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Nutrient and Sediment Losses Under Simulated Rainfall Following Manure Incorporation by Different Methods

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ABSTRACT

Incorporation of manure into cultivated soils is generally recommended to minimize nutrient losses. A 3-yr study was conducted to evaluate sediment and nutrient losses with different tillage methods (moldboard plow, heavy-duty cultivator, double disk, and no-incorporation) for incorporation of beef cattle manure in a silage barley (*Hordeum vulgare* L.) cropping system. Runoff depths, sediment losses, and surface and subsurface nutrient transfers were determined from manured and unmanured field plots at Lethbridge, Alberta, Canada. A Guelph rainfall simulator was used to generate 30 min of runoff. Sediment losses among our tillage treatments (137.4–203.6 kg ha^{-1}) were not significantly different due to compensating differences in runoff depths. Mass losses of total phosphorus (TP) and total nitrogen (TN) in surface runoff were greatest from the no-incorporation (NI) treatments, with reductions in TP loads of 14% for double disk (DD), 43% for cultivator (CU), and 79% for moldboard plow (MP) treatments. Total N load reductions in 2002 were 26% for DD, 70% for CU, and 95% for MP treatments compared to the NI treatments. Nutrient losses following incorporation of manure with the DD or CU methods were not significantly different from the NI treatments. Manure treatments generally had lower runoff depths and sediment losses, and higher phosphorus and nitrogen losses than the control treatments. Subsurface concentrations of NH_4–N, NO_3–N, and TN were greatest from the MP treatments, whereas subsurface phosphorus concentrations were not affected by tillage method. Tillage with a cultivator or double disk minimized combined surface and subsurface nutrient losses immediately after annual manure applications.

Runoff from agricultural land is a major nonpoint source of inorganic and organic forms of nutrients and eroded sediment. Land application of animal manure increases the supply of nutrients in the soil, which may subsequently be transported to surface water bodies in overland flow, especially when left near the soil surface. In Alberta, the Agricultural Operation Practices Act (AOPA) requires incorporation of manure within 48 h of application onto cultivated land (Province of Alberta, 2004). Manure incorporation, however, is not defined in the AOPA and the tillage method to be used is not specified. While incorporation of manure may increase the risk of soil erosion through incorporation of plant material that might otherwise protect the soil surface during spring snowmelt and high intensity rainfall events, tillage may also reduce the risk of dissolved nutrient runoff losses by redistributing nutrients within the soil profile. However, redistribution of nutrients within the soil may increase the risk of nutrient leaching.

Rainfall and overland runoff generally interact with a very thin layer of surface soil. The depth of interaction is influenced by rainfall intensity, runoff energy, and soil slope (Ingram and Woolhiser, 1980). Sharpley (1985) reported that the effective depth of interaction between surface soil and runoff increased from 1.3 to 37.4 mm with an increase in rainfall intensity from 50 to 160 mm h^{-1} and an increase in soil slope from 2 to 20%. Consequently, differences in soil erosion and runoff water quality are strongly related to the depth of tillage and the degree of mixing with surface soil.

Surface applications of fertilizer or manure without incorporation are extremely vulnerable to losses into surface waters, particularly when runoff occurs shortly after application (Hansen et al., 2002; Tabbara, 2003). The potential for nutrient losses in overland flow differs by manure source (Kleinman et al., 2002), and increases with the rate of manure application (Kleinman and Sharpley, 2003), decreases with time after application (Edwards and Daniel, 1994; Eghball et al., 2002), and decreases with successive rainfall events (Sharpley, 1997; Kleinman and Sharpley, 2003).

Plowing or cultivation of soils to incorporate fertilizers or manure reduces the risk of direct transmission of nutrients to surface water; however, incorporation of crop residues and soil amendments increases the potential for soil erosion. Tillage systems have been developed to maintain crop residues near the soil surface, thereby reducing soil erosion and runoff and limiting sediment and nutrient losses from agricultural soils (Hansen et al., 2002). Accumulation of nutrients from fertilizers and crop residues near the soil surface, however, can result in significant concentrations of dissolved nutrients in overland flow from these systems (Seta et al., 1993).

Previous research on the effects of different tillage methods and manure on phosphorus losses in surface runoff has been conducted with dairy, beef, or swine manure on corn (*Zea mays* L.) or corn–soybean [*Glycine max* (L.) Merr.] cropland (Mueller et al., 1984b; Ginting et al., 1998b; Bundy et al., 2001; Daverede et al., 2004). Tillage and manure application effects on nitrogen and

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Abbreviations: CU, cultivator; CUC, cultivator control; CUM, cultivator manure; DD, double disk; DDC, double disk control; DDM, double disk manure; DRP, dissolved reactive phosphorus; FWMC, flow-weighted mean concentration; MP, moldboard plow; MPC, moldboard plow control; MPM, moldboard plow manure; NI, no incorporation; NIC, no-incorporation control; NIM, no-incorporation manure; STP, soil test phosphorus; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids.

phosphorus losses in overland flow or leaching have also been investigated with beef manure in grain sorghum [*Sorghum bicolor* (L.) Moench]–winter wheat (*Triticum aestivum* L.) cropping systems (Eghball and Gilley, 1999) and in corn production systems (Zhao et al., 2001). Solid beef manure from cattle feedlots in Alberta is generally applied to silage barley stubble at nitrogen-based rates and is usually incorporated with a double disk or heavy-duty cultivator.

The objective of this study was to compare tillage methods for incorporation of beef cattle manure through evaluation of nutrient and sediment losses in surface runoff and nutrient concentrations in subsurface leachate during field rainfall simulations conducted within a week of manure application in a silage barley cropping system.

MATERIALS AND METHODS

Experimental Design and Site Characterization

A field study was conducted from 2000 to 2002 on a Dark Brown Chernozemic (Typic Haploboroll) clay loam soil (Lethbridge–Whitney series) at the Lethbridge Research Station, Agriculture and Agri-Food Canada, Lethbridge, Alberta. The pH of the surface soil is about 7.5, clay content is 250 g kg^{-1}, sand content is 420 g kg^{-1}, and organic matter content is about 26 g kg^{-1}. A randomized complete block design with four replications was established in the spring of 2000. Each block contained eight 6-m-wide by 10-m-long plots. The mean slope of the plots was 35 mm m^{-1}.

Treatments consisted of two rates of solid beef cattle manure (0 and 60 Mg ha^{-1}, wet weight) and four tillage methods (surface application without incorporation, and incorporation with a single pass of a double-disk, a heavy-duty cultivator, or a moldboard plow). Individual treatments were designated as cultivator control (CUC), cultivator manure (CUM), double disk control (DDC), double disk manure (DDM), moldboard plow control (MPC), moldboard plow manure (MPM), no-incorporation control (NIC), and no-incorporation manure (NIM). The depth of tillage was approximately 10 to 15 cm for the double-disk and cultivator, and about 25 to 30 cm for the moldboard plow. Tillage was completed (parallel to the slope) on the day of manure application. Plots were harrowed and then seeded (both perpendicular to the slope) to barley (cv. Duke) in early May each year. Crops were harvested at the silage stage in late July. Irrigation water was applied using a wheel-move sprinkler system to meet the water use requirements of the crop. Manure was applied by hand to one replicate at a time following harvest each year. A garden rake was then used to redistribute the manure uniformly within the main plot.

Beef cattle manure was obtained from the feedlot at the Lethbridge Research Station. Five manure samples were collected from the manure source before the application on each replicate. Available nitrogen (NO_3–N and NH_4–N) in the manure was determined by extracting field-moist samples (10 g manure and 200 mL of 2 *M* KCl) and NH_4–N was determined by automated salicylate (Rhine et al., 1998), while NO_3–N was measured by hydrazine reduction (Kempers and Luft, 1988). The remainder of each sample was air-dried, ground (<2 mm), and extracted for chemical analyses. Available phosphorus (ortho-P) extracts were prepared by shaking 1 g of manure and 25 mL of Kelowna extract (Van Lierop, 1988). Finely ground samples (<150 μm) were prepared for total C, N, and P analyses. Total P was determined using a wet-oxidation procedure (Parkinson and Allen, 1975) and ortho-P was measured on an autoanalyzer by the ascorbic acid reduction method (Murphy and Riley, 1962). Total carbon (TC) and total nitrogen (TN) were measured by the Dumas automated combustion method (McGill and Fiqueiredo, 1993) on a carbon–nitrogen–sulfur analyzer (Carla Erba, Milan, Italy).

