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Tillage and Nutrient Source Effects on Water Quality and Corn Grain Yield from a Flat Landscape

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ABSTRACT

Beneficial effects of leaving residue at the soil surface are well documented for steep lands, but not for flat lands that are drained with surface inlets and tile lines. This study quantified the effects of tillage and nutrient source on tile line and surface inlet water quality under continuous corn (*Zea mays* L.) from relatively flat lands (<3%). Tillage treatments were either fall chisel or moldboard plow. Nutrient sources were either fall injected liquid hog manure or spring incorporated urea. The experiment was on a Webster–Canisteo clay loam (Typic Endoaquolls) at Lamberton, MN. Surface inlet runoff was analyzed for flow, total solids, NO_3–N, NH_4–N, dissolved P, and total P. Tile line effluent was analyzed for flow, NO_3–N, and NH_4–N. In four years of rainstorm and snowmelt events there were few significant differences ($p < 0.10$) in water quality of surface inlet or tile drainage between treatments. Residue cover minimally reduced soil erosion during both snowmelt and rainfall runoff events. There was a slight reduction in mineral N losses via surface inlets from manure treatments. There was also a slight decrease ($p = 0.025$) in corn grain yield from chisel-plow plots (9.7 Mg ha^{-1}) compared with moldboard-plow plots (10.1 Mg ha^{-1}). Chisel plowing (approximately 30% residue cover) alone is not sufficient to reduce nonpoint source sediment pollution from these poorly drained flat lands to the extent (40% reduction) desired by regulatory agencies.

Agricultural management practices in the U.S. Midwest have been blamed for a general decline in water quality (Burkart and Kolpin, 1993; Meador and Goldstein, 2003) and specifically for the development of the hypoxic zone in the Gulf of Mexico (Rabalais et al., 1999; Turner and Rabalais, 1994). Current best management practices have been developed to maximize crop production while minimizing pollutant losses. These practices include rate, timing, and type of nutrient applications and presence of some residue cover after tillage. While the beneficial outcomes of these practices on sloping landscapes are well documented, the same cannot be said for relatively flat landscapes drained with tile lines and surface inlets, where the physics of water flow and pollutant transport are very different.

It has long been known that tile line effluent is a significant source of NO_3–N loading to surface waters. Since the 1960s studies have shown nitrate concentrations commonly exceed the 10 mg L^{-1} NO_3–N federal drinking water standard and are often related to fertilizer N addition (Gast et al., 1978; Baker and Johnson, 1981; Jaynes et al., 2001). Differences in climate, soil properties, and management affect the variability in pollutant concentrations and loadings from drainage effluent (Baker et al., 1975; Sims et al., 1998; Hanway and Laflen, 1974; Kladivko et al., 1991; Randall et al., 2000). It has also long been known that surface soil cover can reduce soil erosion and particulate-associated nonpoint-source pollution. The beneficial effects of 15 to 30% crop residue cover have been shown to reduce soil erosion by as much as 50 to 90% depending on precipitation, slope, and soil properties (Wischmeier, 1973; Ketcheson and Stonehouse, 1983).

Tillage studies in northern latitudes (>40°) have shown chisel plow–based tillage practices (approximately 30% residue cover) generally reduce yield in a continuous corn cropping system due to residue buildup that keeps soils from warming and drying in the spring. Yield reductions of 502 to 565 kg ha^{-1} were observed in multiyear studies on poorly drained soils under chisel plow compared with moldboard plow tillage systems. However, yield was greater for a chisel plow–based system on a well-drained soil (Randall et al., 1996).

In one of the few studies on flat landscapes, Ginting et al. (2000) showed that storm events large enough to cause ponding at the surface inlet allowed sufficient time for entrained particles to settle thus limiting sediment and sorbed P transport to surface waters. However, prolonged ponding caused P desorption from soil colloids resulting in higher concentrations of soluble P leaving fields. In a simulated 10-yr return interval rainfall, Ginting et al. (2003) reported relatively minor losses of sediment and both forms of P from flat landscapes regardless of surface residue cover.

The chemical forms of applied nutrients, the cropping and tillage management systems, and the climatic factors all interact to affect off-site delivery of pollutants. For instance, there is a concern that using manure as an N source adds P in excess of crop needs thus becoming more of a problem in surface inlet losses (Sims et al., 1998). Soluble nutrient availability to plants and in turn off-site transport also depends on the extent of manure or fertilizer mixing with the soil. Therefore, tillage and nutrient interactions are important in understanding nutrient losses from both surface inlet flow and tile drainage.

These factors illustrate the complexity of interactions that control pollutant losses via surface inlet flow and tile drainage on both steep and relatively flat landscapes. Since much of the Midwest is relatively flat, research is needed in such landscapes to determine if the conclu-

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

sions drawn from studies on steeper slopes hold in flat landscapes as well. An area that is relatively flat in the upper Midwest is the Minnesota River basin. In this 3.86-million-ha watershed, 33 and 71% of the area is less than 2 and 6% slope, respectively (University of Minnesota, 2001). However, the Minnesota River is a major carrier of nonpoint-source pollution (sediment, N and P) from southwestern and south-central Minnesota to the Mississippi River. United States Geological Survey monitoring studies have shown that the annual suspended sediment load for the Minnesota River at Mankato, MN, has varied from 0.18 to 3.27 million Mg per year from 1968 to 1992 (Payne, 1994). Therefore, there is an increased interest in finding management practices that can reduce nonpoint source sediment pollution to the Minnesota River without significantly affecting crop yield.

The Minnesota Pollution Control Agency has estimated that a 40% reduction in sediment load is necessary to achieve federally mandated water quality goals in the lower Minnesota River. The agency has recommended the use of conservation tillage practices such as chisel plowing that leave about 30% residue cover at the soil surface (Minnesota River Assessment Project, 1994). This study was designed to quantify the effect of a conservation tillage practice (chisel plowing) vs. moldboard plowing with the addition of manure or commercial fertilizer (urea and triple superphosphate). The study focused on water, sediment, mineral N, and P losses in surface inlet flow and in tile drainage, and on corn yield from a flat landscape (<3% slope) in the Minnesota River basin. Soil and crop management in this study was intended to simulate practices of local producers.

