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SEASONAL CHANGES IN FLOW AND NITRATE-N LOSS FROM SUBSURFACE DRAINS

D. L. Bjorneberg, R. S. Kanwar, S. W. Melvin

ABSTRACT. *Subsurface drainage from thirty-six, 0.4-ha plots was monitored for three years (1990 to 1992) from chisel plow, moldboard plow, ridge till, and no-till systems with continuous corn and corn-soybean rotations. Data were analyzed in four seasonal stages to determine variations in drain flows and nitrate-N contents in drain effluent. The hypothesis of this study was that differences among tillage systems would change during the monitoring season as rainfall patterns varied and as plots were fertilized and cultivated.*

Forty-five to 85% of the annual nitrate-N loss through subsurface drainage occurred in the spring and fall when crops were not actively growing. These losses, however, were not significantly different among tillage systems. Relative changes in drain flows and nitrate-N concentrations before and after summer cultivation were similar among the four tillage systems even though no-till and ridge till systems were undisturbed before this time. Nitrate-N losses or concentrations did not increase during the stage following fertilizer application.

No-till plots had significantly higher subsurface drain flow than moldboard plow plots only under continuous corn, possibly an effect of reduced yields from long-term no-till continuous corn. Nitrate-N concentrations in drain effluent from moldboard and chisel plow systems, however, were significantly greater than concentrations from no-till and ridge till systems for all crop rotations. Lower nitrate-N concentrations from no-till and ridge till systems may have resulted from greater bypass flow, denitrification, and immobilization under nonplowed systems. ***Keywords.*** *Subsurface drainage, Nitrate-nitrogen, Tillage, Seasonal changes, Bypass flow.*

Subsurface drainage is important for agricultural production in the Midwest, but nitrate-N concentrations in drain effluent often exceed the 10 mg/L maximum contaminant level set by the Environmental Protection Agency for drinking water (Baker et al., 1975; Baker and Johnson, 1981; Devitt et al., 1976; Kanwar et al., 1988; Kladivko et al., 1991). Drain effluent may increase the nitrate-N concentration of the outlet water body, increasing the health hazard if the water body is used as a drinking water source.

Conservation tillage reduces runoff (Baker and Laflen, 1983; Pesant et al., 1987) and potentially increases infiltration. However, infiltration may also increase on freshly tilled soils. Freese et al. (1993) noted that chisel and moldboard plow treatments had lower infiltration rates than no-till before spring tillage, but higher infiltration rates shortly after spring tillage. Tillage also disturbs preferential flow paths near the soil surface (Ehlers, 1975). Although macropores account for a small percentage of the total horizontal surface area, macropore flow accounts for a large portion of the total vertical flux through soil (Dunn and Phillips, 1991; Edwards et al., 1989). Preferential flow is nonuniform and bypasses much of the soil matrix. More bypass water flow has been measured in no-till soil than in moldboard plowed soil (Wu et al., 1995). Singh and Kanwar (1991) also measured more immobile pore-water in soil columns from no-till plots compared to columns from conventionally tilled plots.

In addition to altering water flow, tillage incorporates crop residue, enhancing decomposition and altering microbial activity in soil. More organic matter, nutrients, and soil enzymes accumulate near the surface of no-till soil compared to conventionally tilled soil (Blevins et al., 1983; Dick et al., 1991; Rice and Smith, 1984). Doran (1980) also measured more aerobic microorganisms, facultative anaerobes, and denitrifiers in the top 7.5 cm of no-till soil than in the same depth of plowed soil. However, these differences were reduced or reversed with depth. Over the entire soil profile, plowed soil had greater mineralization and nitrification potential, while no-till soils had greater denitrification potential.

Drain flow and nitrate-N leaching differences between tilled and untilled soils are unclear. Nitrate-N leaching may decrease as bypass flow increases if percolating water bypasses the soil where nitrate-N is located. Greater infiltration and preferential flow under no-till may result in greater drain discharge, while denitrification and immobilization may decrease the amount of leachable nitrate-N (Dou et al., 1995). Conversely, uniform flow

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through tilled soil may increase nitrate-N concentration in leachate, but total drain flow may decrease. Randall and Iragavarapu (1995) measured higher subsurface drain flow under no-till than under conventional tillage systems, but total nitrate-N losses were higher under conventional tillage because of higher concentrations. They concluded that tillage systems had minimal impact on nitrate-N losses to subsurface drain flow. Guitjens et al. (1984) noted that management effects on subsurface drainage could not be separated from the natural soil effects.

A three-year study was conducted near Nashua, Iowa, from 1990 to 1992 to determine the effects of conservation tillage and crop rotations on groundwater contamination (Kanwar et al., 1993). The purpose of this article was to use data from that study to investigate seasonal changes in drain flow, nitrate-N concentration, and nitrate-N loss in subsurface drainage from four tillage systems. It was hypothesized that differences among tillage systems would change during the monitoring season as rainfall patterns varied and as plots were fertilized and cultivated.

MATERIALS AND METHODS

EXPERIMENTAL SITE

The research was conducted at Iowa State University's Northeast Research Farm near Nashua, Iowa. Soils at the site are Floyd loam (fine-loamy, mixed, mesic Aquic Hapludolls), Kenyon loam (fine-loamy, mixed, mesic Typic Hapludolls), and Readlyn loam (fine-loamy, mixed, mesic Aquic Hapludolls) (Karlen et al., 1991). These soils are moderately well to poorly drained and lie over loamy glacial till. An impermeable layer occurs approximately 3 m below the soil surface.

