Waste Management

Rate of Fall-Applied Liquid Swine Manure: Effects on Runoff Transport of Sediment and Phosphorus

P. D. Gessel, N. C. Hansen,* J. F. Moncrief, and M. A. Schmitt

ABSTRACT

Reducing the delivery of phosphorus (P) from land-applied manure to surface water is a priority in many watersheds. Manure application rate can be controlled to manage the risk of water quality degradation. The objective of this study was to evaluate how application rate of liquid swine manure affects the transport of sediment and P in runoff. Liquid swine manure was land-applied and incorporated annually in the fall to runoff plots near Morris, Minnesota. Manure application rates were 0, 0.5, 1, and 2 times the rate recommended to supply P for a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation. Runoff volume, sediment, and P transport from snowmelt and rainfall were monitored for 3 yr. When manure was applied at the highest rate, runoff volume and sediment loss were less than the control plots without manure. Reductions in runoff volume and soil loss were not observed for spring runoff when frozen soil conditions controlled infiltration rates. The reduced runoff and sediment loss from manure amended soils compensated for addition of P, resulting in similar runoff losses of total P among manure application rates. However, losses of dissolved P increased with increasing manure application rate for runoff during the spring thaw period. Evaluation of water quality risks from fall-applied manure should contrast the potential P losses in snowmelt runoff with the potential that incorporated manure may reduce runoff and soil loss during the summer.

Reducing the delivery of P from agricultural sources to surface and ground water is the focus of water quality efforts in many watersheds (Sharpley et al., 1994; Carpenter et al., 1998). Water quality problems associated with excess P relate to accelerated eutrophication of inland, estuarine, and coastal waters and include low oxygen levels, reduced aquatic species diversity, turbidity, and undesirable taste and odor in municipal water supplies (Carpenter et al., 1998; National Research Council, 2000; Sharpley et al., 1994; Smith, 1998). In watersheds where livestock production is important, managing land-applied manure is often an important water quality consideration. The risk of P from land-applied manure moving to sensitive waters depends on the interaction of site properties, climatic conditions, and management practices. It is important to understand how management practices such as manure application rate, timing, and method affect water quality.

The effects of land-applied manure on the quality of runoff water have been studied extensively. Surface application of manure without incorporation results in an increased risk of P loss in runoff (Pote et al., 2001; Edwards and Daniel, 1994). Repeated manure applications can also result in the elevation of extractable soil P concentration, resulting in an elevated risk of P loss in runoff (Sharpley et al., 1994; Hansen et al., 2002). To minimize the risk of contaminant losses in runoff, it is recommended that manure be incorporated or injected into the soil at rates that do not result in accumulation of soil P levels (Hansen et al., 2002).

Proper management of land-applied manure can also result in water quality improvements. Incorporated manure improves infiltration and reduces runoff compared with soils without manure (Ginting et al., 1998; Mueller et al., 1984; Gilley and Risse, 2000). Increased infiltration in manured soils resulted in lower total P losses in runoff despite an increase in the P level in the soil after manure was applied. However, studies that have documented improved infiltration and lower runoff after manure application have evaluated land application of solid manure at relatively high application rates. It is not known whether improvements in infiltration, with ensuing reductions in nutrient loading, result when liquid swine manure is applied at lower, P-based application rates. The objective of this study was to evaluate how the application and incorporation of liquid swine manure at varying rates affects runoff volume and the transport of sediment and P in runoff.

MATERIALS AND METHODS

The study was located at the University of Minnesota West Central Research and Outreach Center in Morris, Minnesota on a Forman (fine-loamy, mixed Udic Argiboroll)–Buse (fine-loamy, mixed Udorthentic Haploboroll) complex with a southeastern aspect and 12% slope. Daily weather observations were made at a permanent weather station located 1.3 km from the site and included precipitation, air temperature, soil temperature, and the depth of soil frost.

Twelve runoff plots (22 × 3 m) arranged in a randomized complete block design were established to accommodate three replications of four manure application rates. The plots were bordered with 0.25-m-wide corrugated sheet metal placed vertically into the soil to isolate surface runoff within the defined plot area. On the downslope side of each plot a metal collection flume channeled runoff through a 10-cm-diameter polyvinyl

P.D. Gessel, Utah Department of Environmental Quality, Division of Water Quality, P.O. Box 144870, Salt Lake City, UT 84114-4870. N.C. Hansen, University of Minnesota, WCROC, 46352 State Highway 329, Morris, MN 56267. J.F. Moncrief and M.A. Schmitt, University of Minnesota, Department of Soil, Water, and Climate, 1991 Upper Buford Circle, St. Paul, MN 55108. Received 22 May 2003. *Corresponding author (hansennc@mrs.umn.edu).