MATERIALS AND METHODS

Plots

The experiment consisted of 16 plots, each 9.1 m wide and 18.2 m long (Fig. 1). The plots, constructed in 1994, were isolated to a depth of 1.8 m by trenching around plot borders to install a 12-mil plastic sheet (Zhao et al., 2001b). Perforated plastic tile lines, 10 cm in diameter, installed at a 1-m depth and 1.5 m away from the center boundary along the width of the plot, simulated a tile line spacing of 33 m. Tile lines were then connected to nonperforated PVC pipes that emptied into a monitoring well. Surface inlets connected to nonperforated PVC pipes were located at the lowest surface topographic position (1.5 m from the two boundaries near the monitoring well) in each plot and drained into the monitoring well. Surface inlet and tile flows were kept separate in measurement of flow, collection of samples, and laboratory analysis. Other details of the plot layout are given in Zhao et al. (2001b).

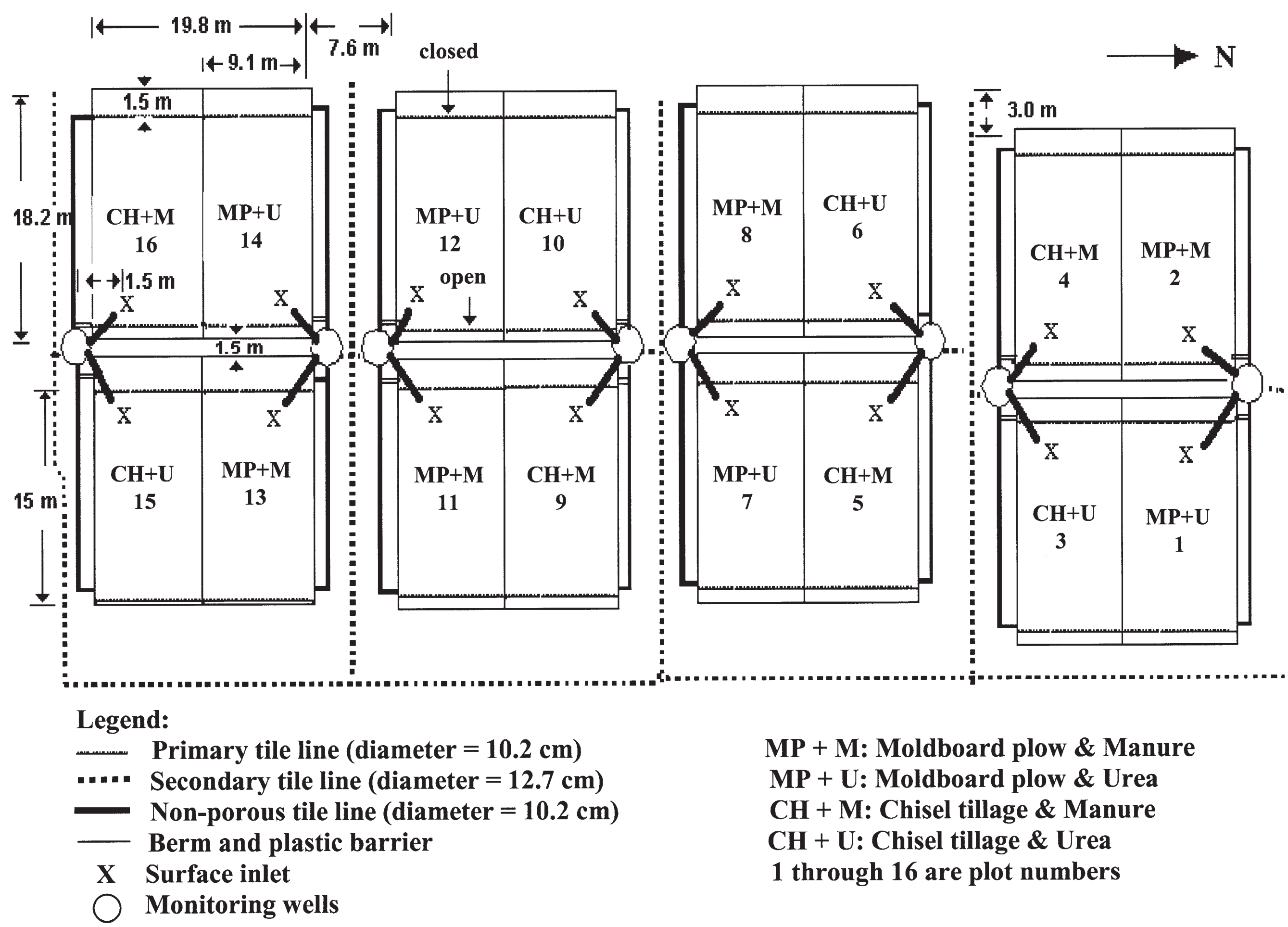

Fig. 1. Plot layout and treatments.

Treatments

The experiment was a randomized split-plot design with four replications. The crop sequence was continuous corn. Main plots were tillage treatment and the sub plots were nutrient source treatment. Corn stalks were chopped with a flail chopper before fall tillage. Tillage treatments were (i) fall moldboard plowing followed by spring field cultivation and harrowing and (ii) fall chisel plowing with twisted shanks preceded by discs followed by spring field cultivation and harrowing. Depth of cultivation was between 30 and 38 cm for the moldboard plow and 15 and 22 cm for the chisel plow. Spring cultivation was between a 5- and 15-cm depth. Nutrient source treatments were (i) fall-applied (injected) liquid hog manure after primary tillage and (ii) spring-applied urea and triple superphosphate before secondary tillage. The source of manure was from a swine finishing operation. Application rates of manure, urea, and triple superphosphate (Table 1) were based on University of Minnesota recommendations for a corn grain yield goal of between 9.5 and 10.7 Mg ha^{-1} (Rehm et al., 1994). This yield goal required 168 kg ha^{-1} available N. For both nutrient source treatments, N applications were adjusted for residual soil N. For the manure treatments, it was assumed that plant-available nitrogen was equal to all mineral N (NH_4–N plus NO_3–N) plus 30% of the organic N in the year of its application plus 15 and 7.5% of the organic N applied in Years 1 and 2 previous to the manure application, respectively (MidWest Plan Service, 1993). Fall application of liquid hog manure was injected with sweeps at rates of 29 000, 32 700, 45 800, and 36 400 L ha^{-1} in 1999, 2000, 2001, and 2002, respectively. These rates were based on the analysis of manure samples taken from the lagoon several weeks before manure application. A total of 10 700 kg ha^{-1} of solids was added to the plots in the course of 4 yr of manure application. Application of triple superphosphate in urea plots varied over time depending on the fall soil test values. No triple superphosphate was applied to the manure plots.

