure application combinations, and manure and biosolids application histories were used to assess these management practice effects on P losses. Runoff from simulated rainfall (76 mm h^{-1}) was collected from 0.83-m^2 areas for 1 h after rainfall initiation and analyzed for dissolved reactive P (DRP), bioavailable P, total P (TP), and sediment. In no-till corn, both DRP concentration and load increased as Bray P1 soil test (STP) increased from 8 to 62 mg kg^{-1}. A 5-yr history of manure or biosolids application greatly increased STP and DRP concentrations in runoff. The 5-yr manure treatment had higher DRP concentration but lower DRP load than the 5-yr biosolids treatment, probably due to residue accumulation and lower runoff in the manure treatment. Studies of tillage and manure application effects on P losses showed that tillage to incorporate manure generally lowered runoff DRP concentration but increased TP concentration and loads due to increased sediment loss. Management practices have a major influence on P losses in runoff in corn production systems that may overshadow the effects of STP alone. Results from this work, showing that some practices may have opposite effects on DRP vs. TP losses, emphasize the need to design management recommendations to minimize losses of those P forms with the greatest pollution potential.

Phosphorus (P) loss in runoff from cropland is an environmental concern because this P often promotes weed and algae growth in lakes and streams. When these weeds and algae die and decompose, dissolved oxygen levels in lakes and streams are depleted, which can lead to odors, fish kills, and a general degradation of the aesthetic and recreational value of the environment. Certain blue-green algae in eutrophic waters form potent toxins that cause taste and odor problems, interfere with treatment of drinking water, and may pose a serious health hazard to humans and livestock (Kotak et al., 1993; Sharpley et al., 1994). Concerns about P losses from agricultural land are increasing, because soil test P values that reflect the amounts of plant-available P in soils, have increased substantially over the past 25 yr. Average soil test P levels in Wisconsin exceed the levels needed for optimum crop production because long-term P additions in manure and/or fertilizer have exceeded P removals in the harvested portion of crops (Bundy, 1998). However, continued land application of manure often is the only practical management option for livestock operations. This emphasizes the need to identify the effects of management practices for controlling P losses in runoff from corn (*Zea mays* L.) production systems across a range of soil test P levels.

Current national policy for nutrient management includes consideration of both P and N application rates in the development of nutrient management plans (NRCS, 1999). This policy requires use of a P-based application rate standard where manure or other organic wastes are applied under various field specific conditions.

Much of the work relating soil P and manure effects on P concentrations in runoff has been done in pasture systems (Sharpley et al., 1977, 1978, 1994; Daniel et al., 1994; Pote et al., 1996, 1999), and Pote et al. (1996, 1999) showed that a wide range of P tests were similarly related to P concentrations in runoff. Several studies have examined the effects of tillage and/or manure applications on P concentrations in runoff from row crop production systems (Hensler et al., 1970; Romkens et al., 1973; Wendt and Corey, 1980; Mueller et al., 1984; Andraski et al., 1985; Sharpley et al., 1992; Gaynor and Findlay, 1995; Ginting et al., 1998; Eghball and Gilley, 1999). However, a comprehensive study of the effects of management practices on P losses in runoff in tilled production systems is not available. The experimental sites selected for this study include management practices that are typical of corn production systems in Wisconsin and other areas of the midwestern USA. Specifically, they include grain-farming systems, where most P inputs are from inorganic P fertilizers with few if any organic P additions. Management practices typical of dairy farming operations that have a history of manure applications combined with various tillage alternatives are also reflected in the experimental sites. Since specific critical values for use of a P-based application rate standard are needed, the objective of this research was to determine management practice effects on P losses in corn production systems.

MATERIALS AND METHODS

Management practice effects on P losses in runoff in corn production systems were determined in three field experiments with different management histories. In general, field plots in these experiments, representing a range in management practices, were subjected to simulated rainfall and P in runoff was determined. Two experiments at Arlington, WI,

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Abbreviations: DRP, dissolved reactive phosphorus; TP, total phosphorus; STP, soil test phosphorus; IPF, inorganic phosphorus fertilizer; CP, chisel plow; ST, shallow till; NT, no till; BAP, bioavailable phosphorus; CV, coefficient of variation.

Table 1. Phosphorus source and application history at three experimental locations.