Published in J. Environ. Qual. 33:1839–1844 (2004).

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: DP, dissolved molybdate-reactive phosphorus; TP, total phosphorus; TS, total solids.

chloride (PVC) pipe to a tipping bucket flow meter. Each time the bucket tipped, a 1.9-cm-diameter PVC pipe collected a portion of the water from the bucket and this was collected in a 5-L polyethylene sample container, creating a composite sample for chemical analysis. The tipping buckets were monitored continuously with a data logger (CR-10X; Campbell Scientific, Logan, UT) and a calibration equation was used to convert tipping rate to runoff volume.

The plots were cropped to corn in 1999 and 2001 and soybean in 2000. Row spacing was 76 cm for both corn and soybean. Cultural and pest management practices were in accordance with University of Minnesota recommendations. Before planting in the spring, secondary tillage was performed with a single pass with a field cultivator. Liquid swine manure was obtained from an anaerobic storage pit located under a farrowing barn. The annual manure applications were broadcast-applied on 5 Nov. 1998, 28 Oct. 1999, and 30 Oct. 2000 and immediately incorporated to 15 cm with a chisel plow traveling up and down the slope. Experimental treatments were:

- Control: tillage with no manure applied.
- 0.5X: liquid swine manure applied at half the agronomic rate.
- 1X: liquid swine manure applied equal to the agronomic rate.
- 2X: liquid swine manure applied at twice the agronomic rate.

The agronomic application rate (1X) was based on initial soil test results (Table 1), University of Minnesota P fertilizer recommendations (Rehm et al., 1995), and the total P content of the manure. The volume of manure and the mass of P applied for the agronomic (1X) rate were 37 m^3 ha^{-1} yr^{-1} and 28 kg ha^{-1} yr^{-1}, respectively. The average solids content of the manure was 1.6%. No supplemental P fertilizer was added for the control and 0.5X treatments. In each plot, a composite soil sample was taken at 0- to 7.5- and 7.5- to 15-cm depths before manure application in 1998 to determine initial conditions and in June 1999 and June 2001 to characterize the effect of manure application rate on soil P status. Samples were oven-dried, ground, and analyzed to measure the concentration of extractable P and organic matter. Extractable soil P was determined using the Olsen method (Frank et al., 1998). Soil organic matter content was measured by loss on ignition

Table 1. Effect of manure application rate on Olsen P and soil organic matter content at depths of 0 to 6 and 6 to 12 cm after one annual manure application (1999) or three annual manure applications (2001), along with soil test P and organic matter content before any manure application (1998).†

Treatment	Olsen P			Organic matter		
	1998	1999	2001	1998	1999	2001
	mg kg^{-1}			g kg^{-1}		
			0–6 cm			
Control	6.0	7.7a	5.0a	44	43a	36a
0.5X	9.3	12bc	11b	44	46a	39a
1X	8.0	11b	16bc	47	44a	41a
2X	9.3	15c	19c	44	46a	43a
$p > F$	–	0.02	0.01	–	0.80	0.14
			6–12 cm			
Control	4.3	4.7a	3.3a	36	37a	35a
0.5X	4.7	6.7a	7.3b	36	39a	35a
1X	4.3	5.7a	7.7b	40	39a	36a
2X	5.3	8.0a	9.0b	36	39a	39a
$p > F$	–	0.36	0.02	–	0.94	0.25

† Manure was applied annually in the fall at rates that varied based on the P recommendation from an initial soil test (1X) for a corn–soybean rotation.

(Combs and Nathan, 1998). The line transect method (Laflen et al., 1981) was used to determine percent residue cover using three 4.0-m-long transects per plot after planting each year. Crop biomass and grain yield were determined each fall by harvesting aboveground biomass from two 3.0-m-long rows within each replication and separately weighting grain and nongrain tissue and correcting for moisture content.

Runoff samples were collected within 6 h following each runoff event and were stored at 4°C. Samples were analyzed for concentration of total solids (TS), total phosphorus (TP), and dissolved molybdate-reactive phosphorus (DP).