Before this experiment, the plots were under different tillage (moldboard plow and ridge tillage) and nutrient source (solid beef manure and urea) treatments for 4 yr (Zhao et al., 2001b). In this experiment, previously fall moldboard-plow plots remained the same and the ridge till plots were fall chisel plowed. Similarly, urea plots were again treated with urea and solid beef manure plots were treated with injected hog manure. The previous experiment also had a continuous corn cropping system but soybean [*Glycine max* (L.) Merr.] was grown the year before this experiment.

Instrumentation and Data Collection

The instrumentation was similar to that of Zhao et al. (2001a) with the exception of sump pumps installed to remove excess drainage water, and installation of Isco (Lincoln, NE) 3700 water samplers housed in weather-resistant plywood shelters. Surface inlet flow was measured with 3.6-L-capacity tipping buckets while tile flow was measured with 0.36-L tipping buckets. Inlet flow rates greater than 3.6 L min^{-1} initiated a signal pulse to the water sampler that drew a 100-mL sample volume from the surface inlet drain pipe. The surface inlet flow samplers were programmed to collect composite samples at 10- and 20-min periods for rain and snowmelt events, respectively. The samplers each contained 24, 1-L bottles, and were programmed to composite flow samples for 2 h per bottle during snowmelt runoff events and for 1 h per bottle for rain events. Tile line flow samples were collected by hand daily, Monday through Friday. Runoff and drainage data continuously recorded on a data logger were used to calculate flow rate, water volume, and pollutant load.

Surface inlet water samples were analyzed for sediment (TS) by drying and weighing, total phosphorus (TP) via perchloric acid digestion (USEPA, 1981), soluble P via dissolved molybdate reactive method (DMRP) (Wendt and Corey, 1980), and nitrate and ammonium concentrations conductimetrically (Carlson, 1978, 1986). Tile line water samples were only analyzed for mineral N (NH_4–N and NO_3–N). Manure samples were analyzed for total N using a modification of the Kjeldahl method (Bremner, 1986), where a heating block was used in lieu of a distillation apparatus. Total P in manure was measured via perchloric acid digestion (USEPA, 1981), whereas mineral N was determined conductimetrically (Carlson, 1978, 1986) after 2 *M* KCl extraction (Keeney and Nelson, 1982).

Soil cores (0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm depth) and manure samples were collected each fall before tillage and analyzed for nutrient management planning purposes. Soil mineral N was determined conductimetrically (Carlson, 1978, 1986) similar to analysis for manure samples. Soil P was determined using the Olsen P method (Olsen and Sommers, 1982). Soil pH was measured using a 1:1 soil to water mixture (McClean, 1986). In fall 2001, one surface (0- to 15-cm depth) bulk density measurement was made per plot at random locations using the excavation method (Blake and Hartge, 1986). Crop residue cover was measured after fall tillage and after spring planting using the line transect method described by Morrison et al. (1993). The plot slopes were measured in 2003 with a clinometer.

Site Characteristics

The study was conducted at the Southwest Research and Outreach Center near Lamberton, MN (44.2° N, 95.3° W). The soils at the experiment site were Webster–Canisteo clay loams (fine-loamy, mixed, superactive, mesic Typic Endoaquolls and fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls, respectively). Both are highly productive but poorly drained soils, developed in depressions from calcareous glacial till (Table 2). Surface slopes ranged from 1.5 to 5% with an average of 3% for the 16 plots. The surface slope of mold-

Table 1. Estimate of available N and total P additions from fall-applied liquid hog manure and spring-applied inorganic fertilizer, 1999–2002. Available N was estimated as mineral N (NH_4–N plus NO_3–N) plus 30% of the organic N in the year of its application plus 15 and 7.5% of the organic N applied in Years 1 and 2 previous to the manure application (MidWest Plan Service, 1993).

	Crop year							
	1999†		2000‡		2001‡		Fall 2002‡	
Nutrient source	Available N	Total P	Available N	Total P	Available N	Total P	Available N	Total P
	kg ha^{-1}							
Manure	123	64	41	11	167	72	56	23
Urea	134	34	146	25	161	0	195	20

† Both manure and urea were applied in spring of 1999.
‡ Manure applied in fall of previous year and urea applied in spring of same year.

Table 2. Characteristics of selected soil horizons from a soil core collected at the north edge of the experimental plots.

Horizon	Lower depth	Carbon Total	Carbon Inorganic	Carbon Total organic	Sand	Silt	Clay
	cm	%					
A	27	2.66	0.00	2.66	34	31	35
Bk	85	2.40	0.22	2.18	30	34	36
C2	108	1.64	1.23	0.41	46	21	33

board-plow plots (3.75%) was significantly ($p = 0.003$) greater than chisel-plow plots (2.25%). Average surface bulk density for the moldboard plow treatments was 1.32 Mg m^{-3} compared with 1.28 Mg m^{-3} for the chisel plow treatments and was not statistically different by treatment or interactions. Assuming a particle density of 2.65 Mg m^{-3}, these bulk densities were equivalent to porosity of 50 and 52% for the moldboard plow and the chisel plow treatments, respectively.

