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Water Quality

Impact of Long-Term Tillage Systems for Continuous Corn on Nitrate Leaching to Tile Drainage

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ABSTRACT

Information is lacking on the long-term impact of tillage systems on NO_3 losses to surface and groundwater. An 11-yr (1982-1992) study was conducted to assess NO_3 losses to subsurface, tile drainage for corn (*Zea mays* L.) grown with continuous conventional tillage (CT) and no tillage (NT) on a poorly drained Webster clay loam soil (fine-loamy, mixed, mesic Typic Haplaquoll) at Waseca, MN. Nitrogen was applied at an annual application rate of 200 kg ha^{-1}. Mean annual subsurface drain flow during the 11-yr period was 35 mm higher for NT (315 mm) compared with CT (280 mm). Flow-weighted nitrate-nitrogen (NO_3-N) concentrations increased dramatically in the wet years (1990 and 1991) following the dry period of 1987 to 1989. Flow-weighted NO_3-N concentrations during the 11-yr period averaged 13.4 and 12.0 mg L^{-1} for CT and NT, respectively. Although subsurface drain flow was 12% higher with NT, NO_3-N losses were about 5% higher with CT mainly due to higher NO_3-N concentrations with CT in the last 2 yr. Corn grain yields and N removal were significantly higher in 6 out of 11 yr with CT compared with NT with no difference between tillage systems in the other 5 yr. Grain yields averaged 8.6 Mg ha^{-1} with CT and 7.3 Mg ha^{-1} with NT during the 11-yr period. Multiple regression equations showed that annual flow-weighted NO_3-N concentration is best predicted from residual soil NO_3 in the 0- to 1.2-m profile and spring rainfall while NO_3-N flux can be predicted well from May and June rainfall. Results from this long-term study indicate that on this poorly drained soil, CT had a positive effect on corn grain yield and N removal compared with NT, but tillage systems had minimal impact on NO_3 losses to subsurface drain flow. Higher drain flow with NT does not necessarily result in higher NO_3-N fluxes lost via subsurface drainage.

SUBSURFACE DRAINAGE is a common agricultural practice in large areas of highly productive but poorly drained soils in the USA, particularly in the upper Midwest. Nutrient composition of the tile drainage reflects nutrient losses below the crop root zone and potentially to groundwater. In areas where the drain tiles discharge into surface ditches or streams, contaminants in subsurface drainage pose a direct threat to surface waters. Research has shown that substantial amounts of sediments, nutrients, and detectable amounts of pesticides are carried in the tile drainage (Baker and Johnson, 1981; Buhler et al., 1993; Kladivko et al., 1991). Monitoring tile effluents can therefore be useful in assessing the impact of agricultural management practices on surface and groundwater quality (Hallberg et al., 1986; Kanwar et al., 1987). Subsurface drains integrate the effects of spatial variability on a field scale and may be a better tool for studying agricultural impacts on water quality than measurement methods such as suction cups and soil cores (Richard and Steenhuis, 1988).

Many U.S. farmers have shifted from conventional tillage (CT) to some form of reduced tillage during the last decade (Logan et al., 1987). Conservation tillage has become widely accepted in row crops like corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] since it reduces energy, minimizes soil erosion and water runoff, and improves water infiltration thereby improving soil's physical structure and productivity (Reganold et al., 1990). However, concern has been raised that increased infiltration in conservation tillage systems may accelerate leaching of pesticides and nutrients to groundwater.

Although groundwater pollution by NO_3 leaching is a common phenomenon for both CT and no till (NT) systems, reports on the effect of tillage systems on NO_3 leaching have been contradictory (Gilliam and Hoyt, 1987). For example, Kanwar et al. (1985) in a rainfall simulation study on a Clarion-Nicollet loam soil in Iowa concluded that only 6% of the total NO_3-N in the soil leached below 150 cm under NT, whereas 27% of the total NO_3-N leached below this depth in the CT plots. Contrary to this in a 3-yr subsurface drainage study on Nicollet loam soil Kanwar et al. (1988) found higher subsurface drain flow and NO_3 leaching losses with NT compared with CT. On the other hand, Kitur et al. (1984) observed no differences in NO_3 leaching between tillage systems on a well-drained Maury silt loam soil in Kentucky.

Tillage has also been shown to affect N use efficiency and crop yields. Lower corn grain yields under continuous corn production were reported with NT (8.7 Mg ha^{-1}) compared with CT (9.6 Mg ha^{-1}) in northeastern USA (Cox et al., 1990). Reduced N uptake by corn under NT systems is usually evident at lower N rates (Kitur et al., 1984; Meisinger et al., 1985). This may be a result of immobilization of surface-applied N fertilizer under NT systems (Kitur et al., 1984) coupled with greater denitrification losses under NT (Rice and Smith, 1982). In a 16-yr study, higher corn grain yields were observed in CT compared with NT during the first 9 yr when no N fertilizer was applied. However, at high N rates yields were approximately equal for CT and NT (Rice et al., 1986). The authors also suggested that

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Abbreviations: ANOVA, analysis of variance; CT, conventional tillage; NT, no tillage; NO_3-N, nitrate-nitrogen; NO_2-N, nitrite-nitrogen reduced N availability observed with NT in some cases is a transient effect.