Total solids concentration was measured by evaporating 200 mL of the runoff sample at 105°C and weighing the remaining solids. Total P concentration was measured using a perchloric acid digestion (Plumb, 1981, p. 3-73 to 3-76). The DP concentration was measured by first filtering the sample through a 0.45-μm pore membrane and then using the ascorbic acid method (Murphy and Riley, 1962). Contaminant loading was calculated for TS, TP, and DP by multiplying the contaminant concentration by the runoff volume.

Analysis of variance was performed using Statistical Analysis System software (SAS Institute, 1999) for soil analysis, runoff and contaminant losses from individual runoff events, and for the annual or seasonal sums of multiple events. Seasonal sums evaluated were spring, consisting of runoff occurring in March and April, and summer, consisting of runoff in June, July, and August. Data for runoff volume, total solids loss, and P losses were transformed to logarithmic (base 10) values to control nonhomogeneous variances. The means reported are geometric means. When treatment effects were significant, the least significant difference test was used to separate means ($\alpha = 0.10$).

RESULTS AND DISCUSSION

Soil Analysis and Crop Residue Cover

Olsen soil P concentration measured in the fall of 1998 before the initial manure application averaged 8 mg kg^{-1} for the 0- to 7.5-cm depth and 4.5 mg kg^{-1} for the 7.5- to 15-cm depth. After the first manure application, Olsen P concentrations measured in June 1999 were higher than the initial levels and differed with manure application rates at the 0- to 6-cm depth (Table 1). Concentrations were highest for the 2X manure application rate. Olsen P concentration did not differ among manure application rates at the 7.5- to 15-cm depth. For soil samples taken in June 2001 after the third manure application, Olsen P concentrations were different among manure application rates for both the 0- to 7.5- and 7.5- to 15-cm sampling depths. In both cases, increasing manure application rates corresponded to higher concentrations of extractable P while the control plots had the lowest concentrations. Differences in extractable P concentration among manure rate treatments were most pronounced near the soil surface. Elevated extractable soil P concentrations usually correspond to higher concentrations of DP in runoff (Hansen et al., 2002). There were no measurable effects of manure application rate on soil organic matter content (Table 1).

Crop residue cover measured after planting averaged 20, 46, and 28% for 1999, 2000, and 2001, respectively. Residue cover was higher in the year following corn harvest (2000) than in years following soybean harvest

Table 2. The effect of manure application rate treatments on crop biomass and grain yield during a 3-yr study.†

	Biomass		Grain yield	
Treatment	Corn	Soybean	Corn	Soybean
	Mg ha^{-1}			
Control	13a	7.4a	6.1a	2.1a
0.5X	17b	7.6a	6.9a	2.2a
1X	17b	6.7a	7.1a	2.4b
2X	18b	5.9a	6.8a	2.5b
$p > F$	0.001	0.10	0.18	0.03

† Corn biomass and grain yield are averaged over two years (1999, 2001) while soybean biomass production and grain yield are from a single year (2000).

(1999 and 2001). Residue cover was not different among manure application rate treatments ($p = 0.51$).

Crop Biomass and Grain Yield

Crop growth as represented by total aboveground biomass and by grain yield was affected by manure application rate (Table 2). Average corn biomass production was greater for all manure application rates than for the control treatment, but there was no significant difference in average corn grain yield. Soybean biomass production was not different among treatments, but grain yield did differ. Soybean grain yield was greater for the 1X and 2X manure rates than for the control and 0.5X treatments.

Precipitation

Annual precipitation varied among the three study years (Fig. 1). In 1999, winter and spring precipitation were close to the long-term average for this location. A wetter than normal summer was followed by a very dry fall and the cumulative annual precipitation was 625 mm. Six runoff events occurred in 1999, one from snowmelt in early spring and five from rainfall in the summer.

Precipitation in 2000 closely followed the normal seasonal distribution and totaled 652 mm. Runoff patterns were similar to the previous year with one event from spring snowmelt and four from summer rainfall. In 2001, precipitation was greater than normal and totaled 792 mm. The largest deviation from the normal precipitation pattern was a 63-mm rainfall occurring on 7 Apr. 2001. This rainfall resulted in the largest single runoff occurrence during the study. At the time of the rain, there was some snow remaining on the plots adding to the water available for runoff and there was frost from 5 to 20 cm below the soil surface that limited infiltration rates. In addition to this event, there was a small snowmelt event on 5 Apr. 2001 and three summer runoff events in 2001.