Before annual rainfall simulations, soil samples were collected from the 0- to 2.5-, 2.5- to 7.5-, and 7.5- to 15-cm depth intervals using an excavation method. Subsamples were taken and dried to determine antecedent soil moisture content. Surface roughness was also measured using the chain method (Saleh, 1993). Deep soil cores (0–0.15, 0.15–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20, and 1.20–1.50 m) were taken before the simulations in the fall of 2000. Soil samples were air-dried, ground (<2 mm), and analyzed. Nitrate N and NH_4–N were determined on extracts from 1 g soil and 25 mL of 2 *M* KCl. Soil test phosphorus (STP) was determined by measuring the ortho-P content of a Kelowna extract (Van Lierop, 1988). Total C, N, and P were determined on finely ground soil samples according to the same methods as the manure samples.

Rainfall Simulations

Simulated rainfall was applied to a 1- × 1-m area within the plots using a portable Guelph rainfall simulator (Tossell et al., 1987). A stainless-steel frame (0.2 m deep) was installed at a depth of about 0.10 m on the upslope end and both sides of the test area, a triangular metal apron was installed at the lower end, and a hole was excavated at the apex of the apron to allow collection of runoff in 1-L containers. A Plexiglas cover was placed over the metal apron to prevent rainfall directly onto the apron. Rainfall was applied using a Fulljet 3/8GG 20W nozzle (Spraying Systems Co., Wheaton, IL) from a height of 0.8 m and at an intensity of approximately 100 mm h^{-1} when operated at a pressure of 96.5 kPa (Miller, 2003). This rainfall intensity for a 30-min duration has a 1-in-50-yr return period in the Lethbridge area. Deionized water was used for all simulations and tests were usually performed within 5 d of manure application. Runoff generated from the plots was collected for 30 min following initiation of continuous runoff.

Runoff samples were collected in 1-min intervals. Volume was measured in the field for each sample and total runoff depth (mm) was determined on the basis of the plot area. Ten subsamples from each run were collected for analysis at 1, 2, 3, 5, 7, 9, 12, 15, 20, and 30 min after commencement of continuous runoff. Water samples were analyzed for dissolved reactive phosphorus (DRP), TP, NO_3–N, NH_4–N, and total nitrogen (TN). Samples analyzed for DRP were centrifuged (10 000 rpm for 10 min) and filtered through 0.45-μm membrane filters within a few minutes following collection. These DRP samples were stored at 4°C until analysis, which occurred within 4 d of collection. Total phosphorus, TN, NO_3–N, and NH_4–N samples were acidified and then frozen. Ammonium N, NO_3–N, and ortho-P (DRP) were determined by the same methods as the soil extracts. Total N and total P were determined using the persulfate digestion method (Methods 4500-N_{org} D and 4500-P B, respectively; American Public Health Association, 1995). A composite sample for the 30-min runoff interval was analyzed for total suspended solids (TSS) by filtering a 100-mL aliquot of runoff water through a 0.45-μm membrane filter and then drying and weighing the filter. Total mass loads were estimated by multiplying subsample concentrations by their respective volumes, and loads were interpolated for intervening times by integrating the area under the curve. Flow-weighted mean concentration (FWMC) was cal-

Table 1. Mean characteristics of the beef cattle manure applied† (n = 20; standard error of the mean in parentheses).

Parameter	2000	2001	2002
Moisture content, g kg^{-1}	440 (29)	400 (22)	1 050 (9)
Total carbon, g kg^{-1}	250 (6)	230 (13)	210 (7)
Total phosphorus, mg kg^{-1}	4 560 (80)	4 670 (210)	4 080 (100)
Available phosphorus, mg kg^{-1}	3 660 (70)	2 360 (140)	2 050 (80)
Total nitrogen, mg kg^{-1}	14 940 (260)	15 250 (970)	14 240 (380)
NH_4–N, mg kg^{-1}	790‡ (36)	2 050 (99)	1 090 (129)
NO_3–N, mg kg^{-1}	150‡ (8)	250 (29)	150 (33)

† All parameters are expressed on a dry-weight basis.
‡ n = 10 in 2000.

culated by dividing the total mass load by the total runoff volume.

In 2001 and 2002, four 25-mm-diameter zero-tension lysimeters (Simmons and Baker, 1993) were installed in the plots at a depth of approximately 60 cm to determine the concentration of constituents in subsurface flow. Subsurface water samples were analyzed for the same chemical constituents and by the same methods as the runoff samples. Subsurface measurements were restricted to concentrations of constituents, since subsurface flow volumes were not measured in this study and mass losses could not be estimated.

Data Analysis

Runoff Analysis

Variables were log transformed to $\log_{10}(x + 1)$ values, as necessary, to satisfy conditions of normality. Proc Mixed (SAS Institute, 2000) was used to analyze runoff data using tillage treatment, manure application, and year as fixed effects, and replicate as a random effect. A repeated year statement using a compound symmetry model was employed for FWMCs and mass loads. Each year of the study was analyzed separately when the tillage by year or manure by year interaction was significant for a given variable. Mean comparisons were performed using Tukey's studentized range test at $P < 0.05$ (SAS Institute, 2000). The Univariate procedure in SAS (SAS Institute, 2000) was used to evaluate residuals for normality and to check for obvious outliers.

Soil Analysis

Soil physical and chemical data obtained for site characterization were analyzed using an analysis of variance procedure (Proc GLM) to determine the initial homogeneity of the site (SAS Institute, 2000). Treatment effects were subsequently evaluated using the same mixed-model analysis as the runoff data, with mean comparisons performed using Tukey's studentized range test at $P < 0.05$ (SAS Institute, 2000). Soil variables were transformed to $\log_{10}(x + 1)$ values, as necessary, before analysis to satisfy conditions of normality. The Univariate procedure in SAS (SAS Institute, 2000) was used to evaluate residuals for normality and to check for obvious outliers. The regression procedure (SAS Institute, 2000) was used to examine relationships between soil nutrient levels and nutrient FWMCs in runoff.

RESULTS AND DISCUSSION

Manure and Soil Characteristics

Beef cattle manure applied to the amended plots was much drier in 2000 and 2001 than in 2002 (Table 1). At least half of the phosphorus and 6 to 15% of the mineral nitrogen (NH_4–N and NO_3–N) in the manure were in plant-available forms. Mean application rates for the 60 Mg ha^{-1} of wet manure applied were approximately 190 kg TP ha^{-1} in 2000, 200 kg TP ha^{-1} in 2001, and 120 kg TP ha^{-1} in 2002 (wet-weight basis). Nitrogen in the manure was applied at mean rates of approximately 620 kg TN ha^{-1} in 2000, 650 kg TN ha^{-1} in 2001, and 420 kg TN ha^{-1} in 2002 (wet-weight basis).

Soil characteristics within the study site were reasonably homogeneous to a depth of 1.5 m before the tillage and manure treatments (Table 2). Mean values for each parameter from plots used for the tillage and manure treatments were not significantly different in all depth intervals.

Following the tillage and manure treatments, mean soil surface roughness was similar for the CUC, DDC, CUM, DDM, MPM, and NIM treatments (Fig. 1a). The surface roughness of the NIM treatment was more than twice as large as the surface roughness of the NIC treatment. Antecedent soil moisture content before the rainfall simulations was highest for the cultivator (CU) and no-incorporation (NI) treatments, and was lowest for the moldboard plow (MP) treatments, but treatment differences were not significant (Fig. 1b).