Tillage, crop rotation, and chemical application practices have not been changed since 1977. Four tillage systems were used—chisel plow (CP), moldboard plow (MP), ridge till (RT), and no-till (NT). Corn-soybean rotation and continuous corn treatments were replicated three times in a randomized complete block design on thirty-six, 0.4-ha plots (67 × 58.5 m). Both the corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] phases of the corn-soybean rotation were planted each year. Consequently, each year there were 12 plots with corn following corn (continuous corn), 12 plots with corn following soybean (rotation corn), and 12 plots with soybean following corn (rotation soybean).

Both CP and MP systems were plowed in mid-November, except in 1991 when wet weather delayed plowing until the spring of 1992. All crops were cultivated during the growing season for weed control. Wheel traffic was not restricted to specific rows. Crops were planted in rows 75 cm apart with a six-row planter having a 150-cm wheel base. Since the combine had a 225-cm wheel base, four of every six rows had a wheel track during the season.

Anhydrous ammonia was knifed into the soil on all corn plots in the spring before secondary tillage on CP and MP systems. Continuous corn plots received 200 kg N/ha while rotation corn plots received 170 kg N/ha. An additional 4 kg N/ha was applied with the planter as starter fertilizer for corn. Soybean plots were not fertilized.

DATA COLLECTION AND ANALYSIS

In 1979, subsurface drains were installed in an east-west direction about 1.2 m deep through the middle and along the north and south borders of each plot. Border drains isolated plots on the north and south sides to reduce chances of cross-contamination between plots. A 9-m grass strip separated the plots on the east and west sides (fig. 1).

Center drain lines were routed to individual meter sumps; border drains were not monitored. Each sump contains a sump pump with flow meter. Flow meters were read manually three times per week (typically Monday, Wednesday, and Friday). Water samples for nitrate-N analysis were collected from the sumps when flow meters were read. Samples were only collected when drains were flowing. Water samples were refrigerated until analyzed at the National Soil Tilth Laboratory in Ames, Iowa. Data collection took place when the soil was not frozen from approximately mid-March to the beginning of December.

Subsurface drain flow, nitrate-N loss, and flow weighted nitrate-N concentration data were analyzed on a seasonal stage basis, rather than annually or monthly, to determine how these parameters varied after tillage and fertilizer application. Each year was divided into four stages based on field operations. Stage 1 was defined as the beginning of the monitoring year before fertilizer application and secondary spring tillage occurred. Stage 2 was designated as the period after secondary tillage, but before all plots were cultivated in the summer. The main part of the growing season was selected as stage 3, from summer cultivation to September 1 when crops were approximately mature. Stage 4 was designated as the end of the monitoring year when crop uptake was minimal. Table 1

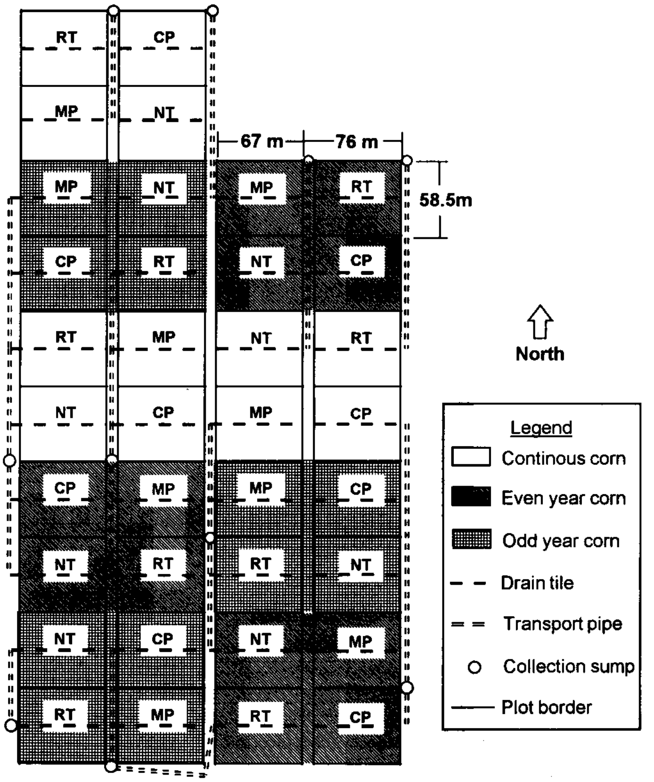

Figure 1–Plot layout at the Nashua water quality site.

Table 1. End date and duration (days) of seasonal stages

Stage	Field Operation	1990		1991		1992	
		Date	Duration	Date	Duration	Date	Duration
1	Apply fertilizer	30 April	0*	13 May	66	01 May	56
2	Cultivate	02 July	50*	20 June	38	03 June	33
3	Approx. maturity	01 Sept.	61	01 Sept.	73	01 Sept.	90
4	End of sampling	29 Nov.	89	04 Dec.	94	11 Dec.	101

* Data collection began 10 May 1990.

shows the end dates and duration for each seasonal stage during the three-year study. Since data collection began after fertilizer application in the first year of the study, data were not available for stage 1 of 1990.