Runoff

In each year, runoff occurred during the spring thaw period under conditions of soil frost and melting snow or in the summer from rainfall (Fig. 1 and Table 3). Of the four runoff events that occurred during the spring thaw, three resulted from melting snow alone, while the 7 Apr. 2001 runoff resulted from the combination of

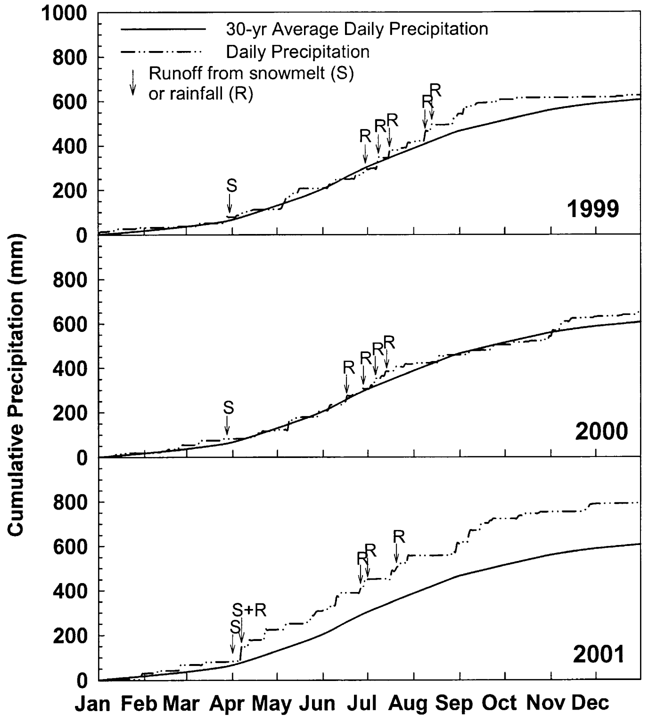

Fig. 1. Cumulative daily precipitation for each year of the study period (1999–2001) compared with the 30-yr average daily cumulative precipitation for Morris, Minnesota. Arrows mark the occurrence of runoff from snowmelt (S) or rainfall (R).

melting snow and rain. The summer runoff events occurred between June and August, a period of high precipitation and potential erosion for row crop production systems in the Upper Midwest. During this time, the undeveloped crop canopy leaves the soil exposed to the erosive effects of rain. During the 3-yr study period, there was no measurable runoff in the fall or winter.

The effect of manure application rate on runoff volume was evaluated for individual runoff events, seasonal totals, and annual totals. There was a significant effect

Table 3. The effect of manure application rate treatments on runoff from individual runoff events during a 3-yr study.†

	Runoff				
	Manure application rate				
Date	0X	0.5X	1X	2X	$p > F$
	mm				
24 Mar. 1999	1.3	0.72	0.33	0.41	0.50
30 June 1999	1.7	1.6	1.2	0.86	0.35
8 July 1999	12	12	11	8.8	0.49
16 July 1999	1.3	0.91	0.76	0.30	0.10
9 Aug. 1999	1.0	0.63	0.84	0.71	0.82
13 Aug. 1999	0.83	0.48	0.64	0.42	0.75
29 Mar. 2000	1.1	0.7	0.81	0.80	0.60
15 June 2000	3.1	1.4	0.83	0.45	0.01
26 June 2000	0.21	0.07	0.11	0.08	0.001
5 July 2000	9.6	6.2	6.3	4.0	0.13
12 July 2000	3.7	2.6	2.5	2.0	0.30
5 Apr. 2001	4.4	4.3	12	5.7	0.49
7 Apr. 2001	16	11	17	9.0	0.88
27 June 2001	4.1	3.1	4.6	2.6	0.01
30 June 2001	5.9	4.1	5.5	3.3	0.01
17 July 2001	5.5	4.3	7.6	2.6	0.64

† Manure was applied annually in the fall at rates that varied based on the P recommendation from an initial soil test (1X) for a corn–soybean rotation.