Total carbon content within the upper 2.5 cm was similar for all of the control treatments (Fig. 1c). The total carbon content of the manure treatments was generally higher than the control treatments, except for the MPM treatment, which was similar to the control treatments. Total carbon content within the upper 2.5 cm of the NIM treatment was not significantly different from the CUM and DDM treatments, even though manure was partially incorporated by these tillage methods.

Total P and TN content of the upper 2.5 cm were reasonably uniform for all of the control treatments

Table 2. Mean soil characteristics before manure application and tillage in 2000 (n = 8; standard error of the mean in parentheses).

Depth	Total carbon	Total P	Soil test P	Total N	NH_4–N	NO_3–N
cm	g kg^{-1}	mg kg^{-1}				
0–15	29.2 (0.5)	478 (18)	34.2 (1.7)	2279 (49)	7.0 (0.2)	5.0 (0.2)
15–30	21.5 (0.9)	496 (17)	16.8 (1.9)	1691 (60)	6.0 (0.2)	3.3 (0.2)
30–60	16.3 (0.9)	500 (14)	3.0 (0.4)	992 (46)	0.6 (0.0)	0.1 (0.0)
60–90	19.1 (0.8)	488 (16)	3.4 (0.2)	661 (39)	0.6 (0.0)	0.1 (0.0)
90–120	15.5 (0.8)	487 (17)	3.0 (0.3)	441 (22)	4.9 (0.2)	2.2 (0.2)
120–150	12.9 (1.0)	495 (21)	3.4 (0.3)	416 (66)	0.5 (0.0)	0.0 (0.0)

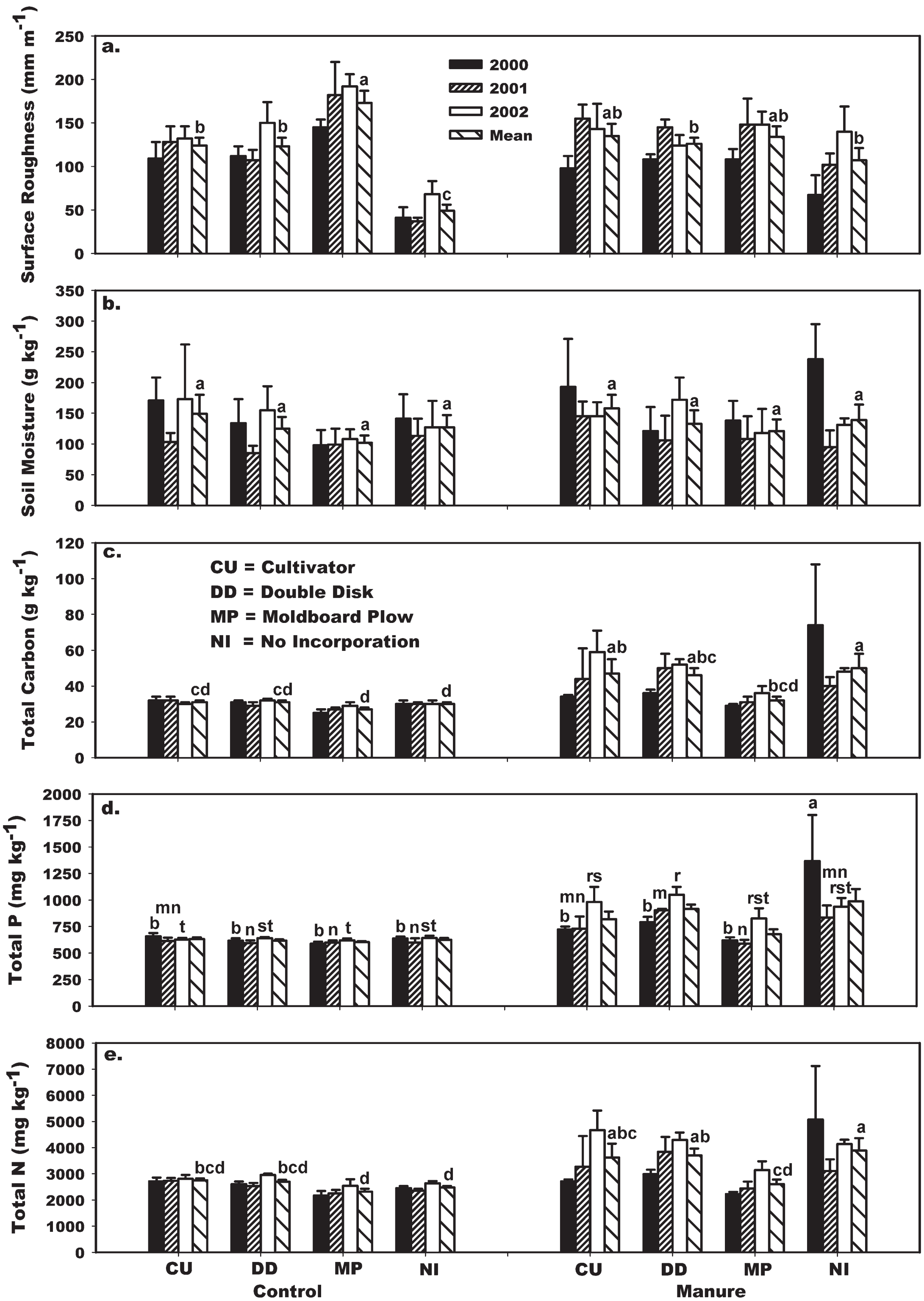

Fig. 1. Mean soil characteristics in the upper 2.5 cm after annual manure application and tillage and before rainfall simulations. Mean values for each parameter followed by the same letter are not significantly different ($P < 0.05$). Differences in each parameter among years were not significant, except for total P. The error bars represent the standard error of the mean.

(Fig. 1d and 1e). Soil test phosphorus in the upper 2.5 cm ranged from 35.3 to 78.0 mg kg^{-1} and mineral nitrogen (NH_4–N and NO_3–N) content was less than 30 mg kg^{-1} for the control treatments (data not shown). Nutrient content of the manure treatments was highest in the upper 2.5 cm and generally decreased with depth, except for the MPM treatment that had higher nutrient content with depth (data below 2.5 cm not shown). Manure treatments had STP levels that were 9 to 42% of TP and mineral nitrogen content ranged from 1 to 3% of

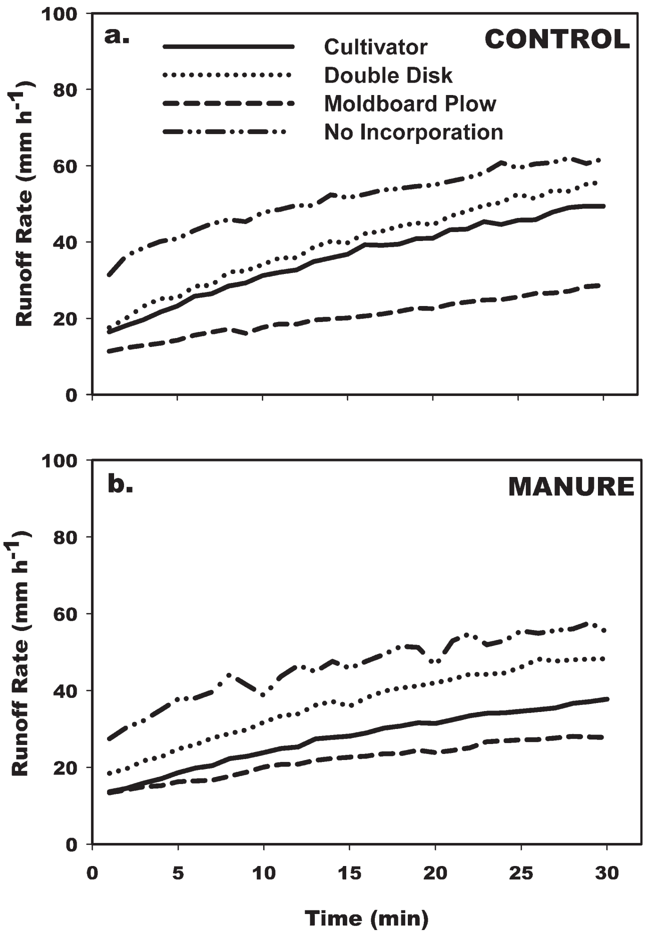

Fig. 2. Mean runoff rates from the four tillage methods for the (a) control and (b) manure treatments.