Nitrate-N loss in drain effluent was calculated for each interval between flow meter readings by the following equation:

$$m = \left(\frac{Q_2 - Q_1}{100}\right)\left(\frac{C_2 + C_1}{2}\right) \qquad (1)$$

where

m = mass of nitrate-N in drain effluent (kg/ha)

Q_1 and Q_2 = cumulative drain flows (mm) for successive flow meter readings

C_1 and C_2 = nitrate-N concentrations (mg/L) in drain effluent when readings 1 and 2 were taken

Flow weighted nitrate-N concentrations for a stage were calculated by dividing the total nitrate-N loss (kg/ha) for the stage by the total drain flow (mm) for the stage and multiplying by 100.

Drain flow and nitrate-N concentration ratios were calculated between stages 2 and 3 to compare flow and concentration changes after summer cultivation. Drain flow ratios were calculated by dividing stage 2 flows by the stage 3 flows. Concentration ratios were similarly calculated using stage 2 and 3 nitrate-N concentrations. A ratio greater than one resulted when drain flow or nitrate-N concentration decreased between stages 2 and 3. The hypothesis was that more preferential flow paths were open at the soil surface under NT and RT systems before summer cultivation compared to after cultivation. Soil surface conditions should be similar between all tillage systems after cultivation. Therefore, drain flow and nitrate-N concentration ratios should be different for NT and RT than for MP and CP.

Treatment means were compared with analysis of variance ($p = 0.05$) for a randomized complete block design. Comparisons between drain flow, nitrate-N loss, and flow weighted nitrate-N concentrations were made for each seasonal stage.

Table 2. Actual and normal rainfall by seasonal stage

Stage	Rainfall (mm)					
	1990		1991		1992	
	Actual	Normal*	Actual	Normal*	Actual	Normal*
1	195†	123†	241	165	115	128
2	284	227	309	133	53	111
3	535	202	184	254	304	315
4	127	206	158	212	269	219
Total‡	1141	758	892	764	741	773

* Fifty-year mean.

† Assumed monitoring season began 10 March although data collection did not begin until 10 May.

‡ Monitoring season total not yearly total.

RESULTS AND DISCUSSION

Rainfall varied from above normal to below normal during the study (table 2). Subsurface drains did not flow during 1988 and 1989 because of severe drought. Low rainfall in these years combined with above normal rainfall in 1990 resulted in nitrate-N losses of 30 to 105 kg/ha and annual flow-weighted nitrate-N concentrations of 20 to 65 mg/L in drain effluent during 1990. Similar results were found by Randall and Iragavarapu (1995) in a southeastern Minnesota study. Annual flow-weighted nitrate-N concentrations decreased in 1991 and 1992, but still exceeded 10 mg/L for most treatments.

No-till continuous corn had lower yields than the other tillage systems for all three years. Three-year average yield from continuous corn (9.4 Mg/ha) was significantly lower ($p = 0.05$) than yield from rotation corn (10.2 Mg/ha) (table 3). Both CP (10.1 Mg/ha) and MP (10.1 Mg/ha) plots had significantly higher three-year average corn yield than RT (9.6 Mg/ha) plots which yielded significantly more than NT (9.3 Mg/ha) plots. For soybean, yields from MP (3.3 Mg/ha) and CP (3.3 Mg/ha) plots were significantly higher than from NT (3.2 Mg/ha) and RT (3.1 Mg/ha) plots.

Seasonal drainage data showed that a large portion of the annual nitrate-N loss in drain effluent occurred before fertilizer was applied (tables 4, 5, and 6). For 1991 and 1992, 35 to 60% of annual nitrate-N loss occurred before fertilizer application. If stage 1, 1990 data were available, annual nitrate-N losses for that year might have shown increases of 20 to 50 kg/ha, based on 1991 and 1992 data. Furthermore, 50 to 85% of annual drain flow and 45 to 85% of annual nitrate-N loss during 1991 and 1992 occurred during stages 1 and 4, when crops were not actively growing. Milburn and Richards (1994) similarly found that 85% of annual drain flow and 70% of annual nitrate-N loss occurred when crops were not actively growing. These high nitrate-N losses early and late in the season demonstrate that nitrogen fertilizer was not the only source of nitrate-N loss in subsurface drainage. Fertilizer was only applied once per year, but mineralization continued throughout the year. Cover crops could potentially reduce these losses by utilizing mineralized

Table 3. Corn and soybean yields for 1990 to 1992

Continuous Corn	Chisel Plow (Mg/ha)	Moldboard Plow (Mg/ha)	Ridge Till (Mg/ha)	No-till (Mg/ha)
1990	11.2	11.5	10.4	9.4
1991	8.8	9.2	8.0	7.3
1992	9.2	9.5	9.0	8.7
Rotation Corn				
1990	11.3	11.1	11.1	11.3
1991	9.9	9.6	9.2	9.0
1992	10.2	9.9	10.0	10.1
Rotation Soybean				
1990	3.4	3.3	3.3	3.4
1991	3.1	3.2	2.8	3.0
1992	3.4	3.5	3.3	3.1

Table 4. Drain flows, nitrate-N losses, and nitrate-N concentrations for continuous corn