Location	Site	Study year	Phosphorus source†	Application rate or history	Year of application	Total P applied
						kg ha^{-1}
Arlington	Inorganic	1998	None	–	–	0
			IPF	Low	1993, 1995	71
			IPF	High	1993, 1995	198
Madison	Organic	1998	None	–	–	0
			Biosolids	2 yr	1994, 1997	331
			Biosolids	5 yr	1994–1998	830
			Manure	5 yr	1994–1998	441
Arlington	Tillage	1999	None	–	–	0
			Manure	1 yr	1999	65

† IPF, inorganic P fertilizer; biosolids source, Madison Metropolitan Sewerage District; manure source, dairy.

and one at Madison, WI, were located on silt loam soils (fine-silty, mixed, mesic Typic Argiudolls). One of the Arlington experiments had not received manure for >40 yr, but included inorganic P fertilizer (IPF) rate treatments (none, low, and high) applied in 1993 and 1995 (inorganic P site). The other experiment at Arlington was a uniformly managed field before establishing tillage and manure treatments in May 1999 (tillage site). The Madison experiment was established in 1994 and consisted of various application histories (treatments) of biosolids and dairy manure applied at rates sufficient to meet the N demand of corn (organic P site). Table 1 summarizes the P source and application history for each site. All sites included four replications of each treatment.

All sites were planted to corn for at least 3 yr before use in these experiments, with grain harvested annually and residues returned to the field. The inorganic P site was in no-till since 1993, except following the 1993 and 1995 IPF applications (none, IPF-low, and IPF-high) when the field was chisel plowed and disked immediately following application to uniformly incorporate the fertilizer. The individual plot size was 18.2 m long by 9.1 m wide.

Treatments at the organic P site included a control (no P addition), biosolids applied at 93 500 L ha^{-1} in 1994 and 1997 (2Y biosolids), biosolids applied at 93 500 L ha^{-1} annually from 1994 through 1998 (5Y biosolids), and dairy manure applied at 89.6 Mg ha^{-1} annually from 1994 through 1998 (5Y manure). Average dry matter contents of biosolids and dairy manure were 60 and 230 g kg^{-1}, respectively. This site was planted to corn annually since 1993 and tillage consisted of fall chisel plowing and field cultivating in spring immediately following treatment application (surface broadcast). Individual plot size was 9.1 m long by 4.6 m wide.

Treatments at the tillage site consisted of three spring tillage systems [chisel plow (CP), shallow till (ST), and no-till (NT)] without and with a spring dairy manure application (1Y manure). Dairy manure was applied at a rate of 72.8 Mg ha^{-1} (170 g kg^{-1} dry matter) before tillage. The site was established in May 1999 in a randomized complete block design using a split-plot arrangement with four replications, with tillage as the main plot treatment and manure as the subplot treatment. Individual plot size was 6.1 m long by 3.0 m wide. The ST treatment was established using a soil finisher (7.6-cm depth), and the CP treatment was established using a chisel plow with 7.6 cm wide twisted shovels (20-cm depth). Secondary tillage was performed in the CP treatment using a soil finisher. Tillage effects on surface residue cover with and without dairy manure additions are shown in Table 2. Simulated rainfall was applied in May 1999 before planting and again in September 1999 following silage harvest (whole plant).

Simulated rainfall was applied using techniques similar to those described by Zemenchik et al. (1996). A portable, multiple intensity rainfall simulator (Meyer and Harmon, 1979) equipped with a Veejet 80150 nozzle (Spraying Systems, Wheaton, IL)[1] located 3 m above the soil surface delivered an application rate of 76 mm h^{-1} with a corresponding energy of 0.278 MJ ha^{-1} mm^{-1}. This rainfall intensity has a recurrence interval of about 50 yr (Huff and Angel, 1992). Steel plot frames (91 cm long by 91 cm wide by 30 cm high) were set in the soil at a 15-cm depth before simulated rain was applied. Runoff was collected at the down-slope side of the plot frame and continuously removed by a 0.02-MPa vacuum (Dixon and Peterson, 1968) and placed in a holding tank.

Runoff was collected for a 60-min period following the onset of simulated rainfall, and the total volume of runoff from each plot was recorded. After mixing to resuspend sediment, subsamples of the runoff were obtained for sediment, dissolved reactive P (DRP), and bioavailable P (BAP) determinations. The subsample for DRP determination was filtered (0.45-μm pore diam.) immediately in the field. Runoff samples for total P (TP) determination were also collected at the tillage site in September. Samples were frozen until the analyses were performed.