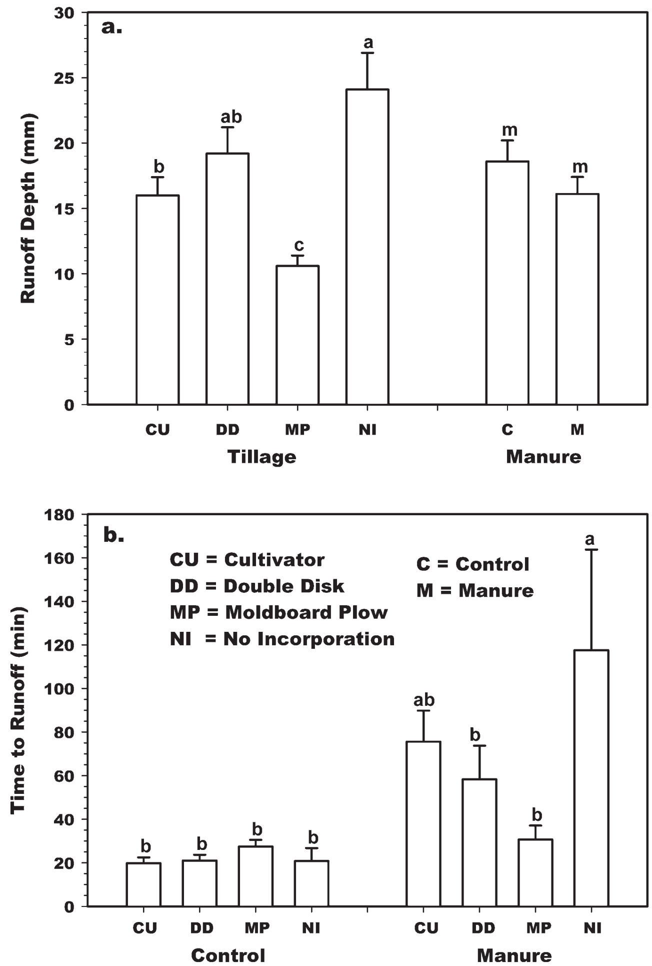

Fig. 3. Mean (a) runoff volume and (b) time to runoff for tillage and manure treatments. Mean values for each parameter followed by the same letter are not significantly different ($P < 0.05$). The error bars represent the standard error of the mean.

TN. The NIM treatment generally had the highest nutrient content in the upper 2.5 cm, except for NO_3–N (data not shown), and the MPM treatment generally had the lowest nutrient content at the surface. The CUM and DDM treatments had similar nutrient content within the upper 15 cm (data below 2.5 cm not shown).

Surface Runoff

The rates of runoff increased gradually throughout the 30-min runoff interval and were highest for the NI treatments and lowest for the MP treatments, regardless of manure application (Fig. 2). Runoff was greatest from NI treatments and was reduced by 20% with a double disk (DD), by 34% using a cultivator, and by 56% with a moldboard plow. Mean runoff depths for the different tillage treatments during the 30-min rainfall simulations ranged from 10.6 to 24.1 mm (Fig. 3a). This represents from 21 to 48% of the irrigation water applied during this 30-min interval. The lowest runoff depths were observed on the MP treatments and the highest overall runoff depths were obtained from the NI treatments. Manure treatments did not have a significant effect on runoff depth. Runoff depths were quite variable from year to year and among the tillage and manure treatments.

Time to runoff data had a significant tillage by manure interaction, so tillage methods were evaluated separately for each manure treatment. The time to commencement of runoff was also extremely variable among the treatments. Time to runoff ranged from 19.8 to 27.5 min for the control treatments and from 30.7 to 117.6 min for the manure treatments (Fig. 3b). Manure treatments generally resulted in greater time to commencement of runoff compared to control treatments, but the increased time to runoff was only significant for the NIM treatment. The amount of simulated rainfall required to induce runoff from the NIM treatment was substantially greater than the other manure treatments (almost four times greater than the MPM treatment); however, runoff depths were eventually greatest from the NI treatments (Fig. 3a).

Direct comparisons with hydrological data from previous runoff studies are complicated by differences in site hydrology, variation in natural precipitation or in rainfall simulation methodology, variability in tillage methods, and differences in manure characteristics and the timing of incorporation. These factors are particularly important in determining runoff rates and depths, but they can also affect other water quality variables.

Several other studies have reported significantly lower

Table 3. Mean concentrations and loads of total suspended solids (TSS) and flow-weighted mean concentrations and loads of dissolved reactive phosphorus (DRP) and total phosphorus (TP) during 30 min of runoff.†

	TSS		TSS load		DRP		DRP load		TP		TP load	
Parameter	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
	— g L^{-1} —		— kg ha^{-1} —		— mg L^{-1} —		— g ha^{-1} —		— mg L^{-1} —		— g ha^{-1} —	
Fixed effects												
Tillage treatment												
Cultivator	1.18ab	0.13	203.6a	35.0	0.79	0.24	127.0	40.3	1.51	0.31	244.5a	56.1
Double disk	0.89bc	0.11	182.8a	34.1	0.90	0.30	214.2	76.8	1.64	0.35	369.6a	91.9
Moldboard plow	1.26a	0.14	137.4a	20.2	0.13	0.02	13.2	1.7	0.91	0.10	92.4b	10.2
No incorporation	0.70c	0.11	193.0a	48.3	1.04	0.25	264.3	85.0	1.65	0.29	429.9a	106.9
Manure treatment												
Control	1.12m	0.09	220.4m	29.6	0.14	0.01	27.9	3.7	0.80	0.05	154.1n	18.5
Manure	0.88n	0.09	132.6n	14.6	1.38	0.21	298.8	60.1	2.14	0.26	431.6m	76.5
Year												
2000	0.66s	0.08	100.2s	22.1	0.83r	0.29	185.4rs	72.9	1.32s	0.32	260.8s	80.5
2001	1.18r	0.11	199.5r	24.8	0.53r	0.14	91.8s	27.8	1.08s	0.15	191.7s	34.4
2002	1.16r	0.11	230.5r	37.7	0.81r	0.18	190.2r	58.0	1.87r	0.24	398.6r	81.0
					F value							
Effects												
Tillage	***		NS		***		***		**		***	
Manure	**		**		***		***		***		***	
Tillage × manure	NS		NS		**		**		**		NS	
Year	**		**		NS		*		***		**	
Tillage × year	NS		NS		NS		NS		NS		NS	
Manure × year	NS		NS		NS		NS		NS		NS	
Tillage × manure × year	NS		NS		NS		NS		NS		NS	

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Mean values for each fixed effect in each column followed by the same letter are not significantly different ($P < 0.05$). SE = standard error of the mean.

runoff volumes from conventional tillage compared with no-till or reduced-till systems (Mueller et al., 1984a; Daverede et al., 2003). Differences in the volume of runoff among various tillage treatments have generally been attributed to differences in crop residue (Daverede et al., 2003), manure application and incorporation (Mueller et al., 1984a; Bundy et al., 2001), and higher infiltration rates and surface roughness in some cultivated soils (Blevins et al., 1990). In contrast, Seta et al. (1993) reported lower runoff volumes and mean runoff rates from no-till treatments than from chisel-plow or moldboard-plow treatments. The higher infiltration rate in their study for the no-till treatment was attributed to less surface sealing and more undisturbed macropores.

Differences in runoff volumes tend to be most apparent in spring, but lessen with time due to the development of the crop canopy and additional cultivation (Hansen et al., 2000b) or to surface crusting (Mueller et al., 1984a). Since our plots were treated after harvest, results are likely comparable to spring conditions.

Manure tends to increase infiltration; therefore, application of manure before tillage generally resulted in lower runoff volumes compared to the control (Mueller et al., 1984a; Ginting et al., 1998a), as was observed in our study.