Lower amounts of soil NO_3-N have been reported under NT compared with CT. Nitrate-N accumulation in the top 1.5 m was reduced by 75% under NT (222 kg ha^{-1}) compared with CT (841 kg ha^{-1}) after 8 yr of continuous tillage for corn on a fine-textured clay loam soil in southern Minnesota (Randall, 1990). In a 3-yr study, Angle et al. (1993) also observed consistently lower NO_3-N concentrations to a 2.1-m depth except in the surface 30 cm for corn grown with NT compared with CT. Lower NO_3-N concentrations with NT were attributed to increased soil moisture, leading to higher denitrification losses of N and to greater immobilization of surface-applied N fertilizer in these tillage systems that leave more crop residue on the soil surface.

Previous research on the effect of tillage systems on NO_3 losses has been either short-term or conducted under extreme leaching conditions. For example, 12.7 cm of rain was applied in about 6 h to simulate a 100-yr storm in the Iowa study by Kanwar et al. (1985). Information is needed on the long-term impact of tillage systems on NO_3 leaching. Therefore, the objectives of this study were to determine if long-term tillage systems have an effect on (i) loss of NO_3 to tile lines, (ii) accumulation of NO_3 in the soil profile, and (iii) N utilization and grain yield of corn.

MATERIALS AND METHODS

The study was conducted on a poorly drained Webster clay loam at the University of Minnesota Southern Experiment Station at Waseca, MN, from 1982 through 1992. Subsurface drainage tile systems were installed in 1975 to eight individual 13.5 by 15.0 m plots with separate drain outlets. Tile lines were spaced to simulate 27-m spacing and placed 1.2 m deep. Individual plots were isolated to a depth of 1.8 m by trenching and installation of 12-mil thick plastic sheeting. The soil characteristics and a detailed drain tile description were given elsewhere (Buhler et al., 1993; Gast et al., 1978). Based on limited drainage data from these plots in 1977 to 1980, the tillage treatments were assigned within each replication to minimize the effect that spatial hydrologic flow variation may have on drainage flow resulting from the two tillage systems.

Corn was planted annually in the entire experimental area starting in 1973. An experiment consisting of various N rates was conducted from 1975 to 1979. No N was applied for the 1980 and 1981 crops. Soil samples taken to 3-m depth and tile water samples taken in 1981 indicated little remaining evidence of the previous treatments. All eight plots received CT through 1981 when four of the plots were converted to NT. The CT and NT plots were replicated four times in a randomized, complete-block design. Conventional tillage consisted of moldboard plowing to a depth of 20-cm each fall followed by secondary tillage (discing or field cultivation) in the spring just before planting. In the NT system, soil disturbance was limited to a 5-cm band created by the fluted coulter during the planting operation. Corn was planted in 76-cm rows perpendicular to the drain tiles. The average corn planting date during the 1982 to 1992 period was 5 May. Fertilizer N as ammonium nitrate was broadcast-applied at a rate of 200 kg N ha^{-1} (the recommended N rate for continuous corn on this soil) each spring before planting. Fertilizer P and K were not applied due to the high soil test levels of these nutrients. Insecticide was applied in a band over the corn row to control soil-borne insects. Weeds were controlled extremely well with a preemergence broadcast-application of herbicides (Buhler et al., 1993).

The experiment was conducted under ambient precipitation. Precipitation data collected daily at a site 0.5 km from the drainage site were summarized as monthly and seasonal totals from 1982 through 1992 (Table 1).

Daily flow rates were determined each day except Saturday and Sunday (unless a precipitation event occurred over the weekend) by measuring the amount of water running from each tile line during a 1-min interval and converting to liters per plot per day. Water samples were collected manually in 250-mL plastic bottles for NO_3-N analysis three times a week (Monday, Wednesday, and Friday) when tile flow exceeded 0.25 mm ha^{-1} d^{-1} (30 mL min^{-1}). Water samples were stored frozen until subsequent laboratory analysis. Nitrate was analyzed by the colorimetric Cd-reduction method; therefore, concentration data included nitrite-nitrogen (NO_2-N), which was assumed to be extremely small. Total NO_3-N lost was calculated by multiplying the NO_3-N concentration for each sample by the total calculated flow for the same period. Flow-weighted average NO_3-N concentrations were calculated by taking the NO_3-N flux for the period of interest and dividing that sum by the total flow volume.

Corn was harvested in mid-October of each year. Yield was

Table 1. Growing season precipitation at Waseca, MN, during the study period.