	1990			1991			1992		
	Drain Flow (mm)	Nitrate-N Loss (kg/ha)	Nitrate-N Conc. (mg/L)	Drain Flow (mm)	Nitrate-N Loss (kg/ha)	Nitrate-N Conc. (mg/L)	Drain Flow (mm)	Nitrate-N Loss (kg/ha)	Nitrate-N Conc. (mg/L)
Stage 1									
CP				123 ab*	38	31 b	48	8	16 a
MP				93 b	35	38 a	46	9	19 a
RT				167 a	36	22 c	59	7	11 b
NT				167 a	34	21 c	57	8	12 b
Stage 2									
CP	66 ab	45	67 b	125 a	33	27 b	15	2	17 a
MP	17 b	15	86 a	71 b	23	32 a	11	2	19 a
RT	72 a	39	58 bc	135 a	27	20 c	8	1	12 b
NT	114 a	55	49 c	127 a	23	18 c	22	3	13 b
Stage 3									
CP	103	48	47 b	16 a	4	27	21 ab	3	14
MP	64	38	59 a	9 c	3	32	11 b	2	14
RT	108	41	38 c	13 b	3	23	7 b	1	9
NT	136	46	33 d	18 a	4	19	35 a	4	11
Stage 4									
CP	14	6	44 a	8	1	11	44	6	13
MP	9	5	54 a	10	2	12	42	6	13
RT	11	3	27 b	11	1	11	30	3	9
NT	23	6	26 b	24	2	9	64	6	10
Seasonal									
CP	183 b	100	54 b	272 a	76	28 b	128	19	15
MP	90 c	58	64 a	185 b	63	34 a	111	19	16
RT	191 ab	83	44 c	326 a	68	21 c	104	11	11
NT	275 a	107	39 c	336 a	63	19 c	178	20	11

* Different letters designate significant differences between tillage system averages for a stage or year (p = 0.05).

nitrogen in the fall and early spring. Water use by cover crops may also reduce drain flow.

TILLAGE EFFECTS ON SEASONAL CHANGES IN SUBSURFACE DRAINAGE

Secondary spring tillage and summer cultivation did not alter subsurface drainage for a seasonal stage. The NT systems usually had the highest drain flows and lowest nitrate-N concentrations, while MP systems usually had the lowest flows and highest concentrations, regardless of seasonal stage. The CP rotation corn and rotation soybean were exceptions. These CP plots had the highest drain flows and nitrate-N concentrations for several stages (tables 4, 5, and 6).

Table 5. Drain flows, nitrate-N losses, and nitrate-N concentrations for rotation corn

	1990			1991			1992		
	Drain Flow (mm)	Nitrate-N Loss (kg/ha)	Nitrate-N Conc. (mg/L)	Drain Flow (mm)	Nitrate-N Loss (kg/ha)	Nitrate-N Conc. (mg/L)	Drain Flow (mm)	Nitrate-N Loss (kg/ha)	Nitrate-N Conc. (mg/L)
Stage 1									
CP				91	19	21	53	6	12
MP				76	18	23	31	4	13
RT				75	14	18	38	4	11
NT				78	14	17	29	3	10
Stage 2									
CP	66	24	39	77	16	21	17	2	13 ab*
MP	41	15	39	60	15	22	11	2	15 a
RT	49	16	31	69	13	18	12	2	12 b
NT	62	21	34	82	14	17	6	1	12 b
Stage 3									
CP	104	24	24 a	6	1	21	24	2	10 a
MP	77	18	24 a	6	2	24	15	2	12 a
RT	74	13	19 b	9	2	22	25	2	10 a
NT	91	15	16 b	10	2	19	1	0	6 b
Stage 4									
CP	23	4	14	3	0	10	72	6	8
MP	28	5	18	8	1	10	40	3	8
RT	19	2	12	7	1	9	56	4	8
NT	4	1	10	9	1	7	23	0	6
Seasonal									
CP	193	52	28	177	37	21	165	17	10
MP	145	38	27	150	36	22	97	10	11
RT	143	30	22	160	30	18	131	12	10
NT	158	37	23	179	31	17	59	5	8

* Different letters designate significant differences between tillage system averages for a stage or year (p=0.05).

Table 6. Drain flows, nitrate-N losses and nitrate-N concentrations for rotation soybean

	1990			1991			1992		
	Drain Flow (mm)	Nitrate-N Loss (kg/ha)	Nitrate-N Conc. (mg/L)	Drain Flow (mm)	Nitrate-N Loss (kg/ha)	Nitrate-N Conc. (mg/L)	Drain Flow (mm)	Nitrate-N Loss (kg/ha)	Nitrate-N Conc. (mg/L)
Stage 1									
CP				155	26	16 a*	28	4	13
MP				141	24	17 a	30	4	12
RT				151	19	13 b	41	5	11
NT				146	18	12 b	23	2	9
Stage 2									
CP	48	22	44 a	132	18 a	13 a	6	1	14
MP	35	17	48 a	98	14 b	14 a	11	2	13
RT	52	17	33 b	108	12 b	11 b	10	1	12
NT	59	19	32 b	125	13 b	10 b	6	1	10
Stage 3									
CP	96	27	28 a	19	2	13 a	2	0	13 a
MP	60	21	31 a	17	2	15 a	2	0	12 b
RT	74	15	19 b	12	1	10 b	11	1	10 c
NT	99	17	17 b	12	1	10 b	6	1	8 c
Stage 4									
CP	12	3	23 a	13	1	8	33	3	10
MP	11	3	22 a	14	1	10	37	5	12
RT	12	2	12 b	5	0	10	27	3	10
NT	11	2	12 b	4	0	9	13	1	9
Seasonal									
CP	157	51	33 b	318	46	15 a	70	8	12
MP	107	41	37 a	270	42	15 a	80	12	12
RT	138	34	24 c	276	32	12 b	89	10	11
NT	169	37	22 c	287	32	11 b	48	5	9

* Different letters designate significant differences between tillage system averages for a stage or year (p = 0.05).