Slope, surface residue cover, and antecedent soil moisture (0- to 7-cm depth) were determined for each plot before simulated rainfall application. The slope of each plot was determined using a clinometer placed on the edges of the plot frames. Surface residue cover for each plot was determined inside the plot frame using the pin-drop method (Morrison et al., 1996). Corn plants within each plot frame were cut near the base and removed, and soil samples (0- to 2-cm and 0- to 7-cm depths) were obtained from the outside perimeter of each frame.

Sediment concentration in runoff and antecedent soil moisture content were determined by weighing before and after drying at 105°C. Dissolved reactive P in runoff filtrate samples was determined using the ascorbic acid method (Murphy and Riley, 1962). Bioavailable P in unfiltered runoff samples was determined using the iron-oxide paper strip method (Sharpley, 1993). Total P was determined by ammonium persulfate and sulfuric acid digestion on aliquots of unfiltered runoff suspension (USEPA, 1993). Soil samples (0- to 2-cm and 0- to 15-cm depths) obtained before simulated rainfall application were dried at 32°C, ground to pass a 2-mm sieve, and extracted for P using the Bray-Kurtz P1 method (Frank et al., 1998). All P analyses were performed colorimetrically using the ascorbic acid method (Murphy and Riley, 1962).

An analysis of variance was performed for treatment effects on antecedent soil moisture, surface residue, runoff, and DRP, BAP, and TP concentrations and loads at each site using PROC ANOVA (SAS Inst., 1992). Significant differences among treat-

[1] Mention of company or product name does not constitute endorsement by the Univ. of Wisconsin-Madison to the exclusion of others.

Table 2. Management practice effects on antecedent soil moisture content, surface residue cover, runoff, sediment concentration and load, and bioavailable P (BAP) concentration and load at three sites.

Site	Date of simulated rainfall	Tillage†	P source and history	Soil moisture	Surface residue	Runoff	Sediment conc.	Sediment load	BAP conc.	BAP load
				g kg^{-1}	%	mm	g L^{-1}	kg ha^{-1}	mg L^{-1}	g ha^{-1}
Inorganic	July 1998	NT	None	171b‡	44	33	11.1	3933	0.10b	35b
			IPF-low	164b	63	25	9.8	2248	0.30a	75a
			IPF-high	206a	63	29	6.1	1864	0.25a	73a
			P > F	*0.03*	*0.12*	*0.29*	*0.79*	*0.63*	*<0.01*	*0.01*
			LSD(0.05)	*24*	*31*	*13*	*18.1*	*5341*	*0.05*	*25*
			CV, %	*3*	*14*	*11*	*116*	*115*	*14*	*24*
Organic	Oct. 1998	CP	None	167b	28c	56a	6.4a	3576a	0.06c	35b
			2Y biosolids	212ab	40b	55ab	4.2b	2266b	0.15c	81b
			5Y biosolids	166b	44b	48b	4.1b	1957b	0.38b	182a
			5Y manure	259a	83a	11c	2.8b	450c	0.74a	74b
			P > F	*0.02*	*<0.01*	*<0.01*	*0.01*	*<0.01*	*<0.01*	*<0.01*
			LSD(0.05)	*59*	*11*	*0.7*	*1.9*	*612*	*0.20*	*63*
			CV, %	*18*	*14*	*11*	*27*	*19*	*38*	*43*
Tillage	May 1999	CP	None	269	26d	4b	4.3a	156b	0.11b	6
		ST	None	208	49c	2b	3.2ab	81b	0.09b	2
		NT	None	204	79b	11a	3.4ab	438a	0.05b	6
		CP	1Y manure	216	50c	1b	1.6bc	24b	0.10b	1
		ST	1Y manure	221	58c	2b	1.8bc	31b	0.14b	3
		NT	1Y manure	247	99a	1b	0.6c	8b	1.41a	11
			P > F	*0.61*	*<0.01*	*<0.01*	*0.03*	*0.01*	*<0.01*	*0.43*
			LSD(0.05)	*88*	*20*	*4*	*2.3*	*240*	*0.48*	*11*
			CV, %	*27*	*22*	*73*	*61*	*130*	*101*	*156*
	Sept. 1999	CP	None	156b	16d	29a	7.3ab	2223a	0.20ab	57a
		ST	None	146b	20cd	22ab	7.8a	1740ab	0.23ab	52a
		NT	None	166b	47b	17bc	4.3bc	855bc	0.10b	19b
		CP	1Y manure	156b	23cd	14bc	7.4ab	1065bc	0.31a	37ab
		ST	1Y manure	163b	27c	12cd	4.9abc	607c	0.27a	32ab
		NT	1Y manure	198a	74a	5d	2.6c	125c	0.30a	14b
			P > F	*<0.01*	*<0.01*	*<0.01*	*0.03*	*<0.01*	*0.06*	*0.02*
			LSD(0.05)	*25*	*8*	*9*	*3.3*	*1005*	*0.14*	*27*
			CV, %	*10*	*15*	*36*	*39*	*61*	*41*	*52*