Year	Growing season total	Month						
		April	May	June	July	August	September	October
30-yr normal† (mm)	618	67	96	114	102	101	85	53
	% of normal							
1982	103	105	172	40	36	116	127	179
1983	127	162	131	100	132	116	126	151
1984	103	189	79	114	85	36	72	223
1985	97	126	48	57	62	131	161	130
1986	125	156	100	176	97	60	166	136
1987	92	16	55	78	181	135	60	85
1988	67	92	53	30	15	108	159	15
1989	65	122	41	49	98	61	70	10
1990	124	106	141	149	153	162	45	65
1991	151	163	206	83	216	158	137	67
1992	114	120	78	87	107	151	96	204

† 1951–1980 normals.

determined by harvesting 13.7-m sections of two rows from the center of each plot with a plot combine. Composite subsamples of grain were ground to pass a 1-mm sieve and analyzed for total N (Technicon Industrial Method, no. 325-74W Sept. 1974; Ammoniacal Nitrogen/BD Acid Digests; Technicon Industrial Systems, Tarrytown, NY).

After corn harvest and when the soil temperatures were below 10°C, soil cores (4.1-cm diam.) were collected with a hydraulic probe to a 2.4-m depth in 30-cm increments. Soil samples were taken only to a 1.5-m depth in 1982 and a 1.8 m depth in 1983. The holes were backfilled with the soil not kept for analysis and the surface closed to prevent inflow. Two cores were taken from each plot and composited into a single sample at each depth. Soil samples were oven-dried at 40°C, ground, and analyzed for NO_3-N using the colorimetric Cd-reduction method.

Fifteen soil cores (1.9-cm diam.) were also taken from each plot in the fall of 1992 before moldboard plowing. Samples were collected to a 30-cm depth. The top 15 cm was divided into three 5-cm sections and the bottom 15 cm was divided into two 7.5-cm sections. Samples were composited by depth and analyzed for total N to determine the long-term effect of tillage on total N content of the soil.

Data were subjected to analysis of variance procedures using the ANOVA procedure of SAS (SAS Inst., 1988). Differences among treatment means were compared at the 0.05 level of significance. Stepwise multiple regression analysis was performed using the REG procedure of SAS to determine the independent variables that best predict annual flow-weighted NO_3-N concentrations and NO_3-N flux in tile drainage water. The stepwise technique calculates F statistics that reflect the variable's contribution to the model if it is included. Variables that produce a significant F statistic at the 0.10 level are added one by one to the model. After a variable is added, however, the stepwise method looks at all variables already included in the model and deletes any variable that does not produce an F statistic significant at the 0.10 level. Only after this check is made and the necessary deletions accomplished can another variable be added to the model. The stepwise process ends when none of the variables outside the model has an F statistic significant at the 0.10 level.

RESULTS AND DISCUSSION

Drain Flow, Nitrate-Nitrogen Concentration, and Nitrate-Nitrogen Losses to Tile Drainage

Precipitation was the major factor affecting drain flow, as is evident by higher drain flows in wet years and lower flows in the dry years. Typical drain flow began in mid- to late-March and continued until mid-July. Flow commenced again in late-September and continued through October. During the dry years (1987–1989), flow occurred only during 4 August to 24 August, 27 April to 26 May, and 28 April to 3 June periods in 1987, 1988, and 1989, respectively. During the wet 1990 to 1992 period, flow began each March and continued until November.

Total subsurface drain flow was consistently higher with NT compared with CT in all years except 1984

Table 2. Mean NO_3-N concentrations, total subsurface flow, and estimated NO_3-N loss in subsurface flow from 1982 through 1992.

Year	Tillage system	Total flow	Flow-weighted NO_3-N concentration	NO_3-N loss
		mm ha^{-1} ± SE	mg L^{-1} ± SE	kg ha^{-1} ± SE
1982†	CT	28 ± 5	4.8 ± 1.3	1.4 ± 0.4
	NT	44 ± 9	6.0 ± 0.8	2.9 ± 0.8
1983	CT	522 ± 75	8.1 ± 1.6	41.1 ± 12.9
	NT	569 ± 89	9.0 ± 0.4	49.4 ± 9.3
1984	CT	353 ± 90	10.6 ± 1.6	39.3 ± 14.4
	NT	324 ± 56	15.0 ± 3.7	36.8 ± 7.7
1985	CT	143 ± 23	12.8 ± 1.6	17.2 ± 2.6
	NT	173 ± 32	12.5 ± 1.2	20.0 ± 3.4
1986	CT	402 ± 56	14.0 ± 1.4	55.3 ± 6.1
	NT	441 ± 94	13.6 ± 1.3	60.0 ± 9.0
1987	CT	42 ± 16	9.2 ± 0.7	3.8 ± 1.3
	NT	42 ± 10	7.8 ± 0.3	3.2 ± 0.7
1988	CT	46 ± 8	14.7 ± 1.6	6.4 ± 0.9
	NT	64 ± 16	9.4 ± 0.9	5.9 ± 1.3
1989	CT	26 ± 11	11.5 ± 5.7	2.5 ± 1.7
	NT	38 ± 9	13.4 ± 1.7	5.0 ± 1.7
1990	CT	486 ± 94	23.9 ± 4.4	111.9 ± 9.4
	NT	525 ± 110	20.8 ± 0.8	112.2 ± 20.9
1991	CT	618 ± 122	24.0 ± 1.3	138.7 ± 15.5
	NT	732 ± 209	15.3 ± 0.6	113.1 ± 27.8
1992	CT	417 ± 107	13.5 ± 0.8	55.0 ± 8.0
	NT	510 ± 160	8.9 ± 0.2	43.1 ± 12.7

† Subsurface drains flowed during October–December only.