Precipitation

Water quality measurements covered a period from 5 May 1999 after snowmelt through 22 August 2002. Total precipitation from 1 May 1999 through 22 Aug. 2002 during the study period was 2370 mm. The 4-yr annual average of 660 mm yr^{-1} was close to the 30-yr annual average of 670 mm yr^{-1}. However, 1999 and 2002 were dry years that were offset by a very wet year in 2001 (Table 3). During the course of the study, more precipitation events induced tile line flow than surface inlet flow. This was due to interactions between antecedent moisture condition and precipitation intensity that indicated more precipitation events occurred on dry soil surfaces, or fell at rates less than the infiltration capacity of the soil.

The largest snowmelt event occurred in late March and early April 2001 when 20.2 cm of water stored in the snow pack between 15 Oct. 2000 and 15 Mar. 2001 melted. The largest rain event of the experiment occurred 21–25 July 2001 when 162 mm of rain fell. The highest monthly precipitation occurred in April 2001 (212 mm) from a series of rain events 21–30 April. In a single rain event on 23 Apr. 2001 a total of 89 mm of water fell.

Most of the runoff events in 1999, 2000, and 2002 were relatively small (a few tips of the tipping buckets per event). However, over the duration of the experiment, 10 rain events greater than 18 mm induced surface inlet flow large enough to trigger sample collection by the Isco samplers. The average depth of precipitation for these 10 flow-inducing events was 57 mm.

Table 3. Precipitation measured at the Southwest Research and Outreach Center at Lamberton, MN.

Period	Annual precipitation	Number of events sampled: Tile flow	Number of events sampled: Surface inlet flow
	mm		
1999†	520 (380)	4	3
2000	680	10	7
2001	860	7	5
2002†	580 (460)	9	9
Total during water quality sampling period	2370	30	24
Average annual	660		
30-Year average annual	670		

† Numbers in parentheses refer to the amount of precipitation that fell during the duration of water quality sampling. 1999 includes precipitation events between 5 May and 31 December. 2002 includes precipitation events between 1 January and 22 August.

Statistical Analysis

Analysis of variance (ANOVA) of tillage, nutrient source, and their interactions on water quality parameters, crop yield, residue cover, and surface slope was performed using the MINITAB13 (Ryan et al., 2000) statistical package. Statistical significance was checked at the 0.1 probability level. Soil depth was used as a split assuming randomization in the analysis of soil N by depth.

RESULTS AND DISCUSSION

Residue Cover

The 4-yr average percentage residue cover after fall primary tillage was significantly ($p < 0.001$) less on moldboard-plow plots (11%) than chisel-plow plots (45%). This difference in residue cover is due to the dramatically different level of soil disturbance induced by the two tillage implements. A moldboard plow inverts the soil thus burying the surface residue whereas a chisel plow lifts and shatters the soil thus leaving some residue at the soil surface. There was no significant difference in residue cover due to nutrient source treatments. In all years, the secondary cultivation and harrowing for seedbed preparation further reduced the percentage residue cover. The annual average cover after secondary tillage decreased to 7 and 23% in moldboard and chisel plots, respectively.

Soil Nitrogen

There were no significant differences in soil NO_3 or soil NH_4 at any depth due to tillage treatments in any year of the study; hence data by tillage are not presented. However, there was a significant decrease ($p < 0.10$) in soil NO_3 and soil NH_4 with depth in most years (Table 4). This is expected because manure and urea fertilizer were applied in the top part of the soil profile. The only exception to this trend occurred in 2002 where there was no significant difference with depth for soil NH_4.

In general, soil NO_3 levels were higher from the urea than the manure treatments. This was possibly due to slow release of manure organic N that is efficiently taken up by the crop thus leaving less NO_3–N in the soil after the fall harvest when soil tests were conducted.

Although under application of manure NO_3–N in some crop years, 2000 and 2002, corresponds to statistically lower soil test NO_3–N levels in manure plots it does not always appear to be the main factor causing lower soil NO_3–N levels in manure plots. This is evident by noting that in the 2001 crop year NO_3–N application rates for manure (167 kg ha^{-1}) and urea (161 kg ha^{-1}) were similar, but soil test NO_3–N levels in manure plots were still much less than urea plots (0.9 and 3.0 mg kg^{-1} for manure and urea, respectively).

Table 4. Mineral N distribution with soil depth for the manure and the urea treatments at four different times during the study period.

Nutrient source	Depth	April 1999		October 1999		October 2000		October 2001		October 2002	
		NH_4	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4†	NO_3
	cm	mg kg^{-1}									
Manure	0–30	2.9	3.6	2.9	6.9	5.0	6.0	4.4	1.6	5.4	5.4
	30–60	1.4	4.3	1.8	0.9	2.1	1.7	2.1	0.1	2.0	4.1
	60–90	0.9	3.5	1.6	1.6	missing	missing	1.3	1.0	1.9	3.6
	average	1.7	3.8‡	2.1	3.1	3.5	2.5‡	2.6	0.9‡	3.1‡	4.4‡
Urea	0–30	2.8	3.3	3.7	7.2	5.5	7.6	4.8	4.6	6.5	8.8
	30–60	1.1	3.6	1.9	1.8	2.1	4.7	2.2	1.1	2.5	9.5
	60–90	1.0	2.6	1.4	1.7	missing	missing	1.2	3.2	2.0	6.2
	average	1.6	3.2‡	2.3	3.6	3.8	4.1‡	2.7	3.0‡	3.7‡	8.2‡

† Except soil NH_4 in 2002, all concentrations of soil NO_3 and soil NH_4 were significantly different ($p < 0.10$) by depth for nutrient source treatment and are not footnoted.

‡ Average concentrations were significantly different ($p < 0.10$) by nutrient source treatment, but not by tillage treatment. No significant tillage effects were observed for any year at any depth.

Soil Phosphorus

There was no statistical difference in soil P level after fall harvest for 1999 through 2002 by tillage treatment but there was a significantly ($p < 0.005$) higher soil P level in the plots treated with manure than in plots treated with triple superphosphate (Table 5). The 4-yr average soil P level was 24 and 12 mg kg^{-1} for manure- and urea-treated plots, respectively. Soil P levels did not appear to track P addition from either manure or triple superphosphate. The difficulty of applying the recommended amount of manure as a fertilizer source was echoed by Randall et al. (2000). It is likely that soil P levels in manure plots would have been even higher if manure application in 2000 and 2002 had been sufficient to meet crop N needs.