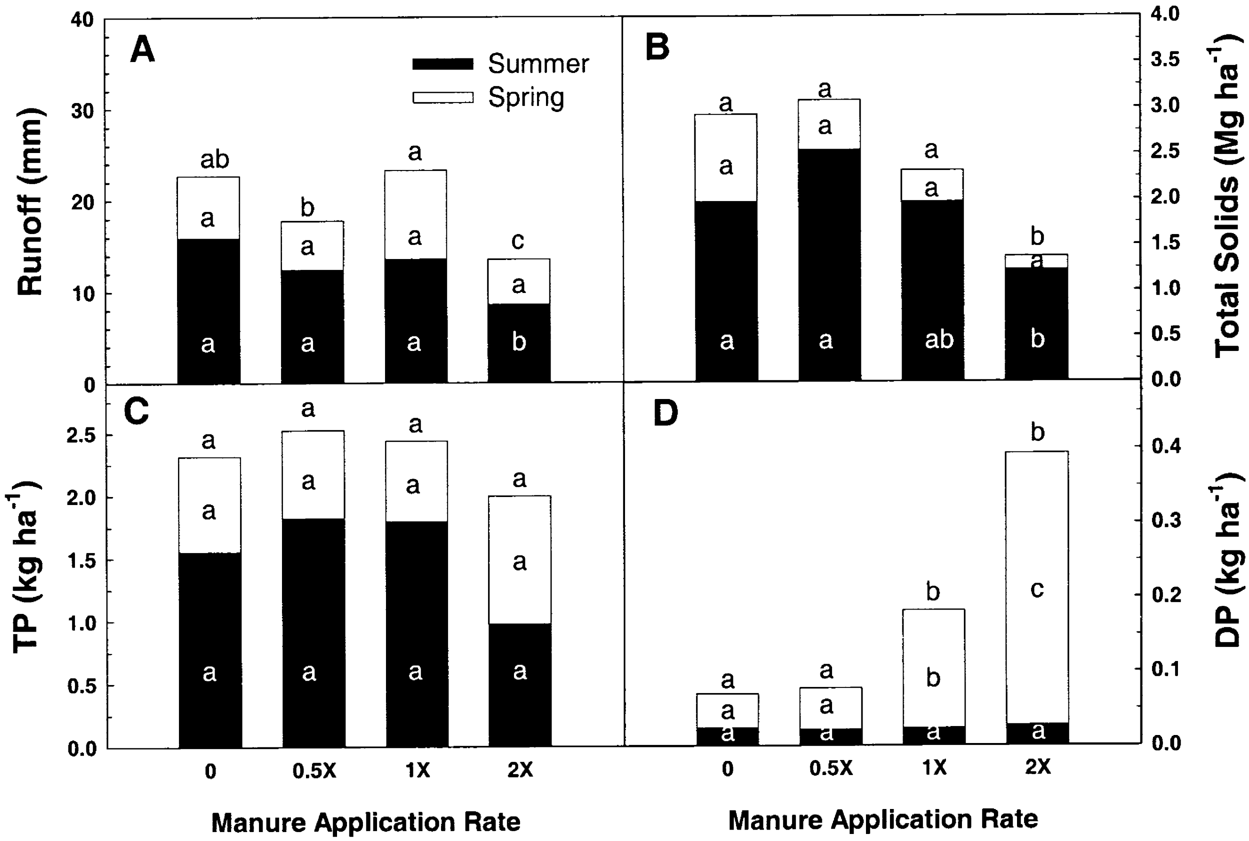

Fig. 2. The effect of manure application rate on average annual (A) runoff, (B) total solids (TS) loss, (C) total phosphorus (TP) loss, and (D) dissolved molybdate-reactive phosphorus (DP) loss from 1999–2001. Bars are split to indicate the contribution of spring and summer seasons to the annual totals. Bars with the same letters are not significantly different ($P < 0.10$) when comparing across manure application rates for spring, summer, and annual segments of each bar. Manure was applied annually in the fall based on the P recommendation from an initial soil test (1X) for a corn–soybean rotation.

of manure application rate on runoff volume for 5 of 16 runoff events, all of which occurred during the summer months (Table 3). For each of the five events with significant treatment effects, runoff was less for the 2X manure rate than for the other rate treatments.

The sum of runoff for the summer period (Fig. 2) was affected by manure application rate ($p = 0.01$) and by year ($p = 0.07$), and there was no interaction of year and application rate ($p = 0.66$). Summer runoff was less for the 2X manure application rate than for the 0X, 0.5X, and 1X treatments. The sum of runoff for the spring period varied among years ($p < 0.001$) but was not affected by manure application rate ($p = 0.36$).