(Table 2). Drain flow averaged only 38 and 48 mm with CT and NT, respectively, during the 1987 to 1989 period when the growing season precipitation was only 63 to 87% of the long-term normal. However, in the five wet years (1983, 1986, and 1990–1992), drain flow under NT averaged 66 mm more compared with CT (555 and 489 mm for NT and CT, respectively).

Although the difference in drain flow between the two tillage systems was usually not large in the first 9 yr of the study, the consistently higher drainage with NT during this time coupled with the considerably higher drain flow with NT in the last 2 yr resulted in 407 mm more cumulative flow with NT over the 11-yr period (Fig. 1). It should be noted, however, that hydrologic spatial

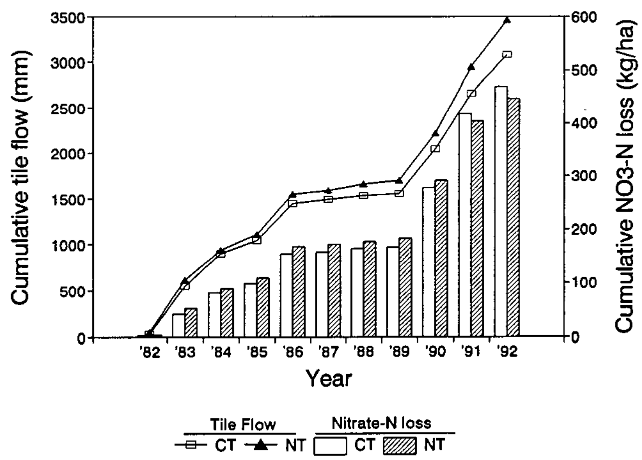

Fig. 1. Cumulative subsurface drain flow for 11 yr and NO_3-N losses in the drain flow under the two tillage systems during the 1982 to 1992 period.

variability among the plots was high as shown by the standard errors. The mean drain flow differences between tillage systems do not exceed the standard errors; however, they are quite consistent during the 11-yr period. This is especially true in the wet years when NT yields were significantly less than with CT.

Higher infiltration rates have been reported in established long-term NT plots compared with those of CT (Chang and Lindwall, 1989; Lal and Van Doren, 1990). Increased drain flow under NT plots in this study is attributed to the combined effect of reduced evapotranspiration and increased infiltration in this system. Surface runoff was not measured and was considered to be minimal on this 0 to 2% slope site. Soil hydraulic conductivity measurements taken after the tillage systems were in effect for 3 yr on the same plots indicated increased hydraulic conductivity for the NT plots due to the presence of vertical macropores in this system (Culley et al., 1987).

Flow-weighted NO_3-N concentrations in the tile water averaged 13.4 mg L^{-1} for CT and 12.0 for NT over the 11-yr period. The magnitude in differences between the two tillage systems increased in the drought year (1988) and again in the wet years (1990-1992). Higher concentrations of NO_3-N with CT compared with NT in those years may have been due to increased net N mineralization in this system (Levanon et al., 1993). The dramatic increase in NO_3-N concentrations in tile water during the 1990 to 1991 period was likely due to the carryover of unused fertilizer N from the dry years of 1987 to 1989 under both tillage systems. Residual N from previous dry years plus some of the N applied as fertilizer leached during the wet spring months in both 1990 and 1991 and resulted in higher concentrations of NO_3-N in the tile water. Nitrate-N losses did not differ appreciably between the tillage systems until 1991 (Table 2). Nitrate-N losses to drain tiles were lowest during 1987 to 1989 under both tillage systems mainly due to lower drain flows. Higher drain flows coupled with higher NO_3-N concentrations contributed to more NO_3-N leaching losses to drain tiles during the 1990 to 1991 period under both tillage systems. Higher NO_3-N losses under CT in 1991 were primarily due to higher concentrations of NO_3-N in the tile water in this system. These results are consistent with those of Kanwar et al. (1988), who found higher NO_3-N concentrations and losses in the tile water with CT in the third and last year of the experiment.

Even though more water was draining from the NT soil, higher NO_3-N losses did not occur compared with those from CT. This may have been due to a combination of lower soil NO_3-N levels with NT and preferential flow where the bulk of the water moving through the NT soil profile may have bypassed the soil matrix (Thomas and Philips, 1979), therefore resulting in lower NO_3-N losses in this system. However, procedures used in this study did not allow direct measurement of preferential flow.

Corn Grain Yield and Nitrogen Removal

Corn grain yield and N removal in the grain were significantly higher with CT compared with NT in 6 out of 11 yr (Table 3). In the first 6 yr, grain yields and N removal in the grain tended to be slightly higher with CT, but the differences between the two tillage systems were only significant in 2 yr. Yields and N removal between the two systems started to widen in the seventh year (1988), although hot and dry conditions limited yield and raised experimental variability (CV). In the last 4 yr, yields from CT averaged 2.6 Mg ha^{-1} (40%) greater than those of NT. Averaged over the 11 yr, grain yield and grain N removal were 15 and 18% higher, respectively, for CT compared with the NT system.