Water Losses

In general, there was a large variation in surface inlet and tile drain flow (Table 6) among plots due to inherent field variability and climate variability between years. Because of the natural variation in the field plots, the differences in water losses between tillage and nutrient source treatments were not significantly different with the exception of tile flows in one year.

In 1999 there was a significant difference ($p = 0.075$) by nutrient source treatment in tile flow with urea-treated plots losing more water (3.4 cm) than manure-treated plots (2.9 cm) (Table 6). In 2001 there was a significant difference ($p = 0.10$) by tillage treatment for tile flow with moldboard-plow plots draining more water (39.2 cm) than chisel plots (23.9 cm). The high annual loss of water (via a combination of surface inlet and tile flow) in 2001 was due to the unusually heavy snow pack that developed during the winter of 2000–2001. In 2001, 83% of the annual surface inlet flow was due to the snowmelt event, while 48% of the annual tile flow resulted from snowmelt. The lack of differences in tile flow between nutrient source treatments over four years even after eight years of cumulative manure application from two consecutive studies suggests a minor influence of manure on soil structure and in turn on water infiltration in these high clay soils. This is consistent with observations of Zhao (1998) who also found no difference in total tile drainage from the same experimental plots after 4 yr of solid beef manure application. This could possibly be because this soil is high in native organic matter and is already strongly aggregated. Mbagwu (1989) also showed minimal improvement in soil physical condition of clay soils from manure application.

The 20% of average annual precipitation lost from the plots as a combination of surface inlet flow and tile flow (Table 6) falls between 22% annual combined surface inlet and tile losses observed by Zhao (1998) for 1996 on the same plots and 14% runoff for the Cottonwood watershed, in which the plots are located, based on river gauge data (Baker et al., 1979). In most years, tile flow exceeded surface inlet flow in spite of high soil clay content. This difference was due to low intensity storms, gentle slopes, strong soil aggregation, and macropore flow, as evidenced by turbid tile line flows during some events. The exception to this trend was 2002, when surface inlet flow exceeded tile flow. This may have been due to the high intensity storm events that occurred June through August that year. For the duration of the study water loss was split about 25 and 75% between surface inlet flow and tile drainage. This suggests that most precipitation events were low intensity storms and likely did not exceed the infiltration capacity of the soil.

Table 5. Temporal variation in soil pH and soil P test values (0- to 15-cm depth) for two tillage and two nutrient source treatments.

Treatment	Spring 1999		Fall 1999		Fall 2000		Fall 2001		Fall 2002		4-yr average
	pH	Olsen P	pH	Olsen P	pH	Olsen P	pH	Olsen P	pH	Olsen P	Olsen P
		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}	
Moldboard plow											
Manure	7.8	17.3	7.7	26.0	7.9	29.0	7.7	21.0	missing	18.3	22.3
Urea	7.7	7.1	7.7	8.4	7.9	18.4	7.7	9.1	missing	20.0	12.6
Chisel plow											
Manure	7.7	20.5	7.6	26.3	7.7	36.5	7.8	22.0	missing	22.0	25.5
Urea	7.6	5.8	7.6	10.8	7.8	20.3	7.7	7.5	missing	13.3	11.5

Table 6. Annual percentage of rain and snow water equivalent lost via surface inlet flow and tile flow.

Year	Precipitation	16-plot average		Annual % loss, surface inlet + tile
		Surface inlet	Tile	
	mm	cm		%
1999†	378	0.2	3.2 (N)‡	9
2000	676	3.0	4.0	10
2001§	857	7.8	31.5 (T)‡	46
2002†	462	4.0	2.7	15
Average	593	3.8	10.4	20

† 1999 includes precipitation events between 5 May and 31 December. 2002 includes precipitation events between 1 January and 22 August.
‡ N, nutrient source effect only; T, tillage effect only.
§ Blocks 1 and 4 were removed for analysis of 2001 flow data due to overflow additions from adjacent fields.

Water Quality—Storm Event Basis

Tracking sediment and nutrient pollutant losses on a storm event basis for a single year revealed important physical, phenological, and climate processes that interacted to affect annual pollutant loading of surface waters. Four major rain events occurred in 2000 on 26 February (31 mm), 18 May (56 mm), 1 July (32 mm), and 9 August (36 mm) (Table 7). These events roughly corresponded to slightly thawed soil conditions, bare soil right after planting, medium canopy cover, and full canopy cover, respectively. Maximum rainfall intensity on 1 July and 9 August was less than 25 mm h^{-1}. Rain intensities were not recorded on 26 February and 18 May. However, average rain intensity on 18 May at a station about 16 km (10 mi) from the experimental site was 3.8 mm h^{-1} for a period of 23 h.

Although the rain event on 26 February was a major event, it resulted in little runoff because it fell at low intensity, and because the soil was already partially thawed due to unusually warm air temperatures before the rain event. The thawed soil allowed most of the rain to be absorbed. For this event, NO_3–N loss in surface inlet flow was significantly ($p = 0.026$) higher from the urea plots (174 g ha^{-1}) than the manure plots (120 g ha^{-1}). However, the total losses of NO_3–N for this event in terms of annual loads were very small and differences between the treatments were inconsequential (Table 7).

After planting (18 May), there was a continuous decrease in both surface inlet flow and sediment loss for subsequent rain events (Table 7). This was because of the increase in canopy cover that protected soil from detachment and transport as well as due to increase in soil water storage capacity as the crop depleted soil water and provided storage capacity for subsequent rains. For the 18 May storm event, there was a significant tillage by nutrient source interaction effect on tile flow. Chisel plow–urea (2.3 cm) and moldboard plow–manure (1.5 cm) plots had greater drainage than chisel plow–manure (1.1 cm) or moldboard plow–urea (1.0 cm) plots (Table 7). The reason for these interactions on flow is not clear. However, they did not produce any significant difference in pollutant losses.