† NT = no-till; CP = chisel plow; ST = shallow till; IPF = inorganic P fertilizer.
‡ Where $P > F$ is ≤ 0.05, mean values for each site and date followed by the same letter are not significantly different at the 0.05 probability level.

ment means were evaluated using a protected least significant difference (LSD) test at the 0.05 probability level.

RESULTS AND DISCUSSION

Soil Moisture, Surface Residue, and Runoff

Management practice effects on antecedent soil moisture content, surface residue, and runoff are shown in Table 2. At the inorganic P site, P rate history effects on surface residue and runoff were not significant, although surface residue was slightly greater and runoff slightly less in the IPF-low and IPF-high treatments relative to the control. The higher surface residue in the IPF-treated plots likely resulted from greater annual dry matter production in these treatments at the higher available soil P levels. Antecedent soil moisture differences between the IPF-high treatment and the IPF-low and control treatments were not due to surface residue differences and apparently resulted from spatial variation at the site.

At the organic P site, soil moisture content tended to increase as surface residue cover increased (Table 2). Surface residue cover was significantly higher in the 2Y and 5Y biosolids treatments compared with the control treatment, but significantly lower than the 5Y manure treatment. The higher surface residue cover in the 5Y manure treatment was due to accumulation of undecomposed bedding straw from the manure. Cumulative organic matter additions in biosolids and manure from 1994 through 1998 were 12, 30, and 103 Mg ha^{-1} for the 2Y biosolids, 5Y biosolids, and 5Y manure treatments, respectively, and were inversely related to runoff (55, 48, and 11 mm, respectively). Runoff in the control (56 mm) was similar to the 2Y biosolids treatment.

At the tillage site, tillage and manure treatments significantly affected surface residue cover and runoff for the May and September simulated rainfall application dates. Treatment differences in antecedent soil moisture content were not apparent in May, but moisture was significantly higher in the NT–1Y manure treatment in September. Surface residue cover ranged from 26 to 99% in May and from 16 to 74% in September. Residue cover was higher in the 1Y manure treatments and decreased with more aggressive tillage (CP < ST < NT). In May, highest runoff occurred in the NT–none (no manure) treatment (11 mm) and was significantly greater than the remaining treatments (1–4 mm). In September, runoff amounts were 2 to 14 times greater than in May. The higher runoff was not due to antecedent soil moisture differences since initial moisture contents were actually lower in September. Differences were likely due to less residue and greater surface sealing of the soil in September, especially in the spring tilled treatments (CP and ST). Less soil surface sealing in NT was also observed in May compared with September and was likely due to over-winter freezing–thawing effects on surface soil porosity. Mueller et al. (1984) also reported increased runoff as the growing season progressed. It is interesting to note that where no manure was applied, runoff was significantly greater in NT than CP in May, but significantly lower in September. Runoff in September decreased as residue cover increased due to tillage and manure treatments. Although residue cover was lower in the CP– and ST–manure treatments compared with the NT–none treatment, runoff amounts were not significantly different, suggesting that manure additions containing high amounts of organic matter may have as much, or more influence, on increased water infiltration rates than crop surface residue. Previous studies also found that the addition of manure reduced runoff using both natural and simulated rainfall methods (Hensler et al., 1970; Converse et al., 1976; Mueller et al., 1984).

Sediment Losses in Runoff

Management practice effects on sediment concentration and load in runoff are shown in Table 2. At the inorganic P site, sediment losses ranged from 1864 to 3933 kg ha^{-1}, but the effect of P rate history on sediment concentration and load in runoff was not significant, although average concentrations and loads were lower in the IPF–low and –high treatments compared with the control treatment. This is consistent with the trend toward higher residue cover in the IPF–low and IPF–high treatments.