Total Suspended Solids

Total suspended solids (TSS) concentrations were greatest from MP treatments and least from the NI treatments (Table 3). However, TSS loads were not significantly different among the tillage treatments (Table 3). Manure treatments significantly reduced both TSS loads and concentrations compared to the control treatments. The TSS concentrations and loads were significantly lower in 2000 than in subsequent years (Table 3).

A number of studies have shown that partial incorporation of crop residues and manure is usually more effective at reducing sediment losses than conventional tillage with a moldboard plow (Mueller et al., 1984a; Ginting et al., 1998a; Zhao et al., 2001). Differences in runoff volume among various tillage systems, however, sometimes compensate for variation in sediment concentrations, resulting in no difference in sediment losses among the tillage treatments (Hansen et al., 2000b). In our study, sediment concentration was highest from the MP treatments and lower from the other treatments. Runoff volumes were generally lowest from the MP treatments; therefore, overall sediment losses among our tillage treatments were not significantly different.

Phosphorus

Dissolved Reactive Phosphorus

Tillage methods were evaluated separately for each manure treatment because the tillage by manure interaction was significant (Table 3, Fig. 4). For both the control and manure treatments, the DRP FWMC was highest for the NI treatments, but there were no significant differences observed among the control tillage treatments. The DRP FWMC for the MPM treatment was significantly lower than the other three manure treatments, and was similar to the control treatments. Mass loads of DRP showed a similar pattern to the DRP FWMC results, except that a significant year effect was observed, with DRP loads significantly greater in 2002 than in 2001 (Table 3).

Although FWMC is theoretically independent of run-

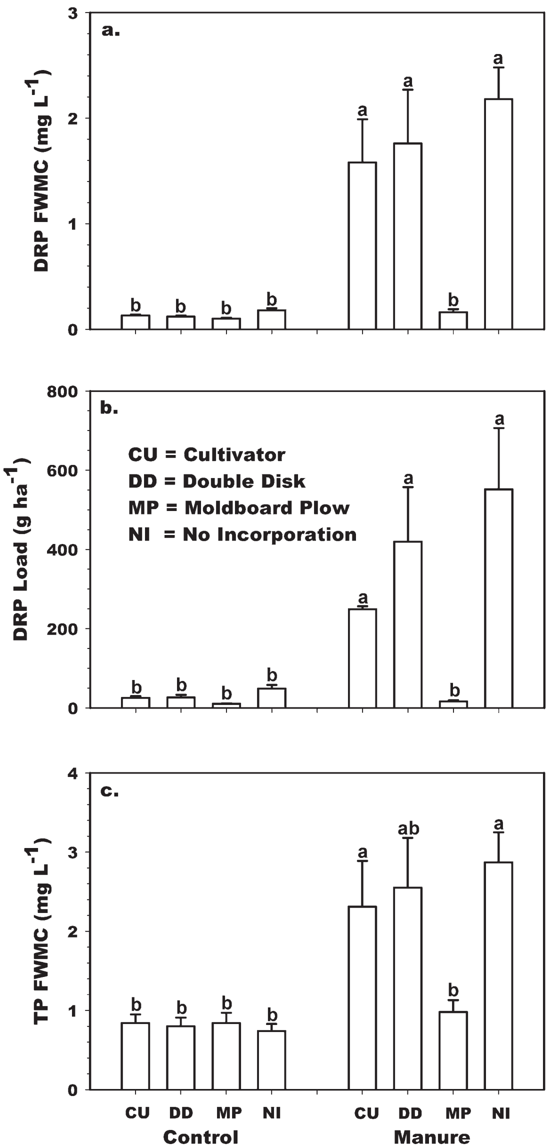

Fig. 4. Mean (a) dissolved reactive phosphorus flow-weighted concentration (DRP FWMC), (b) DRP load, and (c) total phosphorus flow-weighted concentration (TP FWMC) for the tillage and manure treatments. Mean values for each parameter followed by the same letter are not significantly different ($P < 0.05$). The error bars represent the standard error of the mean.

off volume, or potentially even inversely related to runoff volume, this did not seem to be the case with our manure treatments. Additional phosphorus was mobilized, rather than diluted, by the larger runoff volumes (data not shown). This would not be surprising for particulate forms of P, as erosion generally increases with increasing runoff volume, but it is somewhat unexpected for DRP concentrations. Pierson et al. (2001) observed similar phenomena within individual natural runoff events from plots receiving applications of poultry litter. They attributed increased DRP losses to the increased solubilization of P from the litter by the greater runoff volume and to channelization of flows, in which DRP may have initially been adsorbed and later released. On pasture plots from three different soil types, Pote et al. (1999) noted that the soil type with the lowest runoff volumes also had the lowest DRP concentrations in runoff. They attributed the differences to higher rates of infiltration, which moved available phosphorus out of the zone of interaction with the runoff, and found that the relationship between STP and DRP for the three soils could be explained if differences in runoff volume were taken into account. Several other studies have shown no relationship between runoff volume and DRP concentration (Menzel et al., 1978; Torbert et al., 2002; Kleinman et al., 2004).

In general, incorporation of crop residue and manure reduced losses of DRP compared to NI treatments; however, there were no significant differences among the most common tillage methods, CU and DD, and the NI treatments. Most previous studies have compared losses between no-incorporation (unincorporated manure) or reduced tillage (usually ridge tillage) and conventional tillage (chisel or moldboard plow), with mixed results. Most of these studies reported higher DRP losses from no-incorporation or reduced-tillage methods (Mueller et al., 1984b; Ginting et al., 1998b; Eghball and Gilley, 1999; Bundy et al., 2001; Zhao et al., 2001; Daverede et al., 2004); nevertheless, Hansen et al. (2000a) reported the opposite trend. Higher DRP losses under no-till or reduced-tillage systems have been attributed to leaching from crop residues, retention of snow, and the buildup of phosphorus near the soil surface in these treatments. We observed the same trends among the NIM treatments and the other incorporation methods; however, given that average TP and STP levels in the uppermost soils were very similar among the DD and CU treatments (Fig. 1d, Fig. 5), it is not surprising that DRP losses were comparable among the DD and CU treatments.

Numerous studies have examined relationships between STP and the DRP or TP concentration in surface runoff for assessment of site vulnerability to P losses in overland flow (Sharpley et al., 2001, 2002, 2003; Hansen et al., 2002; Kleinman et al., 2004; Schroeder et al., 2004). In our study, weak but significant relationships were observed between STP (10–150 mg kg^{-1}) and log(DRP FWMC + 1) in runoff from our control treatments (Fig. 5a) and between STP (25–600 mg kg^{-1}) and log(DRP FWMC + 1) of the manure treatments (Fig. 5b). These weak relationships between STP and DRP FWMC reflect the high degree of variability among the tillage and manure treatments. Kleinman et al. (2004) evaluated P extraction coefficients for log(DRP + 1)-transformed concentrations in runoff in relation to Mehlich-3 STP from a number of experiments and reported that extraction coefficients (regression slopes) for alkaline soils ranged from 0.0002 to 0.0018 (Sharpley, 1995; Fang et al., 2002; Torbert et al., 2002). Our extraction coefficients (0.0006 for the control and 0.0005 for the manure treatments) were within this range. Kleinman et al. (2002) showed that DRP concentrations in runoff following recent manure applications on the soil surface are primarily related to water-extractable P content of the manure rather than STP. Incorporation of P amendments into the soil generally eliminates differences in runoff P concentration and load between manure-