There were few significant ($p < 0.1$) differences between tillage or nutrient source treatments for both surface inlet flow and tile drainage water quality parameters for other storm events. The absence of significant differences between tillage treatments suggests that (i) residue cover differences between moldboard plow and chisel plow treatments after secondary tillage were too small to have a major influence on soil detachment or on sediment transport, and/or (ii) soil properties (including slope) were such that there was minimal difference in the amount of runoff and drainage between the treatments.

The importance of an individual storm event at an inopportune time on annual pollutant loads is apparent in the contribution from the 18 May 2000 event that occurred shortly after planting when nutrients were most susceptible to leaching and runoff because soil nutrient concentrations were high and surface cover was low. This event resulted in 47 and 38% of the annual surface inlet flow and tile flow, respectively, and accounted for 62, 41, and 44% of the annual surface inlet sediment load, tile NO_3–N, and NH_4–N loads, respectively (Tables 7 and 8).

For steep lands, it has been established that surface residues not only help lower soil detachment but also act as a barrier as sediment is transported down slope with runoff water. This study showed that the effectiveness of residue to act as a barrier to downslope movement of sediment is minimized due to low runoff velocities on relatively flat landscapes (<3% slope) that have high clay content soils.

Loads—Annual Basis

There were several significant differences in pollutant loads leaving the plots during the course of the study (Table 8), but the differences were not consistent for each year due to climate variability and soil heterogeneity. In 1999 there was a significant difference ($p = 0.075$) by nutrient source treatment in tile flow with urea-treated plots losing more water (3.4 cm) than manure-treated plots (2.9 cm). Consequently, there were also

Table 7. Averaged over all treatments, the nutrient and sediment losses via surface inlet and tile drainage for four storm events in 2000.†

Date	Precipitation	Surface inlet flow						Tile drainage		
		Flow	NH_4	NO_3	TP	DMRP	TS	Flow‡	NH_4	NO_3
	mm	cm	g ha^{-1}				kg ha^{-1}	cm	g ha^{-1}	
26 February	31	trace	5.4	147 (N)§	21.8	2.4	11.4	trace	5.4	27.7
18 May	56	1.4	20.6	344.8	446.2	30.2	467.4	1.5 (T × N)¶	44.1	2823
1 July	32	0.7	6.1	509.6	794.0	51.9	164.8	0.3	4.8	231.6
9 August	36	0.1	2.4	48.3	18.7	2.4	20.6	0.1	0.0	104.4

† TP, total phosphorus; DMRP, dissolved molybdate reactive phosphorus; TS, total solids.
‡ Tile flow is cumulative for the duration that soil drained after the rain event.
§ N, nutrient source effect only ($p < 0.10$).
¶ T × N, tillage and nutrient source interaction effects ($p < 0.10$).

Table 8. Averaged over all treatments, the annual nutrient and sediment losses via surface inlet and tile drainage for the duration of the study.†

Year	Surface inlet flow							Tile drainage			
	Flow	NH_4	NO_3	$NO_3 + NH_4$	TP	DMRP	TS	Flow	NH_4	NO_3	$NO_3 + NH_4$
	cm	kg ha^{-1}						cm	kg ha^{-1}		
1999‡	0.2	0.0	0.1	0.1	0.1	0.0	72.7	3.2 (N)§	0.8	0.6 (N)§	1.3 (N)§
2000	3.0	0.0	0.7	0.7	0.9	0.1	752.5	4.0	0.1	6.9	7.0
2001	7.8	1.1	2.0	3.0	4.1	0.3	2845.4	31.5 (T)§	0.7	29.5	30.2
2002‡	4.0	0.1	0.45 (N)§	0.57 (N)§	1.0	0.1	1813.1	2.7	0.0	2.5	2.5

† TP, total phosphorus; DMRP, dissolved molybdate reactive phosphorus; TS, total solids.
‡ 1999 includes precipitation events between 5 May and 31 December. 2002 includes precipitation events between 1 January and 22 August.
§ N, nutrient source effect only; T, tillage effect only.

significant differences in tile drainage losses of NO_3–N ($p = 0.07$) and combined $NO_3 + NH_4$–N ($p = 0.094$) losses by nutrient source treatments. In both cases more N was lost from the urea-treated plots. The NO_3–N and $NO_3 + NH_4$–N losses from urea-treated plots were 0.97 and 1.63 kg ha^{-1} respectively, compared with 0.24 and 1.02 kg ha^{-1}, respectively, from manure-treated plots. The significantly greater losses of mineral N from urea-treated plots in 1999 were partly attributable to flow differences and partly to the susceptibility of inorganic forms of N to leach and the potential of organic forms (manure) of N to decrease N leaching due to slow availability of mineralized N throughout the growing season. High ammonium losses in 1999 and 2001 were most likely due to preferential flow paths providing a direct conduit to the tile lines. Indirect evidence of preferential flow was observed as turbid ("lightly colored") water flowing through the tile lines immediately after heavy rain or rapid snow melt events.

In 2000 and 2001 there were no significant differences by tillage or nutrient source treatment or their interactions on losses or concentrations of pollutants leaving the plots through either surface inlets or tile drainage (Table 8). In 2002 there was a significant difference ($p = 0.054$) by nutrient source treatment for surface losses of NO_3–N and combined $NO_3 + NH_4$–N. In both cases more N was lost from the urea-treated plots. Losses of surface NO_3–N and $NO_3 + NH_4$–N from urea-treated plots were 0.63 and 0.77 kg ha^{-1}, respectively, while losses of surface NO_3–N and $NO_3 + NH_4$–N from manure-treated plots were 0.26 and 0.37 kg ha^{-1}, respectively. The lower losses from manure compared with urea plots suggested slow but continuous release of manure organic N that was taken up by the crop more efficiently. Additionally, the inorganic fertilizer was not incorporated as deeply as the injected liquid hog manure (approximately 15 cm). This may have left it more susceptible to surface transport, especially in a year like 2002, which had more intense storms than previous years as indicated by the greater surface inlet flow losses (Table 8).