These results are different from those observed on well-drained soils in Kentucky (Rice et al., 1986) where, at a N fertilizer rate of 168 kg ha^{-1}, there was either no difference in corn grain yield between the two tillage systems or NT yielded greater than CT. In our study, plant population was not different between the two tillage systems, but early to midseason growth was consistently better with the CT system. This was especially true in the last 4 yr, where crop maturity was delayed markedly in the NT system. The reason for slower early growth was not determined in this study, but could be due to a

Table 3. Corn grain yield and N removal in the tile drainage plots from 1982 through 1992.

Year	Tillage system	Grain yield	N removal
		Mg ha^{-1}	kg ha^{-1}
1982	CT	9.2	91
	NT	9.0	85
	CV (%)	10.0	16.0
1983	CT	6.6	82
	NT	6.4	81
	CV (%)	6.8	12.5
1984†	CT	7.4	98
	NT	6.7	84
	CV (%)	7.2	5.0
1985†	CT	10.1	116
	NT	9.1	103
	CV (%)	2.5	3.3
1986	CT	9.0	101
	NT	8.5	90
	CV (%)	4.8	9.3
1987	CT	9.9	121
	NT	9.6	110
	CV (%)	7.2	6.4
1988	CT	6.3	88
	NT	5.2	72
	CV (%)	19.0	14.0
1989†	CT	9.6	113
	NT	8.0	96
	CV (%)	2.6	4.0
1990†	CT	9.2	113
	NT	6.6	71
	CV (%)	4.8	11.0
1991†	CT	10.2	116
	NT	7.6	75
	CV (%)	3.1	9.8
1992†	CT	7.6	93
	NT	4.0	54
	CV (%)	4.8	12.0

† Significant grain yield and N removal differences (at 5% level) for the two tillage treatments.

combination of lower soil temperature, higher water content limiting O_2, allelopathy, and greater soil consolidation in the top 20 cm with long-term continuous NT. These factors would all slow early root proliferation and plant growth. Consequently, grain yields, grain N removal, and N use efficiency were lower with NT compared with CT.

Soil Nitrate-Nitrogen Content

To better understand the NO_3–N changes in tile drainage water, soil NO_3–N was determined in the root zone (0- to 1.5-m) and the profile immediately below the root zone (1.5- to 2.4-m). In 5 out of 11 yr, CT had higher amounts of NO_3 in the profile compared with NT (Fig. 2). Higher soil NO_3–N levels with CT tended to be associated with the dry years and the first wet year (1990) following the dry years. Averaged over the 3 dry years (1987–1989), NT contained only 30% (90 kg ha^{-1}) of the NO_3–N contained in the 0- to 1.5-m profile of the CT system. The differences between the tillage systems were negligible when averaged over the wetter-than-normal years (1983, 1986, and 1990–1992). It is surprising, however, that even with 220% above-normal precipitation in the month of October 1984, the total NO_3–N content in the profile was high under both tillage systems in that year. Drought conditions in 1988 resulted in lower grain yields and grain N uptake; as a result, residual NO_3–N levels in the profile were high in both tillage systems. Most of the residual NO_3 may have remained in the soil profile during the dry year of 1989 and started to leach with percolating water beginning in 1990. Due to the high NO_3–N fluxes in 1990, 1991, and 1992, lower amounts of residual NO_3–N remained in the 0- to 1.5-m profile at the end of each of those years.

The higher amounts of soil NO_3 with CT compared with NT could be due to greater net N mineralization in the CT system (Levanon et al., 1993) or greater immobilization and/or denitrification leading to lower amounts of NO_3–N under NT. Immobilization of surface-applied N is a likely explanation for lower NO_3 with NT at this site where surface residue accumulation after planting averaged 94% during the last 6 yr. Higher rates of denitrification have been reported with NT compared with CT (Aulakh et al., 1984; Rice and Smith, 1982). Increased soil water content due to reduced evapotranspiration in NT probably led to enhanced population of denitrifying organisms, resulting in more denitrification losses in this system compared with CT (Angle et al., 1993). Contrary to the findings in the 0- to 1.5-m profile, consistent differences were not noticed between the two tillage systems in the 1.5- to 2.4-m profile (data not shown).