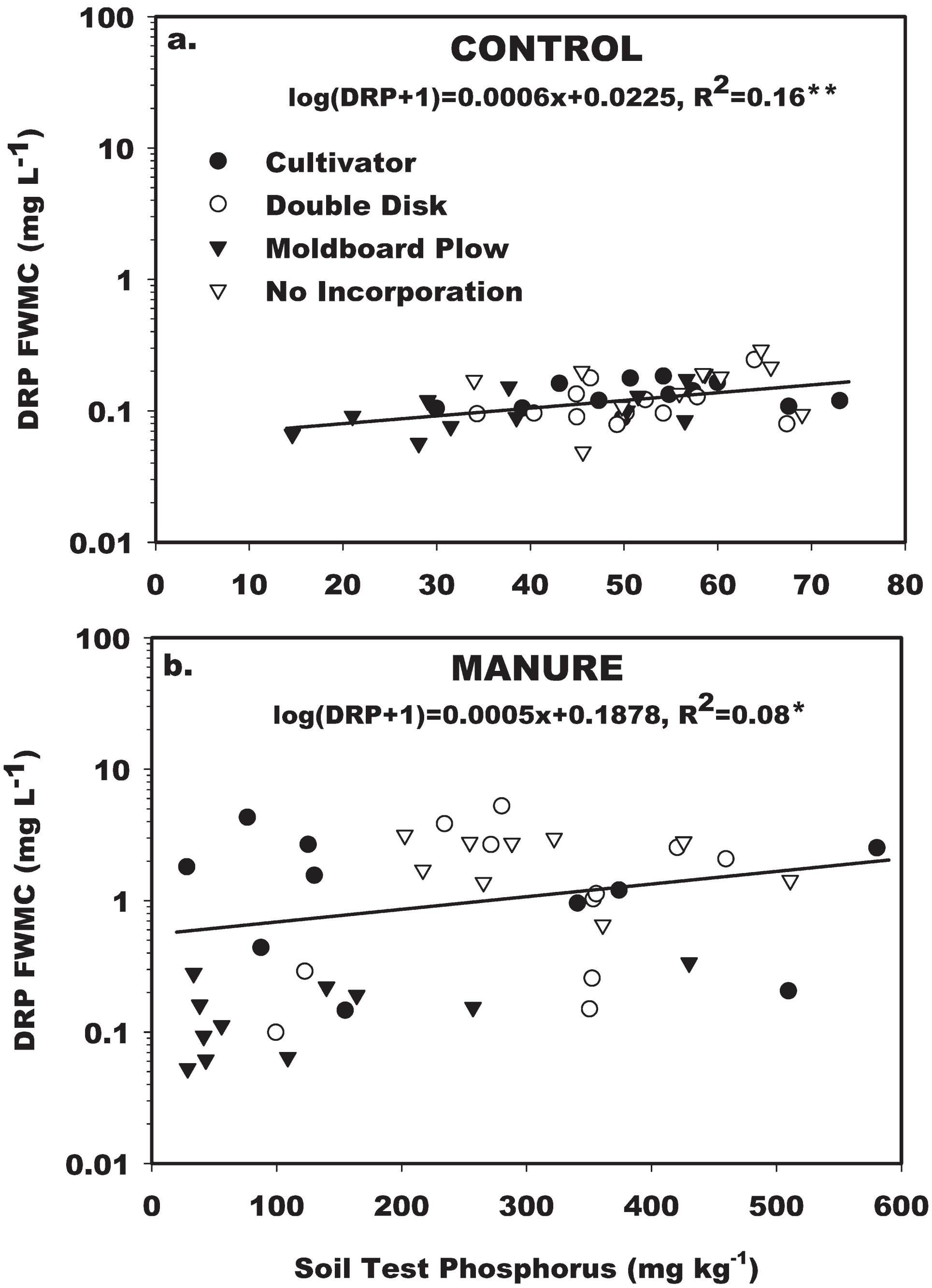

Fig. 5. Relationships between soil test phosphorus and dissolved reactive phosphorus flow-weighted mean concentration (DRP FWMC) for the (a) control and (b) manure treatments.

amended and unamended treatments (Kleinman et al., 2002; Daverede et al., 2004).

Total Phosphorus

A significant interaction was observed between tillage and manure treatments so control and manure treatments were analyzed separately for TP FWMC (Table 3, Fig. 4c). The TP FWMC was greatest from the NIM treatment, followed by the CUM, DDM, and MPM treatments. The TP FWMC was significantly greater in 2002 than in 2000 and 2001 (Table 3).

The NI treatments had the greatest TP loads followed by the DD and CU treatments (Table 3). The TP losses for the MP treatments were significantly lower than the other three tillage treatments. Manure treatments had significantly higher TP losses than the control treatments. The TP loads were significantly greater in 2002 than in 2000 and 2001. An increase in 2002 may be attributed to a combination of the accumulation of TP near the soil surface with time in most of the manure treatments (Fig. 1d) and the wetter conditions in 2002.

Bundy et al. (2001) reported that no-till and unincorporated manure applications generally reduced TP loads in runoff compared to unamended soils or incorporated

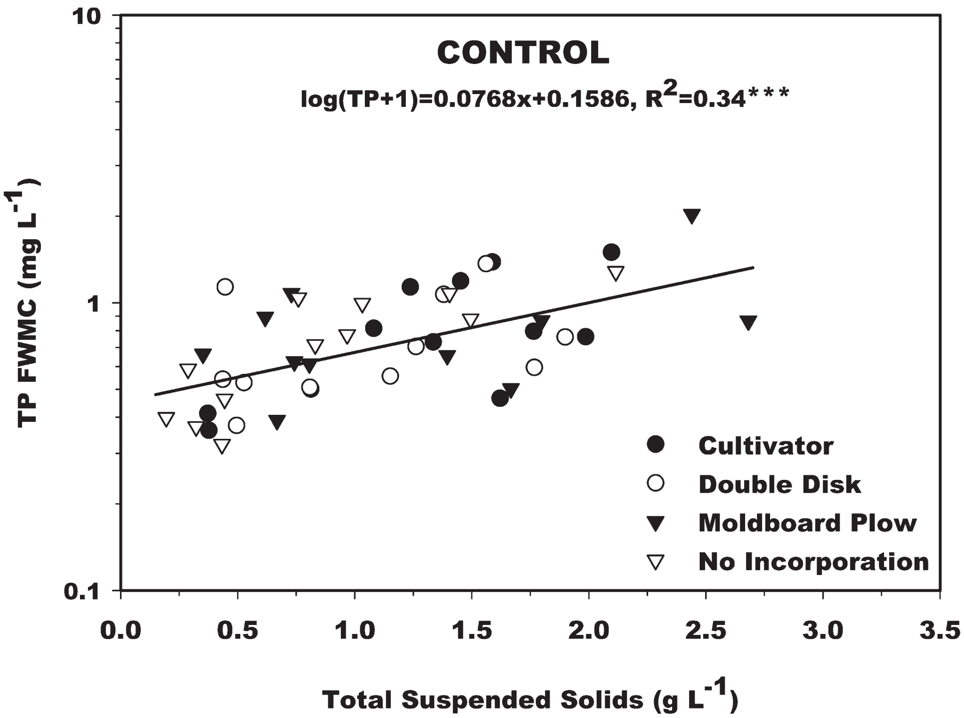

Fig. 6. Relationship between total suspended solids and total phosphorus flow-weighted mean concentration (TP FWMC) during runoff from the control treatments.

manure due to lower sediment losses. In contrast, numerous studies report higher TP losses from conventional tillage following manure application, due to higher sediment losses than from no-till or reduced-tillage systems (Ginting et al., 1998b; Eghball and Gilley, 1999; Hansen et al., 2000a). In our study, TSS concentrations were greatest from the MP treatments; nevertheless, the MPM treatment had lower TP losses than other treatments due to the lower runoff volumes. Similarly, CUM and DDM treatments had lower TP losses than the NIM treatment, despite higher sediment concentrations. Although TP losses in runoff were lower in the MPM treatment, accumulation of phosphorus within the root zone (data not shown) and increased sediment losses make this incorporation method unsuitable for most soils.

Most previous studies on tillage methods have been conducted during a single year (Eghball and Gilley, 1999; Bundy et al., 2001). Our results suggest that there may be considerable year-to-year variability in phosphorus losses from different incorporation methods. These differences are likely due to a combination of factors, including climatic factors, variability in manure phosphorus concentration and application rates, and the inherent variability in generating runoff using a rainfall simulator (Mueller et al., 1984b).