Drain flow was significantly different among tillage systems only under continuous corn, but never during stage 4 (table 4). This indicates that tillage effects on drain flows may have been reduced later in the growing season when corn was not growing. When significant differences occurred, NT always had higher drain flow than MP. Chisel plow had similar or higher drain flows than MP, while drain flow from RT was usually greater than MP and similar to NT.

Tillage significantly affected nitrate-N concentrations in drain effluent. As with drain flow, differences among treatments did not change during the monitoring season. Moldboard plow had significantly higher concentrations than NT and RT under continuous corn for 7 of the 11 stages during this study (table 4). Moldboard plow also had significantly higher concentrations than RT and NT for two stages under rotation corn and seven stages under rotation soybean (tables 5 and 6).

Concentration ratios or flow ratios were not significantly different among tillage systems (data not shown). One trend that occurred for all three years was higher nitrate-N concentration ratios for NT and RT under soybean rotation. Concentration ratios were higher because nitrate-N concentrations decreased more between stages 2 and 3 for NT and RT systems than for MP and CP systems. Lack of significant differences in these ratios indicated that summer cultivation did not effect previously untilled NT and RT plots differently than MP and CP plots.

RAINFALL EFFECTS ON SEASONAL CHANGES IN SUBSURFACE DRAINAGE

Flow weighted nitrate-N concentrations in drain effluent from continuous corn were very high in 1990 and generally decreased between stages throughout the study (fig. 2). Average concentrations from the four tillage systems under continuous corn ranged from 25 to 90 mg/L for stage 2 of 1990 and decreased to 10 to 15 mg/L by stage 4 of 1992. Drains did not flow during 1988 and 1989, and soil nitrate-N concentrations were high in the spring of 1990, especially for treatments that were planted to corn in 1989 (Weed and Kanwar, 1996). Above normal rainfall during stages 1, 2, and 3 of 1990 caused high drain flow rates and consequently high nitrate-N loss in drain effluent.

Nitrate-N concentrations did not notably increase between stages 1 and 2 after fertilizer application at the end of stage 1. Concentration changes between stages 1 and 2 were not known for 1990 because data collection did not begin until 10 May. Concentrations decreased between stages 1 and 2 of 1991 and slightly increased between these stages of 1992 (table 4). More than two times the normal rainfall amount occurred during stage 2 of 1991, which may have diluted nitrate-N that leached through the soil during this stage. The slight concentration increase between stages 1 and 2 of 1992 may have resulted from below normal rainfall during stage 2, which possibly concentrated nitrate-N moving through the soil. The only other concentration increase between stages for continuous corn occurred between stages 2 and 3 of 1991, when rainfall changed from above normal to 30% below normal.

Average nitrate-N concentrations under rotation corn followed similar trends as continuous corn except concentrations remained essentially constant between stages 1 and 2 of 1991 (table 5). If above normal rainfall during stage 2 diluted concentrations in drain effluent under continuous corn, then less dilution must have taken place under rotation corn, since concentrations did not decrease for three of the four tillage systems. Less dilution may have taken place because less preferential flow occurred under corn following soybean compared to corn following corn.

Flow weighted nitrate-N concentrations under rotation soybean decreased between stages 1 and 2 of 1991 (table 6), similar to continuous corn. Since concentrations did not decrease between these stages for rotation corn, the previous crop may have influenced the concentration change. Both continuous corn and rotation soybean had higher average drain flow volumes during stages 1 and 2 of 1991 than rotation corn. If the nitrate-N in drain effluent under continuous corn and rotation soybean was diluted by preferential flow, then more preferential flow must have occurred under these rotations compared to corn following soybean (rotation corn). At the same time, mineralization under corn following soybean may have released more nitrate-N than on the other rotations, causing concentrations in drain effluent between stages 1 and 2 of 1991 to remain constant for rotation corn, but decrease for continuous corn and rotation soybean.

Nitrate-N concentrations increased slightly for most soybean plots between stages 1 and 2 of 1992. Since soybean plots were not fertilized, the concentration increase resulted from something other than applied nitrogen. As stated previously, below normal rainfall during stage 2 of 1992 may have increased the nitrate-N concentration in drain effluent. Since concentrations increased slightly under all crop and tillage systems during this period, the cause seems to be related to weather not management. In addition to physical effects on leaching, rainfall likely altered microbial activity. Above normal rainfall may have resulted in conditions favoring denitrification and net immobilization while below normal rainfall conditions may have favored net mineralization.

RELATIONSHIP BETWEEN DRAIN FLOW AND NITRATE-N LOSS

Nitrate-N loss through subsurface drains from continuous corn treatments had similar trends as drain flow throughout the three-year study (figs. 3 and 4). The similarity between figures 3 and 4 indicates that the mass of nitrate-N lost through subsurface drainage correlates mainly with the volume of water drained, not the nitrate-N concentration. Previous studies have also concluded that nitrate-N loss through subsurface drains relates mainly to the quantity of drain flow (Bolton et al., 1970; Devitt et al., 1976).