Annual runoff volume varied among manure application rates ($p = 0.01$). Runoff volume was less for the 2X manure rate than for the 0X, 0.5X, and 1X manure application rates (Fig. 2A). The reduction in annual runoff volume was controlled by the effect of manure applied at the 2X rate on runoff during the summer period. Other research has shown that incorporated manure reduces storm runoff (Gilley and Risse, 2000; Ginting et al., 1998; Mueller et al., 1984). These studies evaluated the effects of applying solid manures that often include livestock bedding materials such as straw and they do not determine if changes in runoff are due to an increase in surface residue cover or to changes in soil physical properties. The reduction in runoff observed in the current study occurred following application of liquid swine manure, a practice that did not add to surface residue cover. The observed differences in summer runoff may be due to differences in crop canopy cover among manure rate treatments or may be the result of changes in soil properties as a result of the applied liquid manure. Although we measured differences in total biomass production for the corn crop at then end of the growing seasons (Table 2), we do not suspect that canopy differences due to the manure rate treatments were responsible for the observed differences in runoff. Most of the runoff occurred in June and July, a time when canopy was small for all treatments. During this time, we observed little difference in canopy cover. Further, we measured no differences in soybean biomass production (Table 2) but still observed runoff differences among manure rate treatments during the soybean year (Table 3). Therefore, we believe that the observed reduction in runoff with incorporated manure was a result of improved soil infiltration rates. However, further research is needed to identify the specific mechanisms controlling the observed differences in runoff. A reduction in runoff was not observed at low rates of liquid manure application and it is not known whether additional reductions in runoff would be achieved with application rates higher than those used in this study.

Contaminant Losses

Total Solids

The loss of total solids in runoff occurred predominantly in summer and ranged from 1.4 to 3.1 Mg ha^{-1} yr^{-1}. Total solids loss from summer events was affected by manure application rate ($p = 0.09$) and study year ($p = 0.01$), and there was no year by application rate interaction ($p = 0.76$). Losses were less from the 2X application rate than for the control and 0.5X treatments. Total solids loss from the spring period was different among years ($p < 0.001$) but was not affected by manure application rate ($p = 0.77$). Solids losses were very small for spring snowmelt runoff.

Average annual loss of total solids in runoff (Fig. 2B) was significantly different among manure application rates ($p = 0.02$). The loss of total solids was less for the 2X rate than for the 0X, 0.5X, and 1X rates. As observed for runoff volume, the incorporation of liquid swine manure reduced erosion and total solids loss in summer runoff. The reduction in soil loss was not observed for low manure application rates. No reduction in erosion was observed during the spring thaw, when soil frost was present.

Phosphorus

Total P loading (Fig. 2C) averaged 2.3 kg ha^{-1} yr^{-1} and was not different among manure application rates ($p = 0.11$). On average, 65% of the total P loss came from summer runoff and the remainder came from spring, predominantly from the 7 Apr. 2001 rainfall. There were no significant treatment effects on the losses of total P when considering seasonal totals for spring ($p = 0.77$) or summer ($p = 0.16$). Thus, liquid swine manure applied and incorporated at P-based rates did not significantly increase total P loading in runoff, despite the addition of P to the soil. These results illustrate that a reduction in runoff associated with incorporated manure can partially offset a greater P concentration in the soil and in runoff.

Annual loss of dissolved P (Fig. 2D) was different among manure application rates ($p = 0.01$). Losses from the 1X and 2X treatments were greater than losses from the control and 0.5X treatments. Dissolved P losses ranged from 3% of total P losses for the control treatment to 20% of total P losses for the 2X application rate. The majority of the DP losses came from the spring runoff period and was mostly due to the large runoff event on 7 Apr. 2001. Loss of DP was different among manure application rates for spring events ($p = 0.001$) but was not different for summer events ($p = 0.79$). The fraction of TP loss that occurred as DP differed for spring and summer runoff periods. The percent of TP lost as DP averaged 18 and 2% for spring and summer runoff, respectively.