Relationships between STP and the log (TP FWMC + 1) of both manure and control treatments were not significant in this study. Total P concentrations in runoff from some soils are directly related to sediment concentrations in runoff (Cox and Hendricks, 2000; Aase et al., 2001; Andraski and Bundy, 2003; Kleinman et al., 2004). In our study, a weak but significant linear relationship was only detected between TSS and log(TP FWMC + 1) for the control treatments (Fig. 6).

Nitrogen

Ammonium N

Tillage method had no significant effect on NH_4–N FWMCs, but the effect of manure was significant, with greater FWMCs observed from manure treatments (Table 4). All NH_4–N FWMCs were below 2.5 mg L^{-1}, a guideline used for protection of aquatic life (USEPA, 1986).

Several studies have reported significantly lower NH_4–N concentrations from conventionally tilled plots than from reduced- or no-till plots (Seta et al., 1993; Eghball and Gilley, 1999; Zhao et al., 2001); however, we detected no differences in NH_4–N concentration between no-incorporation manure plots and other tillage methods.

For total NH_4–N loads, both tillage and manure had significant effects (Table 4). Losses of NH_4–N were greatest from the NI treatments and both the NI and DD treatment losses were significantly greater than the MP treatments due to higher runoff volumes. Ammonium N losses were also significantly greater from manure treatments than from the control treatments, which can be attributed to higher concentrations of NH_4–N from manure treatments.

Eghball and Gilley (1999) also reported significantly higher NH_4–N losses from no-till treatments than from disked treatments during a field rainfall simulation experiment, with generally higher NH_4–N losses from compost, manure, and fertilizer treatments than from control treatments. Conversely, in a 3-yr monitoring study in two watersheds in Maryland, Angle et al. (1984) observed significantly greater NH_4–N losses from a conventional-tilled watershed than from a no-till watershed.

Table 4. Flow-weighted mean concentrations and loads of NH_4–N, NO_3–N, and total nitrogen (TN) during 30 min of runoff.†

	NH_4–N		NH_4–N load		NO_3–N		NO_3–N load		TN		TN load	
Parameter	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
	— mg L^{-1} —		— g ha^{-1} —		— mg L^{-1} —		— g ha^{-1} —		— mg L^{-1} —		— g ha^{-1} —	
Fixed effects												
Tillage treatment												
Cultivator	0.28a	0.14	43.4ab	22.3	0.31ab	0.09	55.3a	16.6	2.20ab	0.55	347.0a	88.8
Double disk	0.27a	0.07	61.5a	18.4	0.98a	0.50	250.3a	131.2	2.65a	0.93	607.7a	250.2
Moldboard plow	0.08a	0.00	8.8b	0.8	0.05b	0.01	5.8b	1.0	0.84b	0.11	93.6b	13.6
No incorporation	0.29a	0.08	78.2a	30.9	0.30ab	0.10	65.0a	18.4	1.75ab	0.35	456.2a	129.7
Manure treatment												
Control	0.08n	0.00	16.5n	2.2	0.08n	0.02	21.5n	5.8	1.02n	0.09	200.5	30.2
Manure	0.40m	0.09	83.6m	21.4	0.80m	0.28	181.9m	74.6	2.82m	0.60	574.2	158.5
Year												
2000	0.27r	0.13	49.3r	22.6	0.70r	0.43	180.0r	112.9	2.66r	0.83	543.3	217.5
2001	0.19r	0.05	36.7r	10.2	0.29r	0.08	50.6r	12.8	2.07r	0.30	356.8	59.9
2002	0.23r	0.05	57.9r	21.4	0.29r	0.09	67.9r	21.3	0.93s	0.24	240.5	89.8
					F value							
Effects												
Tillage	NS		**		*		**		*		***	
Manure	***		***		**		**		***		**	
Tillage × manure	NS		NS		NS		NS		NS		NS	
Year	NS		NS		NS		NS		***		**	
Tillage × year	NS		NS		NS		NS		NS		NS	
Manure × year	NS		NS		NS		NS		NS		*	
Tillage × manure × year	NS		NS		NS		NS		NS		NS	

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Mean values for each fixed effect in each column followed by the same letter are not significantly different ($P < 0.05$). SE = standard error of the mean.

Nitrate N

The NO_3–N FWMCs were significantly affected by tillage and manure (Table 4). Nitrate N FWMCs were highest from the DD treatments and were significantly lower from the MP treatments. Manure treatments had NO_3–N FWMCs that were significantly greater than the control treatments. None of the NO_3–N FWMCs exceeded the drinking water guideline of 10 mg L^{-1} in the surface runoff.

As in our study, Eghball and Gilley (1999) reported greater NO_3–N concentrations from disked plots compared to no-till plots, which they attributed to high concentrations of NO_3–N in the surface soil and the disturbance from tillage. Eghball and Gilley (1999) also reported much higher values for NO_3–N concentrations in runoff from manured plots (average: 22.4–26.6 mg L^{-1}); however, the source water used in their study averaged 21 to 23 mg NO_3–N L^{-1}. Nitrate N FWMCs in our study were similar to those reported in a laboratory rainfall simulation of well-mixed, manured soils from Alberta (Wright et al., 2003).

The DD treatments also had the highest mass losses of NO_3–N, followed by the NI, CU, and MP treatments (Table 4). The NO_3–N losses from the MP treatments were significantly lower than the other treatments. Nitrate N losses were significantly greater from the manure treatments than from the control treatments.

Zhao et al. (2001) also reported lower NO_3–N losses in surface runoff from MPM treatments compared with other tillage methods (ridge-tillage); however, losses of NO_3–N in surface runoff accounted for only a small portion of total NO_3–N losses. No differences in NO_3–N losses were detected between disked and no-till treatments in an initial dry run, but greater losses were observed from disked plots than no-till plots under saturated conditions (Eghball and Gilley, 1999).

Total Nitrogen

Total N FWMCs were greatest from the DD treatments, followed by the CU, NI, and MP treatments; however, differences were only significant for the DD and MP treatments (Table 4). Total N FWMCs in runoff were significantly greater in 2000 and 2001 than in 2002.

Total N losses were significantly lower from the MP treatments than from the CU, DD, and NI treatments (Table 4) and were greatest from the DD treatments. Manure treatments had significantly greater TN losses than the control treatments in 2002 (data not shown). Eghball and Gilley (1999) reported no significant differences in TN losses between disked and no-till treatments from an initial dry run; however, losses were significantly higher from disked plots in a second run on saturated plots.

Phosphorus and Nitrogen Leaching

Nearly all simulation tests produced subsurface leachate volumes that exceeded the capacity of the lysimeters, except for a few occasions on NIC plots where runoff occurred very rapidly and no sample was collected. Tillage had no significant effect on subsurface DRP or TP concentrations at a depth of 60 cm (Table 5). The DRP concentrations were 21 to 30% of the TP concentrations for the tillage treatments. Manure treatments had significantly higher subsurface DRP and TP concentrations than the control treatments (Table 5). The mean concentration of TP as DRP was about 6% for the control treatments and 37% for the manure treatments. Subsurface TP concentrations were signifi-

Table 5. Mean concentration of dissolved reactive phosphorus (DRP), total phosphorus (TP), NH_4–N, NO_3–N, and total nitrogen (TN) in lysimeters during 30 min of runoff.†

	DRP		TP		NH_4–N		NO_3–N		TN	
Parameter	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	mg L^{-1}									
Fixed effects										
Tillage treatment										
Cultivator	1.70a	0.54	5.63a	0.83	0.54b	0.08	18.45	1.77	31.53	4.71
Double disk	1.63a	0.47	5.91a	0.83	0.84ab	0.15	19.33	1.98	37.02	5.31
Moldboard plow	1.25a	0.45	5.95a	0.93	1.71a	0.57	24.74	3.64	46.81	6.20
No incorporation	1.93a	0.40	8.20a	1.32	0.97ab	0.31	10.02	2.10	15.63	2.67
Manure treatment										
Control	0.31n	0.03	4.86n	0.68	0.46n	0.04	16.48	1.47	26.16n	3.22
Manure	2.91m	0.31	7.91m	0.64	1.67m	0.35	20.85	2.58	40.91m	4.36
Year										
2001	1.40r	0.31	4.69s	0.43	0.98r	0.33	20.66	0.68	44.86	3.63
2002	1.88r	0.34	8.31r	0.82	1.06r	0.19	16.50	2.69	22.20	3.33
	F value									
Effects										
Tillage	NS		NS		*		***		***	
Manure	***		**		***		*		***	
Tillage × manure	NS		NS		NS		NS		NS	
Year	NS		***		NS		NS		***	
Tillage × year	NS		NS		NS		**		*	
Manure × year	NS		NS		NS		*		NS	
Tillage × manure × year	NS		NS		NS		NS		NS	

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Mean values for each fixed effect in each column followed by the same letter are not significantly different ($P < 0.05$). SE = standard error of the mean.

cantly higher in 2002 than in 2001 and tended to be greater from NI plots. This finding suggests that leaching of P may increase with time after repeated manure applications and that undisturbed soil macropores may allow greater leaching of phosphorus, especially particulate forms (Beauchemin et al., 1998). Soil moisture conditions were also much wetter in 2002 than in 2001 due to above normal precipitation in 2002.