Since drain flow, nitrate-N loss, and nitrate-N concentrations are all related, a convenient method for

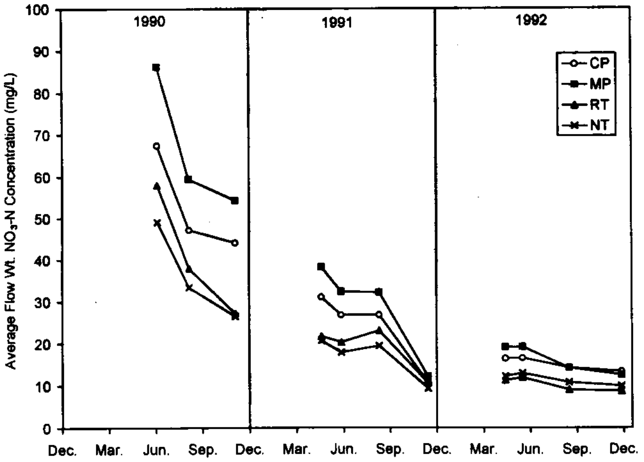

Figure 2–Average flow weighted nitrate-N concentrations in drain effluent by stage for continuous corn.

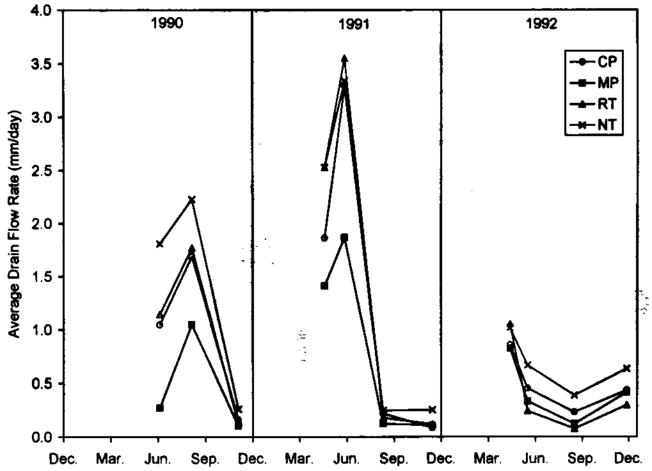

Figure 3–Average drain flow rate by stage for continuous corn.

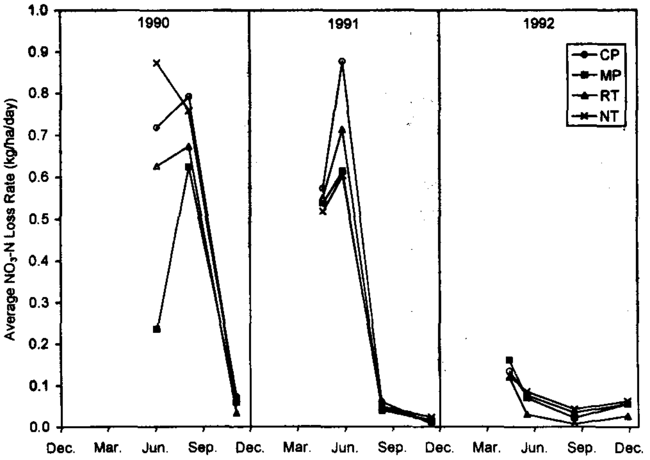

Figure 4–Average nitrate-N loss rate through subsurface drains by stage for continuous corn.

viewing these data is plotting cumulative drain flow against cumulative nitrate-N loss. The slope from a linear regression of data for an experimental plot is analogous to the average nitrate-N concentration for that plot. The flow weighted concentration equals the slope of a line from the origin to the last data point, while the regression slope is the best fit of all data points.

The relationship between drain flow and nitrate-N loss was essentially linear for all seasonal stages, showing that nitrate-N concentrations were relatively constant over a stage. A graph of MP and NT continuous corn data for 1992 was included as an example (fig. 5). Coefficients of determination exceeded 0.90 for 117 of the 132 linear regressions of drain flow and nitrate-N loss data for the three replications of a tillage system within a crop rotation (with y-intercept = 0). Ten of the 15 coefficients that did not exceed 0.90 were RT or NT systems. Differences in slopes for tillage systems, compared by t-tests, were highly significant ($p = 0.01$) for all stages, crops, and years (table 7). Regression equations for a particular stage, however, changed each year as soil and weather conditions changed, and therefore the equations were not predictive. Plotting drain flow against nitrate-N loss was merely another method for viewing and comparing data.

Under continuous corn, MP had significantly higher slopes than other tillage systems for all 11 stages of the study. Moldboard plow also had significantly higher slopes than other tillage systems for six stages under rotation corn and eight stages under rotation soybean. Both NT and RT had significantly lower slopes than MP and CP for all stages under continuous corn, 9 stages under rotation corn, and 10 stages under rotation soybean (table 7).