Sediment concentration and load in runoff were significantly lower in the biosolids and manure treatments compared with the control treatment at the organic P site. Sediment load was lowest in the 5Y manure treatment (450 kg ha^{-1}) due to lower runoff amount and sediment concentration. The lower sediment load in the biosolids treatments (avg. 2112 kg ha^{-1}) compared with the control (3576 kg ha^{-1}) was primarily due to lower sediment concentrations in runoff as a result of greater surface residue.

Treatment effects on sediment concentration and load in runoff were significant at the tillage site at both dates, but concentration and load were much greater in September than May. Loads tended to be lower where manure was applied. In May, sediment loads in runoff were generally low (8–438 kg ha^{-1}) and were highest in the NT–none treatment. In September, sediment loads were nine times greater than in May and ranged from 125 to 2223 kg ha^{-1}. Loads decreased as surface residue increased and were generally lower in the manure treatments. Average sediment losses in runoff in September were 1644, 1403, and 490 kg ha^{-1} for the CP, ST, and NT tillage treatments, respectively, and 1606 and 599 kg ha^{-1} for the control and manure treatments, respectively. Mueller et al. (1984) also found that the addition of manure in CP and NT corn systems tended to reduce sediment concentrations and loads in runoff.

Phosphorus Losses in Runoff

Management practice effects on DRP concentration and load in runoff for the inorganic P, organic P, tillage (May), and tillage (September) sites are shown in Fig. 1, 2, 3, and 4, respectively. Also shown are the soil test P (STP) values (0- to 2-cm depth) for each treatment. At

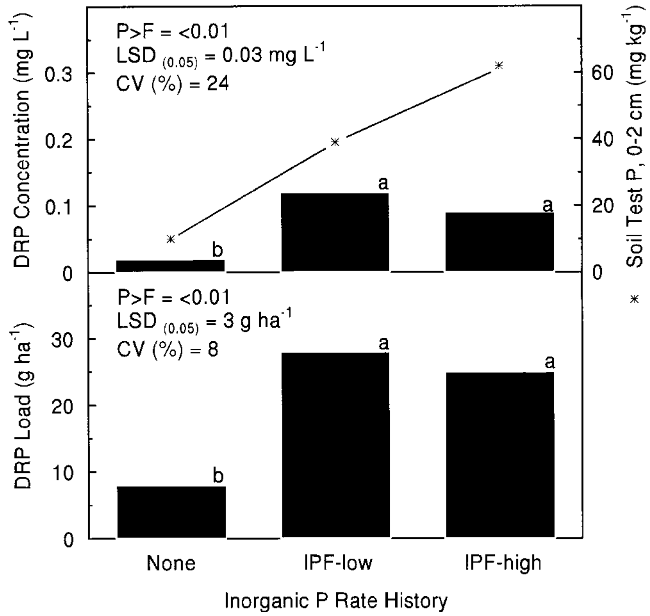

Fig. 1. Effect of inorganic P fertilizer (IPF) rate on dissolved reactive P (DRP) concentration and load in runoff (histograms) and soil test P values (0- to 2-cm depth), July 1998. Where $P > F$ is ≤0.05, mean values followed by the same letter are not significantly different at the 0.05 probability level.

the inorganic P site, STP values ranged from 10 to 62 mg kg^{-1} and increased as IPF rate increased; however, DRP concentrations were similar in the IPF–low and IPF–high treatments (Fig. 1). The P values in soil and runoff in the IPF–low and IPF–high treatments are likely representative of a grain-farming system where P inputs are largely or entirely from inorganic fertilizers. Agronomic soil test levels (15-cm depth) in these treatments were at the low end of the excessively high category for corn (33 and 51 mg Bray P1 kg^{-1}, respectively).