McDowell and Sharpley (2001) also reported elevated DRP and TP concentrations up to 1 yr after manure application. The proportion of TP as DRP was much greater than in our study, ranging from 87 to 88% before manure application, and from 80 to 86% 1 yr after manure was applied. The concentrations of phosphorus and the proportions of phosphorus as particulate in our study were much higher than in other studies (Turner and Haygarth, 2000; McDowell and Sharpley, 2001). This was likely due to differences in collection methods, as zero-tension lysimeters allow for collection of particulate matter (Thompson and Scharf, 1994), and due to the formation of macropores in clay-rich soils (Beauchemin et al., 1998).

Regardless of manure application, NH_4–N and NO_3–N concentrations were greatest in subsurface runoff from MP treatments. Manure treatments also had significantly greater subsurface NH_4–N and NO_3–N concentrations than control treatments. The differences were only significant for NO_3–N concentrations in 2002, a wet year.

The CU, DD, and MP treatments had significantly higher subsurface TN concentrations in 2001 than the NI treatments (Fig. 7). In 2002, the MP treatments had significantly greater TN concentrations than the other tillage treatments. Manure treatments had significantly higher subsurface TN concentrations than the control treatments (Table 5).

In our study, subsurface N concentrations were greatest from the MP treatments, regardless of manure application. The effect of tillage has been mixed, however, in other studies. For example, Zhao et al. (2001) monitored NH_4–N and NO_3–N losses in subsurface tile drainage during simulated rainfall on moldboard plow and ridge tillage systems and reported no differences in NH_4–N and NO_3–N concentrations from the different tillage treatments. Gupta et al. (2004) also studied mineral N (NH_4–N and NO_3–N) leaching in loess soils from Wisconsin under chisel plow and no-till systems with and without application of liquid dairy manure. The concentration of mineral N in leachate was significantly higher for the chisel plow with fall manure application treatment compared to all other treatments. Mineral N concentrations of leachate were significantly higher with manure application than from no-manure treatments. We observed similar mineral N concentrations in subsurface flow as Gupta et al. (2004), with generally greater mineral N leaching from manure than control treatments; however, results cannot be compared directly since soils, manure characteristics, and experimental methods were substantially different in the two studies.

CONCLUSIONS

Incorporation of crop residues and manure generally reduced runoff volumes and reduced losses of DRP, TP, NH_4–N, NO_3–N, and TN compared to NI treatments; however, significant differences in nutrient losses were only detected between the MP and NI treatments. Sediment losses among our tillage treatments were not significantly different due to differences in runoff volumes that offset differences in sediment concentrations. Manure treatments generally had lower runoff volumes, lower sediment losses, and higher DRP, TP, NH_4–N, NO_3–N, and TN losses than the control treatments.

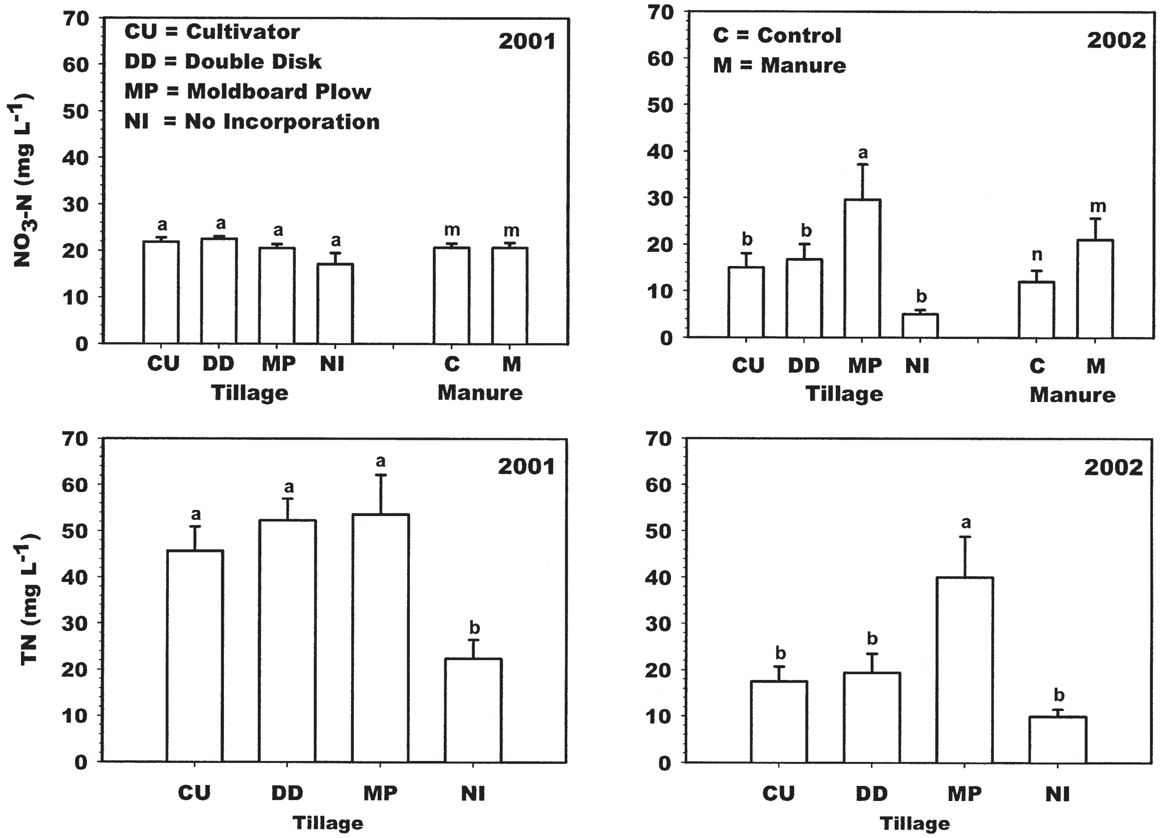

Fig. 7. Mean concentration of nitrate N (NO_3–N) and total nitrogen (TN) in lysimeters in 2001 and 2002. Mean values for each parameter followed by the same letter are not significantly different ($P < 0.05$). The error bars represent the standard error of the mean.

Tillage had no significant effect on subsurface DRP or TP concentrations, but manure treatments had significantly higher subsurface DRP and TP concentrations than control treatments. Tillage effects on subsurface NH_4–N, NO_3–N, and TN concentrations were not consistent among tillage treatments and between years, but MP treatments had significantly higher NO_3–N and TN concentrations than the other tillage treatments in 2002. Manure treatments generally contained significantly higher subsurface NH_4–N, NO_3–N, and TN concentrations than the control treatments, except for subsurface NO_3–N concentration in 2001.

Cultivated soils are susceptible to sediment and nutrient losses following land application of livestock manure. Based on our study, partial incorporation of manure with a cultivator or double disk was the most favorable option for minimization of combined surface and subsurface nutrient losses during rainfall simulations immediately after annual applications of beef cattle manure in a silage barley cropping system.

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