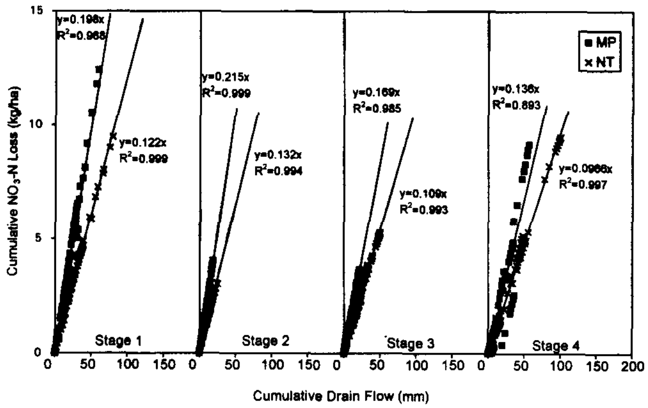

Figure 5–Cumulative nitrate-N loss vs. cumulative drain flow by stage from NT and MP continuous corn plots for 1992.

Table 7. Slopes from linear regression of drain flow (mm) – nitrate-N loss (kg/ha) data

	Continuous Corn			Rotation Corn			Rotation Soybean		
	1990	1991	1992	1990	1991	1992	1990	1991	1992
Stage 1									
CP		0.31 b*	0.15 b		0.20 b	0.12 a		0.17 a	0.14 b
MP		0.39 a	0.20 a		0.24 a	0.12 a		0.17 a	0.16 a
RT		0.22 c	0.12 d		0.18 c	0.11 b		0.13 b	0.12 c
NT		0.20 d	0.12 c		0.16 d	0.10 b		0.13 b	0.10 d
Stage 2									
CP	0.72 b	0.26 b	0.15 b	0.34 a	0.20 b	0.13 b	0.45 b	0.14 b	0.14 b
MP	0.93 a	0.33 a	0.21 a	0.37 a	0.26 a	0.14 a	0.50 a	0.14 a	0.16 a
RT	0.55 c	0.20 c	0.12 d	0.31 b	0.19 c	0.12 c	0.32 c	0.11 c	0.13 c
NT	0.46 d	0.18 d	0.13 c	0.35 a	0.17 d	0.11 d	0.32 c	0.11 c	0.11 d
Stage 3									
CP	0.49 b	0.27 b	0.15 b	0.25 b	0.21 c	0.10 b	0.31 b	0.13 b	0.15 a
MP	0.62 a	0.33 a	0.17 a	0.27 a	0.27 a	0.12 a	0.38 a	0.15 a	0.12 b
RT	0.43 c	0.21 c	0.08 d	0.19 c	0.22 b	0.10 b	0.26 c	0.10 c	0.11 c
NT	0.38 d	0.19 d	0.11 c	0.19 c	0.20 d	0.09 b	0.20 d	0.10 c	0.09 d
Stage 4									
CP	0.47 b	0.16 b	0.12 b	0.17 a	0.13 a	0.08 b	0.24 b	0.10 a	0.10 c
MP	0.60 a	0.18 a	0.14 a	0.16 b	0.13 a	0.07 c	0.29 a	0.10 a	0.14 a
RT	0.27 c	0.13 c	0.09 d	0.11 c	0.10 b	0.08 a	0.16 c	0.08 b	0.11 b
NT	0.25 d	0.13 c	0.10 c	0.10 d	0.09 c	0.06 d	0.13 d	0.07 c	0.10 c

* Different letters designate significant differences between tillage systems for a stage and year ($p = 0.01$).

Higher slopes for MP systems indicate more nitrate-N was lost for every unit of water draining from the plot. Figure 5 shows that tillage had an effect on nitrate-N concentration of drain effluent. Concentration differences between tillage systems did not seem to be the result of simple dilution (i.e., high drain flow results in lower nitrate-N concentration). Experimental plots with the highest nitrate-N concentrations had the lowest drain flow for only three stages. However, plots with the lowest drain flow had the lowest concentration for six stages. Concentration differences may have been partially caused by variations in nitrogen transformations and preferential flow. Preferential flow tends to start near the soil surface in NT systems, but below the tilled layer under conventional tillage (Andreini and Steenhuis, 1990; Steenhuis et al., 1990). Water flowing uniformly through tilled soil has a greater chance of leaching nitrate-N than water bypassing surface soil by preferential flow. More nitrogen may also have been immobilized as organic nitrogen (Kitur et al., 1984; Rice and Smith, 1984) or denitrified (Doran, 1980; Rice and Smith, 1982) under NT and RT.

CONCLUSIONS

Data from this study indicate that NT and RT systems can be used to decrease nitrate-N concentrations in drain effluent compared to MP and CP systems. Tillage, however, did not influence the mass of nitrate-N in drain effluent. The amount of nitrate-N lost through subsurface drains may be reduced by decreasing drain flow through controlled drainage, since nitrate-N loss primarily correlates with drain flow not nitrate-N concentration.

Neither mass nor concentration of nitrate-N in drain effluent increased after nitrogen fertilizer was applied. Differences among tillage systems did not change after summer cultivation, even though NT and RT systems had not been tilled before this time. Lack of significant differences in concentration and flow ratios indicate that summer cultivation did not affect previously untilled NT and RT plots differently from MP and CP plots.

Seasonal changes in nitrate-N concentrations can be explained by changes in rainfall and drain flow, but other factors are included. High nitrate-N losses in subsurface drainage before fertilizer application (35 to 65%) demonstrates the importance of considering the entire nitrogen cycle. Inorganic nitrogen, for example, is released in the soil throughout the year by mineralization, not just when fertilizer is applied. Cover crops or nitrogen management practices, such as the late spring soil nitrate test, should be considered for future study to attempt to reduce the early and late season nitrogen losses.