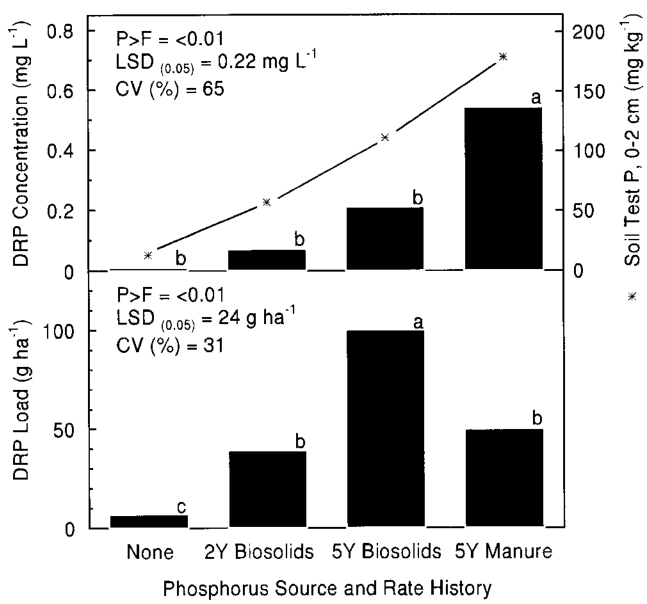

Fig. 2. Effect of biosolids and dairy manure histories on dissolved reactive P (DRP) concentration and load in runoff (histograms) and soil test P (line) values (0- to 2-cm depth), October 1998. Where $P > F$ is ≤0.05, mean values followed by the same letter are not significantly different at the 0.05 probability level.

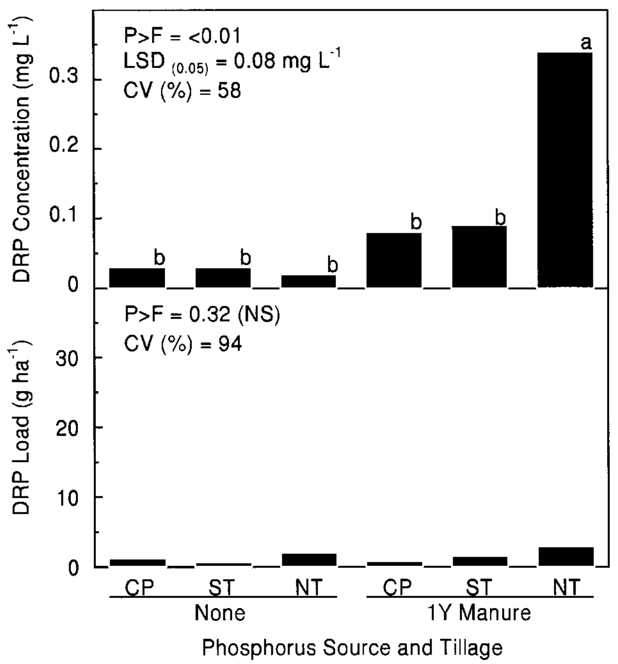

Fig. 3. Effect of spring-applied dairy manure and tillage on dissolved reactive P (DRP) concentration and load in runoff, May 1999. Initial soil test P value was 13 mg kg^{-1} (0- to 2-cm depth). CP = chisel plow; ST = shallow till; NT = no till. Where $P > F$ is ≤0.05, mean values followed by the same letter are not significantly different at the 0.05 probability level; NS, not significant.

At the organic P site, DRP concentrations in runoff ranged from 0.01 to 0.54 mg L^{-1}, with highest concentrations in the 5Y manure treatment (Fig. 2). Concentrations increased as the biosolids rate increased (0.07 mg L^{-1} in 2Y and 0.21 mg L^{-1} in 5Y). Soil test P values ranged from 13 to 179 mg kg^{-1} and were strongly correlated with DRP concentrations in runoff. It is interesting to note that both STP values and DRP concentrations were lower in 5Y biosolids than in 5Y manure, although the total P application rate was nearly two times greater with biosolids (Table 1). Total DRP load in runoff was highest in 5Y biosolids (100 g ha^{-1}), similar in 2Y biosolids (39 g ha^{-1}) and 5Y manure (50 g ha^{-1}), and lowest in the control (7 g ha^{-1}). The lower DRP load in 5Y manure was due to the low runoff amount in this treatment (Table 2). As previously mentioned, the higher cumulative amount of organic matter applied in the 5Y manure treatment apparently increased infiltration and reduced runoff, thus offsetting the high DRP concentration and reducing the DRP load.