During the review of this paper, a concern was raised about the difficulty of comparing N and P losses when N and P application rates are not the same between manure and urea treatments in some years (2000 and 2002). Our results show that even in years when N rates were similar (1999 and 2001), there was no difference in N losses. These two years included the first year (1999) when the carryover effect was minimal and the third year (2001) when there was some carryover effect. Nearly similar N losses between the manure and the urea plots (both when manure N application rate was low and matching) suggest that these high organic matter soils are contributing a substantial amount of N through mineralization. This is further supported by the fact that corn grain yields (discussed later) between manure and urea plots were nearly similar over all years. Higher soil NO_3–N and NH_4–N levels in both nutrient source treatments in 2000 and 2002 (low N manure application years) and lower soil NO_3–N and NH_4–N levels in 2001 (high manure N application year) further suggest that soil mineralization may have been a more important factor in controlling available N and thus N leaching than other factors, including the N application rates. This observation is consistent with the results from another study in Minnesota (Dr. Gary Malzer, personal communication, 2004) where manure application rates varied from 0 to 74 670 L ha^{-1}. Even in the strip that received no manure application, corn grain yield was as high as 11.5 Mg ha^{-1}, which was most likely because a large quantity of N was available from soil mineralization. This strip happened to be on a Webster clay loam soil, the same soil type used this study.

Concentrations—Annual Basis

As with pollutant loads, there was considerable variability in pollutant concentrations leaving the plots in surface inlet flow and tile drainage due to climate and soil heterogeneity (Table 9). However, there were no significant differences due to tillage or nutrient source effects or their interactions for any year in this study. The relatively high N concentration in 1999 through surface inlets was due to spring application of manure and urea at the start of the experiment. In all other years, nutrient sources were fall-applied.

Snowmelt Losses—Annual Basis

The only snowmelt data in this study was for 2001 (Table 10) since the study was initiated after snowmelt runoff in 1999, and there was no snowmelt runoff in 2000 and very slight snowmelt runoff in 2002. Due to sudden warming of a deep snow pack, the snowmelt in 2001 was a major event resulting in about 5.7 cm of surface inlet flow and 15.4 cm of tile drainage. Because of its intensity, there was some contribution of overflow water from an adjacent field to the north (Plots 1 and 2)

Table 9. Averaged over all treatments, the flow-weighted concentration of pollutants in surface inlet flow and tile drainage for the duration of the study.†

Year	Surface inlet flow						Tile drainage		
	NH_4	NO_3	$NO_3 + NH_4$	TP	DMRP	TS	NH_4	NO_3	$NO_3 + NH_4$
	mg L^{-1}								
1999‡	0.2	13.6	13.8	2.7	0.2	2521.0	2.7	2.1	4.7
2000	0.2	2.5	2.7	3.1	0.8	2998.8	0.3	18.6	18.8
2001	0.5	1.5	2.0	3.6	0.2	4829.4	0.5	10.7	10.8
2002‡	0.3	1.4	1.7	2.7	0.1	5994.9	0.1	11.2	11.5

† TP, total phosphorus; DMRP, dissolved molybdate reactive phosphorus; TS, total solids.
‡ 1999 includes precipitation events between 5 May and 31 December. 2002 includes precipitation events between 1 January and 22 August.

and south (Plots 15 and 16). For this reason the north and south blocks were removed from statistical analysis.

For the 2001 snowmelt events there were significant differences in NO_3–N and combined $NO_3 + NH_4$–N ($p = 0.013$ and $p = 0.012$ respectively) losses by tillage treatment in tile flow. Moldboard-plow plots lost more NO_3–N and combined $NO_3 + NH_4$–N (20.04 and 20.10 kg ha^{-1}, respectively) than chisel plots (10.53 and 11.48 kg ha^{-1} for NO_3–N and combined $NO_3 + NH_4$–N, respectively). This increased loss of mineral N from moldboard-plow plots was mainly due to differences in water flow and not due to differences in concentration. Water losses through tile drainage were 10.8 and 19.9 cm for chisel and moldboard plots, respectively. Although infiltration was not measured, this is consistent with the idea that the rougher surface in moldboard-plow plots before spring cultivation would impede surface inlet flow and promote infiltration. Hansen et al. (2000) and Ginting et al. (1998) also showed that spring snowmelt runoff was less from rougher moldboard plow conditions than either chisel plow or ridge till systems.

Dissolved P losses were only 5.8% of the TP losses during the 2001 snowmelt period (Table 10). This is contrary to the findings of Hansen et al. (2000) who found soluble P losses were the dominant form of P loss in snowmelt. Ginting et al. (2000) reported a three-year average soluble P loss of 0.47 kg ha^{-1} compared with 0.1 kg ha^{-1} found in one snowmelt event in this study. This discrepancy is most likely due to rapid melting of an unusually deep snow pack in 2001 thus reducing the interaction time of snowmelt with plant residue and soil particles. These results suggest that soluble P losses during snowmelt depend not only on water losses but also on the rapidity with which the snowmelt occurs. Another reason could be the difference in soil test P levels between various studies.

In 2001, the surface inlet flow from snowmelt represented 73% of the annual surface inlet flow losses (Tables 8 and 10), yet it accounted for only 11% of the annual sediment load. The low sediment loss in spite of high water loss was likely due to the slower velocities of melt water and lack of rain drop impact compared with rain events. Sharratt et al. (2000) measured much higher sediment loss from two recently thawed soils (16 650 kg ha^{-1} average) under simulated rain intensities of 96 mm h^{-1}, thus indicating that high intensity spring rains when soils are slightly thawed could induce large sediment loss.

Corn Yield

There was large variation in corn yield primarily due to climate variation over the four years of the study (Fig. 2). In general, 1999 and 2000 were better growing seasons due to more uniform distribution of moisture throughout the year, while 2001 and 2002 each had wind events that physically damaged the crop late in the growing season.