REFERENCES

Andreini, M. S. and T. S. Steenhuis. 1990. Preferential paths of flow under conventional and conservation tillage. *Geoderma* 46(1-3):85-102.

Baker, J. L., K. L. Campbell, H. P. Johnson and J. J. Hanway. 1975. Nitrate, phosphorus, and sulfate in subsurface drainage water. *J. Environ. Qual.* 4(3):406-412.

Baker, J. L. and H. P. Johnson. 1981. Nitrate-nitrogen in tile drainage as affected by fertilization. *J. Environ. Qual.* 10(4):519-522.

Baker, J. L. and J. M. Laflen. 1983. Water quality consequences of conservation tillage. *J. Soil Water Conserv.* 38(3):186-193.

Blevins, R. L., G. W. Thomas, M. S. Smith, W. W. Frye and P. L. Cornelius. 1983. Changes in soil properties after 10 years continuous non-tilled and conventionally tilled corn. *Soil Tillage Res.* 3(2):135-146.

Bolton, E. F., J. W. Aylesworth and F. R. Hore. 1970. Nutrient losses through tile drains under three cropping systems and two fertility levels on a Brookston clay soil. *Canadian J. Soil Sci.* 50(3):275-279.

Devitt, D., J. Letey, L. J. Lund and J. W. Blair. 1976. Nitrate-nitrogen movement through soil as affected by soil profile characteristics. *J. Environ. Qual.* 5(3):283-288.

Dick, W. A., E. L. McCoy, W. M. Edwards and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. *Agron. J.* 83(1):64-73.

Doran, J. W. 1980. Soil microbial and biochemical changes associated with reduced tillage. *Soil Sci. Soc. Am. J.* 44(4):765-771.

Dou, Z., R. H. Fox and J. D. Toth. 1995. Seasonal soil nitrate dynamics in corn as affected by tillage and nitrogen source. *Soil Sci. Soc. Am. J.* 59(3):858-864.

Dunn, G. H. and R. E. Phillips. 1991. Macroporosity of a well-drained soil under no-till and conventional tillage. *Soil Sci. Soc. Am. J.* 55(3):817-823.

Edwards, W. M., M. J. Shipitalo, L. B. Owens and L. D. Norton. 1989. Water and nitrate movement in earthworm burrows within long-term no-till cornfields. *J. Soil Water Conserv.* 44(3):240-243.

Ehlers, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. *Soil Sci.* 119(3):242-249.

Freese, R. C., D. K. Cassel and H. P. Denton. 1993. Infiltration in a Piedmont soil under three tillage systems. *J. Soil Water Conserv.* 48(3):214-218.

Guitjens, J. C., P. S. Tsai and D. F. Thran. 1984. Quantity and quality variations in subsurface drainage. *Transactions of the ASAE* 27(2):425-428.

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. *Transactions of the ASAE* 31(2):453-461.

Kanwar, R. S., D. Karlen, T. S. Colvin, W. W. Simpkins and V. J. McFadden. 1993. Evaluation of tillage and crop rotation effects on groundwater quality – Nashua project. Completion report prepared for Leopold Center for Sustainable Agriculture, Ames, Iowa. No. 90-41.

Karlen, D. L., E. C. Berry, T. S. Colvin and R. S. Kanwar. 1991. Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa. *Commun. Soil Sci. Plant Anal.* 22(19/20):1985-2003.

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(2):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(1):264-270.

Milburn, P. and J. E. Richards. 1994. Nitrate concentration of subsurface drainage water from a corn field in southern New Brunswick. *Canadian Agric. Eng.* 36(2):69-77.

Pesant, A. R., J. L. Dionne and J. Genest. 1987. Soil and nutrient losses in surface runoff from conventional and no-till corn systems. *Canadian J. Soil Sci.* 67(4):835-843.

Randall, G. W. and T. K. Iragavarapu. 1995. Impact of long-term tillage systems for continuous corn on nitrate leaching to tile drainage. *J. Environ. Qual.* 24(2):360-366.

Rice, C. W. and M. S. Smith. 1982. Denitrification in no-till and plowed soils. *Soil Sci. Soc. Am. J.* 46(6):1168-1173.

Rice, C. W. and M. S. Smith. 1984. Short-term immobilization of fertilizer nitrogen at the surface of no-till and plowed soils. *Soil Sci. Soc. Am. J.* 48(2):295-297.

Singh, P. and R. S. Kanwar. 1991. Preferential solute transport through macropores in large undisturbed saturated soil columns. *J. Environ. Qual.* 20(1):295-300.

Steenhuis, T. S., W. Staubitz, M. S. Andreini, J. Surface, T. L. Richard, R. Paulsen, N. B. Pickering, J. R. Hagerman and L. D. Geohring. 1990. Preferential movement of pesticides and tracers in agricultural soils. *J. Irrig. Drainage Eng.* 16(1):50-66.

Weed, D. A. J. and R. S. Kanwar. 1996. Nitrate and water present in and leaching from root-zone soil. *J. Environ. Qual.* (In press).

Wu, L., J. B. Swan, R. R. Allmaras and S. D. Logsdon. 1995. Tillage and traffic influences on water and solute transport in corn-soybean systems. *Soil Sci. Soc. Am. J.* 59(1):185-191.