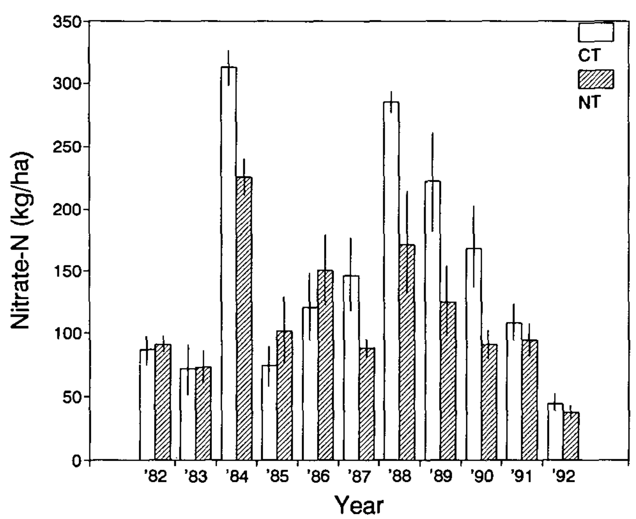

Fig. 2. Soil NO_3-N in the 0- to 1.5-m profile after harvest under the two tillage systems during the 1982 to 1992 period. Vertical lines represent the standard error of the mean.

Total Soil Nitrogen

Soil samples taken to a 30-cm depth in the fall of 1992 indicated that the NT plots had accumulated significantly higher amounts of total N (230 kg ha^{-1}) in the 0- to 5-cm layer compared with CT (Fig. 3). Percent total N did not differ appreciably between the two tillage systems below the 5-cm depth. The higher amounts of total soil N in the 0- to 5-cm depth under NT are probably due to accretion of crop residue on the soil surface, leading to greater immobilization of N in this system. Also, in the CT system, moldboard plowing and secondary tillage operations may have accelerated mineralization of organic matter leading to lower total soil N in the top 5-cm (Blevins et al., 1983).

Eleven-Year Nitrogen Budget

The 11-yr summary (Table 4) indicates that corn grain yields during this period averaged 1.3 Mg ha^{-1} better with CT. Approximately 23% (211 kg ha^{-1}) more N was removed in the grain with CT compared with NT. This was due to both higher yields and slightly higher grain N concentration with CT in some years. As a result, an equivalent of 51 and 42% of the applied fertilizer N was removed in the grain in the CT and NT systems, respectively. After the 11-yr period, total N in the 30-cm profile was 240 kg ha^{-1} higher with NT (Fig. 3). This is approximately the difference in the amount

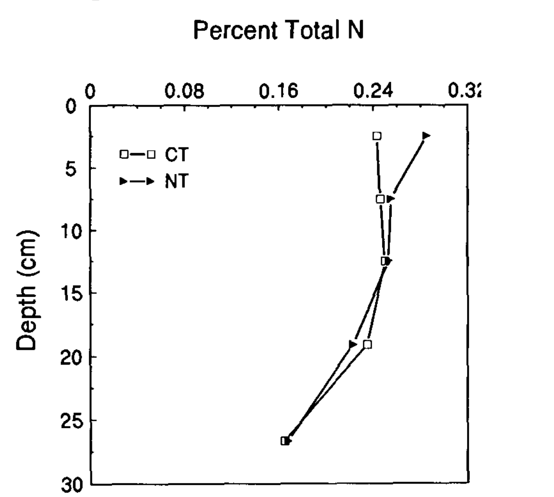

Fig. 3. Total soil N in the 0- to 30-cm zone after 11 yr of no-till and conventional tillage.

Table 4. Cumulative effects of the two tillage systems over the 11-yr period.

Parameter	Tillage system CT	NT
Total fertilizer N applied (kg ha^{-1})	2218	2218
Corn grain removed (Mg ha^{-1})	95.1	80.7
Total grain N removed (kg ha^{-1})	1132	921
N removed in grain as a percent of applied N (%)	51	42
N accumulated as total N in NT compared with CT (kg ha^{-1})	–	240
Total subsurface drain flow (cm)	308	346
Nitrate-N lost in subsurface drain flow (kg ha^{-1})	473	452
N lost via subsurface drain flow as a percent of applied N (%)	21	20

of N removed in the grain between the two tillage systems. The amount of N removed in the grain plus lost in the tile drainage was equivalent to 72 and 62% of the amount applied for CT and NT, respectively. The 240 kg ha^{-1} more total N in the NT soil system accounts for this 10% difference between the two tillage systems. The unaccounted for N in both systems (28% of the total applied) was lost either due to denitrification, leaching into vadose zone, N loss from leaves, or a combination of these processes. Total water flow through the tile lines was 12% higher with NT compared with CT, yet NO_3–N losses were about 5% higher with CT. This was due to higher NO_3–N concentrations in the tile water draining from the CT plots, especially in the last 3 yr. This small difference in NO_3–N flux between tillage systems is insignificant considering the variability in tile flow among the plots. The equivalent of 20 to 21% of the fertilizer N applied was lost to tile drainage with both tillage systems over this 11-yr period.

Predicting Nitrate Losses in Subsurface Drain Flow

Residual NO_3 in the soil profile at the end of the growing season and monthly precipitation from April through September were regressed against the tile flow data using stepwise multiple regression (SAS Inst., 1988) to determine which independent variables best predict annual flow-weighted NO_3–N concentrations in the tile water and annual NO_3–N flux (kg ha^{-1}). Multiple correlation coefficients shown in Table 5 indicate statistically significant equations for predicting both NO_3–N concentration and flux in CT and NT systems. Flow-weighted annual NO_3–N concentration was best predicted by including residual soil NO_3–N from the 0- to 1.2-m depth at the end of the growing season and May rainfall for the CT system and April to June rainfall for the NT system. Nitrate–N in the 0- to 0.6-m profile did not contribute significantly to the prediction equation.