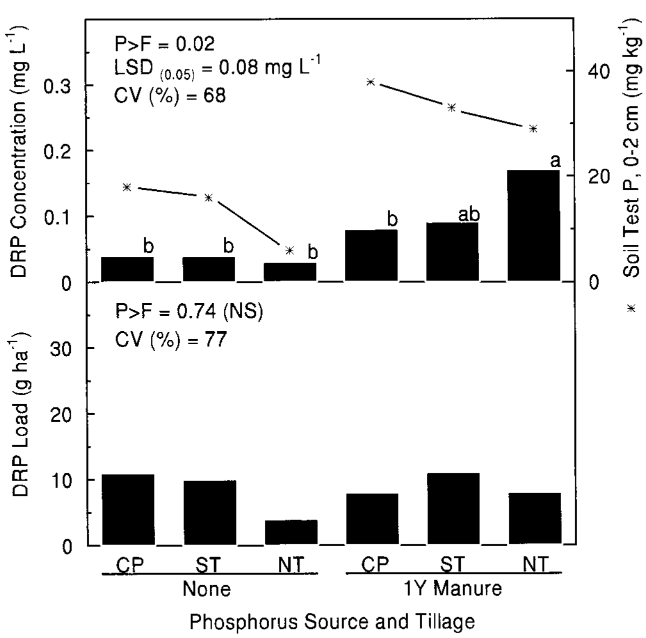

Fig. 4. Effect of spring-applied dairy manure and tillage on dissolved reactive P (DRP) concentration and load in runoff (histograms) and soil test P (line) values (0- to 2-cm depth), September 1999. CP = chisel plow; ST = shallow till; NT = no till. Where $P > F$ is ≤0.05, mean values followed by the same letter are not significantly different at the 0.05 probability level; NS, not significant.

At the tillage site, highest DRP concentrations in runoff occurred in the NT-1Y manure treatment in May (Fig. 3) and September (Fig. 4). Dissolved reactive P concentrations where manure was applied were nearly four times greater in NT compared with CP and ST in May, and about two times greater in September. Where no manure was applied, tillage did not significantly affect DRP concentration in runoff in May or September. A trend toward higher DRP concentrations in runoff occurred where manure was applied regardless of tillage system, but manure additions did not significantly affect DRP load. Similar to the organic site, these results suggest that the addition of manure will likely increase DRP concentrations in runoff but may result in similar or reduced DRP loads. Wendt and Corey (1980) also found that surface-applied manure on corn and alfalfa (*Medicago sativa* L.) increased P concentration in runoff, but did not increase P losses due to increased infiltration where manure was applied. The initial STP value for the tillage site was 13 mg kg^{-1} (0–2 cm) in May before manure application and ranged from 6 to 38 mg kg^{-1} in September. Soil test P values in September were lowest in the NT system, although DRP concentrations in runoff were either similar or higher than in the tilled systems. These results illustrate the important effect of manure management practices on P losses at various STP values and support findings by Sauer et al. (2000), showing that manure additions masked the effects of STP on P concentrations in runoff.

Management practice effects on BAP concentration and load in runoff are shown in Table 2. At the inorganic P site, BAP concentrations and loads were significantly greater in the IPF–low and IPF–high treatments compared with the control and ranged from 0.10 to 0.30 mg L^{-1}.

At the organic P site, BAP concentrations in runoff ranged from 0.06 to 0.74 mg L^{-1} and were lowest in the control and 2Y biosolids, intermediate in 5Y biosolids, and highest in 5Y manure. However, BAP loads were highest in 5Y biosolids, intermediate in 2Y biosolids and 5Y manure, and lowest in the control. The lower BAP load in 5Y manure compared with 5Y biosolids was the result of lower runoff and sediment concentration.

Highest BAP concentrations in runoff in May at the tillage site were in the NT-1Y manure treatment (1.41 mg L^{-1}). Only in the NT system did the addition of manure significantly increase BAP concentration. Where no manure was applied, BAP concentrations were lowest where surface residue cover was highest (NT). Where manure was applied, BAP concentrations were 10 to 14 times higher in NT compared with CP and ST, resulting in greater BAP loads. In September, BAP concentrations were higher than in May with the exception of NT-1Y manure, which decreased to 0.30 mg L^{-1}. Loads were as much as 30 times greater in September compared with May and were lowest in NT relative to CP and ST regardless of manure treatment.

In general, the ratio of BAP to DRP concentrations in runoff decreased as surface residue cover increased, likely due to reduced sediment in runoff with increasing surface residue levels. The exception to this trend is the NT–1Y manure treatment in May.