Dissolved P losses in spring runoff illustrate the potential for increased DP losses when a runoff event follows shortly after manure application or during the spring thaw after fall-applied manure. These losses may be considered as the short-term risks associated with land-applied manure. Many studies evaluating the short-term water quality risks of applied manure use simulated rainfall shortly after manure application (Edwards and Daniel, 1994; Pote et al., 2001). However, short-term studies should be interpreted together with studies that consider longer-term effects such as the effect of applied manure on infiltration rate observed here. The summer runoff events from this study illustrate that the risk of elevated DP losses associated with incorporated manure does not persist. Dissolved P losses from summer events were not greater with increasing manure application rates. Thus, an important consideration in developing recommended manure application practices is the probability that a runoff-inducing event will occur shortly after the manure application.

CONCLUSIONS

Liquid swine manure applied and incorporated into the soil reduced runoff volume during the growing season compared with soil with no applied manure. There was also a reduction in sediment loss during summer runoff associated with applied manure. Despite the addition of P to the soil with applied manure and a corresponding increase in extractable soil P concentration, there was no difference in total P lost in runoff relative to plots without manure applied. The reduction in runoff due to manure compensated for the increase in soil P level. However, there was a higher loss of DP with increasing manure application rates for spring runoff. Runoff and erosion that occurred during spring thaw were controlled by the presence of frost in the soil and were not influenced by manure. Thus, there are both short- and long-term effects of manure application on the quantity and quality of runoff. Evaluation of water quality risks should consider the long-term benefits of incorporated manure on runoff and soil loss, but also consider short-term risk based on the probability of a runoff event occurring shortly following manure application.

REFERENCES

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl. 8:559–568.

Combs, S.M., and M.V. Nathan. 1998. Soil organic matter. p. 53–58. *In* Recommended chemical soil test procedures for the North Central Region. North Central Reg. Res. Publ. 221 (revised). SB 1001. Missouri Agric. Exp. Stn., Columbia.

Edwards, D.R., and T.C. Daniel. 1994. A comparison of runoff quality effects of organic and inorganic fertilizers applied to fescuegrass plots. Water Resour. Bull. 30:35–41.

Frank, K., D. Beegle, and J. Denning. 1998. Phosphorus. p. 21–29. *In* Recommended chemical soil test procedures for the North Central Region. North Central Reg. Res. Publ. 221 (revised). SB 1001. Missouri Agric. Exp. Stn., Columbia.

Gilley, J.E., and L.M. Risse. 2000. Runoff and soil loss as affected by the application of manure. Trans. ASAE 43:1583–1588.

Ginting, D., J.F. Moncrief, S.C. Gupta, and S.D. Evans. 1998. Interaction between manure and tillage system on phosphorus uptake and runoff losses. J. Environ. Qual. 27:1403–1410.

Hansen, N.C., T.C. Daniel, A.N. Sharpley, and J.L. Lemunyon. 2002. The fate and transport of phosphorus in agricultural systems. J. Soil Water Conserv. 57:408–417.

Laflen, J.M., M. Amemiya, and E.A. Hintz. 1981. Measuring residue cover. J. Soil Water Conserv. 32:341–343.

Mueller, D.H., R.C. Wendt, and T.C. Daniel. 1984. Phosphorus losses as affected by tillage and manure application. Soil Sci. Soc. Am. J. 48:901–905.

Murphy, J., and J. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:3–36.

National Research Council. 2000. Clean coastal waters: Understanding and reducing the effects of nutrient pollution. Natl. Academy Press, Washington, DC.

Plumb, R., Jr. 1981. Procedures for handling and chemical analysis of sediment and water samples. Tech. Rep. EPA/CE-81-1. Environ. Lab., U.S. Army Eng. Waterways Exp. Stn., Vicksburg, MS.

Pote, D.H., B.A. Reed, T.C. Daniel, D.J. Nichols, P.A. Moore, Jr., D.R. Edwards, and S. Formica. 2001. Water-quality effects of infiltration rate and manure application rate for soils receiving swine manure. J. Soil Water Conserv. 56:32–37.

Rehm, G., M. Schmitt, and R. Munter. 1995. Fertilizer recommendations for agronomic crops in Minnesota. Minnesota Ext. Serv. Bull. BU-6240-E. Univ. of Minnesota, St. Paul.

SAS Institute. 1999. The SAS system for Windows. Release 8.1. SAS Inst., Cary, NC.

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 23:437–451.

Smith, V.H. 1998. Cultural eutrophication of inland, estuarine, and costal waters. p. 7–49. *In* M.L. Pace and P.M. Groffman (ed.) Successes, limitations, and frontiers in ecosystem science. Springer-Verlag, New York.