Nitrate flux lost annually to subsurface drain flow was a function of rainfall and not residual soil NO_3 (Table 5). Rainfall in May dominated among the independent variables for both tillage systems. June rainfall was also significant in a NT system. Combining the data for both tillage systems emphasized the influence of growing season rainfall on NO_3 flux in drainage water.

SUMMARY AND CONCLUSIONS

Results from this long-term study indicate that NO_3–N concentrations and losses in tile drainage, which generally empties into surface waters, are highly dependent on growing season precipitation and, to a much lesser extent, tillage. On these poorly drained, high organic matter soils, portions of the N cycle leading either to increased availability or losses of N are affected greatly by soil water content. In dry years when plant growth and N uptake are limited and percolation of soil water is negligible, mineralization continues to occur, and mineral N accumulates in the soil profile, especially with CT. The consequences of this mineral N buildup are then realized when precipitation exceeds evapotranspiration. Nitrate–N concentrations in the tile drainage water rise quickly and can more than double those found in years or periods of normal precipitation. As a result, NO_3 contamination of surface waters increases, and the public concern for agriculture's impact on water quality escalates. During this long-term study, annual losses of NO_3–N in the tile water ranged from 1.4 to 139 kg ha^{-1}. In dry years, losses generally were equivalent to less than 3% of the fertilizer N applied, whereas in the wet years losses ranged from 25 to 70% of that applied. Over the 11-yr period, NO_3 losses in tile drainage averaged about 20% of the recommended amount of fertilizer N applied. These data strongly suggest that a soil N test be used in the spring following dry years to measure residual NO_3 in the soil profile and to subsequently refine fertilizer applications by crediting for the NO_3 found. Using this management practice in 1989 and 1990 would likely

Table 5. Multiple regression equations to predict anual flow-weighted NO_3-N concentrations and NO_3-N losses to tile drainage based on 11 yr of soil and precipitation data.

Dependent variable	Tillage system	Intercept	Soil NO_3-N† (kg/ha) 0–0.6 m	0–1.2 m	Precipitation‡ Apr.	May	June	July	Aug.	Sept.	Apr.–June	Coeff. of determination
			b									R^2
Flow-weighted NO_3-N conc. (mg L^{-1})	CT	3.60	–	+0.024	–	+2.497	–	–	–	–	–	86.**
	NT	−0.63	–	+0.048	–	–	–	–	–	–	+2.688	70.*
	Combined	4.19	–	+0.030	–	+1.983	–	–	–	–	–	66.*
NO_3-N loss in tile drainage (kg ha^{-1})	CT	−27.54	–	–	–	+20.955	–	–	–	–	–	94.**
	NT	−31.71	–	–	–	+15.914	+4.392	–	–	–	–	93.**
	Combined	−69.08	–	–	+8.654	+12.486	+4.338	–	+7.192	−2.487	–	98.**

*, ** Significant at the 0.05 and 0.01 P levels, respectively.
† NO_3-N in soil profile at the end of previous year.
‡ Monthly precipitation in mm.

have reduced fertilizer N rates and thus NO_3–N concentrations and flux in 1990 and 1991.

Long-term tillage exerted a much more significant influence on corn production than on NO_3 losses to drainage. Corn yield and N uptake were not greatly affected by tillage in the first few years of the study. However, as the tillage systems matured the difference in corn yield and N uptake between CT and NT began to widen. In the last 4 yr, grain yields with CT were 40% higher than those with NT. The lower yields and reduced N uptake with NT undoubtedly impacted NO_3 losses in the drainage. Lower evapotranspiration demand would have allowed more water to percolate through the profile. When coupled with more unused fertilizer N potentially available for leaching, NO_3 losses from this NT system were greater than one would expect if corn production had been equal to that of CT.

In summary, the findings from this study emphasize the importance of long-term experiments to assess the effect of agricultural management practices on surface and groundwater resources. Short-term (3- or 4-yr) results obtained under unusually wet or dry conditions could be misleading if they are to be used by themselves to develop public policy. As best management practices (BMPs) and nutrient management plans are developed for crop producers, it is critical that long-term studies conducted over a range of climatic conditions be used to provide appropriate guidelines. Detailed plant, soil, and water measurements must be gathered in these studies if interactions between crop production, climate, and environmental impacts are to be uncovered.

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REFERENCES

Angle, J.S., C.M. Gross, R.L. Hill, and M.S. McIntosh. 1993. Soil nitrate concentrations under corn as affected by tillage, manure, and fertilizer applications. J. Environ. Qual. 22:141–147.

Aulakh, M.S., D.A. Rennie, and E.A. Paul. 1984. Gaseous N losses from soils under zero-till as compared to conventional till management systems. J. Environ. Qual. 13:130–136.