Tillage and manure treatment effects on total P (TP) concentration and load in runoff in September were highly significant (Fig. 5). Total P concentration in runoff generally decreased as surface residue increased (see Table 2). The lowest TP concentration occurred in the NT–1Y manure treatment likely due to low sediment concentrations in this treatment (Table 2). Total P load in runoff ranged from 32 to 481 g ha^{-1} and was lowest in the NT–1Y manure treatment. Average TP losses in runoff were 313, 318, and 179 g ha^{-1} for the CP, ST, and NT tillage treatments, respectively, and 407 and 132 g ha^{-1} for the control and manure treatments, respectively. Where no manure was applied, a significant correlation between TP concentration in runoff and concentrations of BAP ($r = 0.68$ $P = 0.01$) and sediment ($r = 0.89$ $P < 0.01$) occurred. Where manure was applied, only sediment concentration was significantly correlated with TP concentration in runoff ($r = 0.77$ $P <$ 0.01). The correlations of TP and DRP concentrations in runoff were not significant ($r = 0.12$ and $r = -0.25$ for control and manure treatments, respectively).

Recommendations emerging from previous studies of management practice effects on P losses in runoff have emphasized control of soluble or DRP losses (Madison et al., 1995). Data in Fig. 4 and 5 show that TP loads from corn production systems can be 3 to 40 times higher than DRP loads from the same treatments. Management practices such as no-tillage and unincorporated manure applications tend to reduce TP loads by controlling sediment loss, while tillage to incorporate manure tends to lower DRP losses but may increase TP loads. The fact that commonly used management practices may have opposite effects on TP vs. DRP losses indicates a need to identify the forms of P in runoff from agricultural systems that will have the greatest negative environmental impacts and to design management recommendations to minimize these losses.

CONCLUSIONS

Results from this study indicate that P applications as inorganic fertilizer, manure, or biosolids increase P concentrations and loads in runoff, particularly if P additions exceed crop P demand. Phosphorus loads in runoff are affected by P source, especially sources with high organic matter contents that promote infiltration and reduce runoff. For example, DRP concentrations in runoff were higher if surface-applied manure was not incorporated, but DRP loads in runoff were not consistently higher due to greater residue cover and reduced runoff where manure was surface-applied. No-tillage and unincorporated manure applications tended to reduce TP loads in runoff by increasing infiltration and lowering sediment loss. Thus, management practices designed to control DRP losses in runoff may promote TP losses in corn production systems. Runoff amounts were much lower in spring than fall possibly due to over-winter changes in soil surface physical properties. The short-term effect of tillage may be to reduce spring DRP losses due to lower runoff compared with no-tillage, but DRP losses later in the growing season may be increased by tillage as soil surface sealing increases due to reduced surface residue cover. This study shows that the relationship between STP and P loss in runoff can be masked if manure is applied and indicates that management practices can play a larger role than STP alone in determining P loss. Results from this work showing that some practices may have opposite effects on DRP vs. TP losses, emphasize the need to design management recommendations to minimize losses of those P forms with the greatest pollution potential.

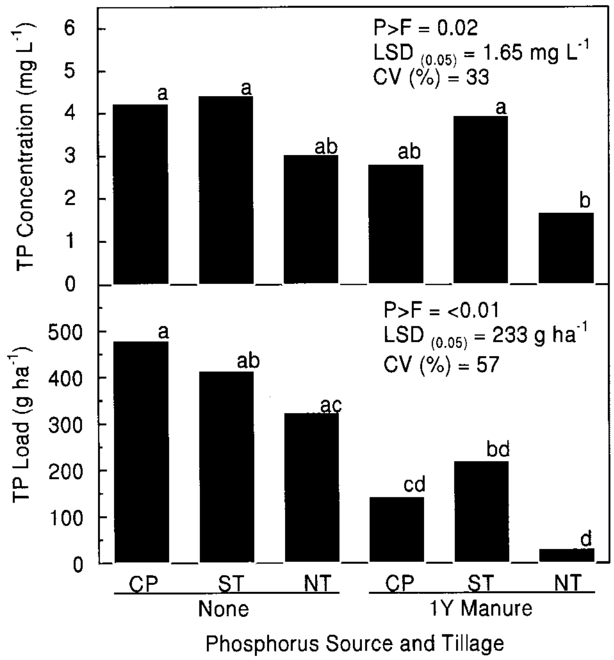

Fig. 5. Effect of spring-applied dairy manure and tillage on total P (TP) concentration and load in runoff, September 1999. CP = chisel plow; ST = shallow till; NT = no till. Where $P > F$ is ≤0.05, mean values followed by the same letter are not significantly different at the 0.05 probability level.

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