In 1999, there was a significant difference in corn grain yield ($p = 0.016$) due to tillage treatments. Moldboard-plow plots (11.4 Mg ha^{-1}) outperformed chisel-plow plots (10.7 Mg ha^{-1}) possibly due to the presence of higher surface residues in chisel-plow plots. In 2000 there was a significant difference in yield ($p = 0.002$) due to nutrient source treatments, where plots treated with manure (11.6 Mg ha^{-1}) outperformed plots treated with urea (10.1 Mg ha^{-1}). This is in spite of the fact that manure N application was three times lower than what was applied as urea N. This difference may be attributed to other nutrients present in manure that were not present in inorganic sources of fertilizer, as well as substantial amounts of N made available through soil mineralization. Our observations on corn yield are different than those of Randall et al. (2000) who found the 4-yr average yield for urea plots was 0.7 Mg ha^{-1} greater than plots treated with dairy manure. There were no other significant treatment or interaction effects on corn yield on a yearly basis. However, there was a significant difference ($p = 0.024$) in 4-yr average corn grain yield due to tillage treatment. The moldboard-plow plots (10.1 Mg ha^{-1}) outperformed the chisel-plow plots (9.7 Mg ha^{-1}), which was consistent with findings of Randall et al.

Table 10. Averaged over all treatments, the snowmelt pollutant losses via surface inlet flow and tile drainage in 2001.†

Surface inlet flow							Tile drainage			
Flow	NH_4	NO_3	$NO_3 + NH_4$	TP	DMRP	TS	Flow	NH_4	NO_3	$NO_3 + NH_4$
cm	kg ha^{-1}						cm	kg ha^{-1}		
5.7	0.2	0.8	1.0	1.7	0.1	298.1	15.4	0.5	15.3 (T)‡	15.8 (T)‡

† TP, total phosphorus; DMRP, dissolved molybdate reactive phosphorus; TS, total solids.
‡ N, nutrient source effect only; T, tillage effect only.

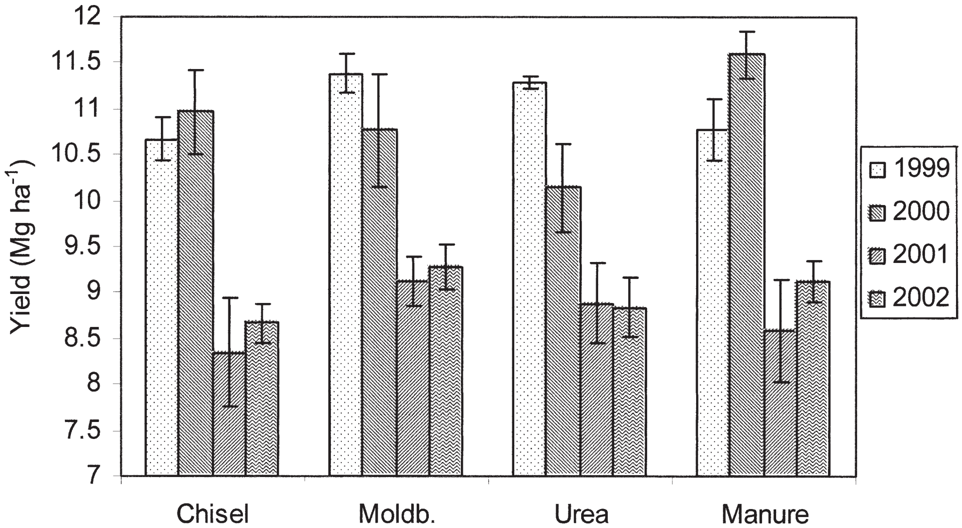

Fig. 2. Variation in corn grain yield 1999 through 2002. Bars represent one standard deviation from the mean. Large variability between years was due to climatic differences.

(1996). The difference in 4-yr average grain yield due to tillage treatment may have been due to residues in the chisel plots that insulated the soil from warming in the spring thus inhibiting crop growth.

CONCLUSIONS

Although this study did not indicate significant water quality benefits from the presence of small quantities of residue cover (approximately 30%) in chisel-plow plots compared with moldboard-plow plots on flat lands (slope = approximately 3%), it did show that there was a slight detrimental effect of residue cover on cumulative corn grain yield over the 4-yr period. Since these results are for only 4 yr, it remains to be seen if higher residue cover in chisel-plow plots at the time of planting helps minimize nonpoint-source pollutant losses and lowers corn grain yield over time as shown by Randall et al. (1996). Since this study was undertaken with continuous corn, the results further suggest that differences in water quality and grain yield will be even less in a corn–soybean rotation, a major cropping system in the Minnesota River basin. This is because residue cover after soybean harvest is much less than that in a continuous corn system, and thus, residue cover differences between tillage types will be minimal at the time of corn planting. However, there are additional benefits of residue cover that were not considered in this study, such as reduced wind erosion losses during fall and winter.

Generally, a lack of major differences in N losses between urea- and manure-treated plots appears to be related to soil mineralization. It seems that soil mineralization overwhelmed the N addition to soil either from manure or from urea applications. This is because even in years when the manure N rates were under-applied, there was no difference in N losses between the manure and the urea plots. Furthermore, corn grain yields were about the same even in years when manure N application rates were lower than urea N rates. For the year (1999) when manure and urea N application rates were similar, the beneficial effect of manure as opposed to urea application was a decrease in combined NO_3–N and NH_4–N losses via tile drainage. This may be partially due to slow but continuous release of manure organic N that was taken up by the crop more efficiently. Another beneficial effect of manure application was increased corn grain yield for 1 yr. This increase in corn yield was possibly due to additional nutrients that may have been present and/or from the nutrients that may have accumulated after many years of manure application. There was some NH_4–N in tile drainage from manure-applied plots and that appeared to be associated with preferential flow paths.

The results show that a chisel plow–based system with approximately 30% residue cover will not be sufficient to dramatically reduce sediment loads from poorly drained flat lands. Taken in the context of the Minnesota River, adoption of conservation tillage such as chisel plowing in the basin will have minimal positive effect on Minnesota River water quality especially to the extent (40% reduction in sediment load) desired by the regulatory agencies (Minnesota River Assessment Project, 1994).

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