Baker, J.L., and H.P. Johnson. 1981. Nitrate-nitrogen in tile drainage as affected by fertilization. J. Environ. Qual. 10:519–522.

Blevins, R.L., M.S. Smith, G.W. Thomas, and W.W. Frye. 1983. Influence of conservation tillage on soil properties. J. Soil Water Conserv. 38:301–305.

Buhler, D.D., G.W. Randall, W.C. Koskinen, and D.L. Wyse. 1993. Atrazine and alachlor losses from subsurface tile drainage of a clay loam soil. J. Environ. Qual. 22:583–588.

Chang, C., and C.W. Lindwall. 1989. Effect of long-term minimum tillage practices on some physical properties of a chernozemic clay loam. Can. J. Soil Sci. 69:443–449.

Cox, W.J., R.W. Zobel, H.M. van Es, and D.J. Otis. 1990. Growth development and yield of maize under three tillage systems in the northeastern U.S.A. Soil Tillage Res. 18:295–310.

Culley, J.L.B., W.E. Larson, and G.W. Randall. 1987. Physical properties of a Typic Haplaquoll under conventional and no-tillage. Soil Sci. Soc. Am. J. 51:1587–1593.

Gast, R.G., W.W. Nelson, and G.W. Randall. 1978. Nitrate accumulation in soils and loss in tile drainage following nitrogen applications to continuous corn. J. Environ. Qual. 18:491–498.

Gilliam, J.W., and G.D. Hoyt. 1987. Effect of conservation tillage on fate and transport of nitrogen. p. 217–240. *In* T.L. Logan et al. (ed.) Effects of conservation tillage on groundwater quality. Lewis Publ., Chelsea, MI.

Hallberg, G.R., J.L. Baker, and G.W. Randall. 1986. Utility of tile-line effluent studies to evaluate the impact of agricultural practices on groundwater. p. 298–326. *In* Proc. Conf. Agricultural Impacts on Ground Water, Omaha, NE. 11–13 Aug. 1986. Natl. Water Well Assoc., Dublin, OH.

Kanwar, R.S., J.L. Baker, and D.G. Baker. 1987. Tillage and N-fertilizer management effects on groundwater quality. Paper 87-2077. ASAE, St. Joseph, MI.

Kanwar, R.S., J.L. Baker, and D.G. Baker. 1988. Tillage and split N-fertilization effects on subsurface drainage water quality and crop yields. Trans. ASAE 31:453–460.

Kanwar, R.S., J.L. Baker, and J.M. Laflen. 1985. Nitrate movement through the soil profile in relation to tillage system and fertilization application method. Trans. ASAE 28:1802–1807.

Kitur, B.K., M.S. Smith, R.L. Blevins, and W.W. Frye. 1984. Fate of ^{15}N-depleted ammonium nitrate applied to no-tillage and conventional tillage corn. Agron. J. 76:240–242.

Kladivko, E.J., G.E. Van Scoyoc, E.J. Monke, K.M. Oates, and W. Pask. 1991. Pesticide and nutrient movement into subsurface tile drains on a silt loam soil in Indiana. J. Environ. Qual. 20: 264–270.

Lal, R., and D.M. Van Doren. 1990. Influence of 25 years of continuous corn production by three tillage methods on water infiltration for two soils in Ohio. Soil Tillage Res. 16:71–84.

Levanon, D., E.E. Codling, J.J. Meisinger, and J.L. Starr. 1993. Mobility of agrochemicals through soil from two tillage systems. J. Environ. Qual. 22:155–161.

Logan, T.J., J.M. Davidson, J.L. Baker, and M.R. Overcash (ed.). 1987. Effects of conservation tillage on ground water quality. Lewis Publ., Chelsea, MI.

Meisinger, J.J., V.A. Bandel, G. Stanford, and J.O. Legg. 1985. Nitrogen utilization of corn under minimal tillage and moldboard plow tillage: I. Four-year results using labeled N fertilizer on an Atlantic coastal plain soil. Agron. J. 77:602–611.

Randall, G.W. 1990. Nitrate-N in the soil profile and tile drainage water as influenced by tillage. Am. J. Indus. Med. 18:457–460.

Reganold, J.P., R.J. Papendick, and J.F. Parr. 1990. Sustainable agriculture. Sci. Am. 262:112–120.

Rice, C.W., and M.S. Smith. 1982. Denitrification in no-till and plowed soils. Soil Sci. Soc. Am. J. 46:1168–1173.

Rice, C.W., M.S. Smith, and R.L. Blevins. 1986. Soil nitrogen availability after long-term continuous no-tillage and conventional tillage corn production. Soil Sci. Soc. Am. J. 50:1206–1210.

Richard, T.L., and T.S. Steenhuis. 1988. Tile drain sampling of preferential flow on a field scale. J. Contam. Hydrol. 3:307–325.

SAS Institute. 1988. User's guide: Statistics. Version 6 ed. SAS Inst., Cary, NC.

Thomas, G.W., and R.E. Phillips. 1979. Consequences of water movement in macropores. J. Environ. Qual. 8:149–152.