Nitrate Leaching to Subsurface Drains as Affected by Drain Spacing and Changes in Crop Production System

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ABSTRACT

Subsurface drainage is a beneficial water management practice in poorly drained soils but may also contribute substantial nitrate N loads to surface waters. This paper summarizes results from a 15-yr drainage study in Indiana that includes three drain spacings (5, 10, and 20 m) managed for 10 yr with chisel tillage in monoculture corn (*Zea mays* L.) and currently managed under a no-till corn–soybean [*Glycine max* (L.) Merr.] rotation. In general, drainflow and nitrate N losses per unit area were greater for narrower drain spacings. Drainflow removed between 8 and 26% of annual rainfall, depending on year and drain spacing. Nitrate N concentrations in drainflow did not vary with spacing, but concentrations have significantly decreased from the beginning to the end of the experiment. Flow-weighted mean concentrations decreased from 28 mg L^{-1} in the 1986–1988 period to 8 mg L^{-1} in the 1997–1999 period. The reduction in concentration was due to both a reduction in fertilizer N rates over the study period and to the addition of a winter cover crop as a "trap crop" after corn in the corn–soybean rotation. Annual nitrate N loads decreased from 38 kg ha^{-1} in the 1986–1988 period to 15 kg ha^{-1} in the 1997–1999 period. Most of the nitrate N losses occurred during the fallow season, when most of the drainage occurred. Results of this study underscore the necessity of long-term research on different soil types and in different climatic zones, to develop appropriate management strategies for both economic crop production and protection of environmental quality.

S UBSURFACE DRAINAGE (often called "tile" drainage) is a common water management practice in agricultural regions with seasonally high water tables. The practice of subsurface drainage provides many agronomic and environmental benefits, including greater water infiltration, lower surface runoff and erosion, and improved crop growth and yield compared with similar agricultural soils without subsurface drainage (Skaggs and Van Schilfgaarde, 1999). Subsurface drains have been found to reduce losses of sediment and phosphorus from agricultural fields but to increase losses of nitrate N through the enhanced leaching of the soil profile (Gilliam et al., 1999). An appropriate balance between increasing drainage intensity (narrower spacing) to improve drainage and decreasing drainage intensity to reduce nitrate N losses needs to be found for different climatic and soil regions. Research on nitrate leaching into subsurface tile drains has been conducted for many years (Logan et al., 1980; Baker and Johnson, 1981), but recent

concerns about the hypoxic zone in the Gulf of Mexico and similar problems worldwide have caused a renewed interest in tile drain studies. Tile drainflow provides an integrated measure of nitrate leaching on a field scale and thus can be an excellent tool for evaluating the impact of soil, climate, and management practices on nitrate losses below the rootzone. Because tile drainflow contributes significant amounts of water and nitrate to ditches and streams during some months of the year, drainage studies provide valuable data for estimating nitrate loads in agricultural watersheds.

Nitrate concentrations and mass losses in subsurface tile drains vary with soil organic matter level, yearly weather variations, fertilizer N rates and timing, drain spacing, cover crop growth, cash crop yield, and water table control practices (Baker and Johnson, 1981; Bergstrom, 1987; Drury et al., 1996; Kladivko et al., 1999; Gentry et al., 2000; Jaynes et al., 2001; Randall and Mulla, 2001; Dinnes et al., 2002). Noncontrollable factors such as precipitation and the mineralization of soil organic matter have a great impact on drainage volumes and nitrate loads (Randall and Goss, 2001), which therefore put limits on the concentrations and loads that can be achieved while using the land for row-crop agriculture. Research on the controllable factors of fertilizer, crop, and drainage system management practices must be done within the larger context of climate and soil organic matter content and ideally over a long enough time period to encompass a typical range of weather variation. There are relatively few long-term (>10 yr) studies of nitrate leaching on a field scale. Our 15-yr study provides an important data set for assessments of nitrate leaching in the Mississippi River basin. Our site is on a low organic matter (approximately 1.3%), loess-derived silt loam soil in southeastern Indiana, which contrasts with the high organic matter soils of most of the drainage studies in Iowa, Minnesota, and Illinois. By comparing results from different soils and climatic zones within the Midwest, scientists and policymakers will hopefully gain greater understanding of the challenges to reducing nitrate loads to subsurface drains.

The objectives of our study were to (i) evaluate the effect of three different drain spacings on water flow and nitrate leaching into subsurface drains over a 15-yr period and (ii) measure changes in nitrate leaching that would result from first converting from conventional monoculture corn with high N fertilizer rates to the same cropping system with lower N rates, and then to a no-till corn–soybean rotation with lower fertilizer N rates and a winter "trap crop."

MATERIALS AND METHODS

A subsurface drainage research facility was established in 1983 at the Southeastern Purdue Agricultural Center (SEPAC)

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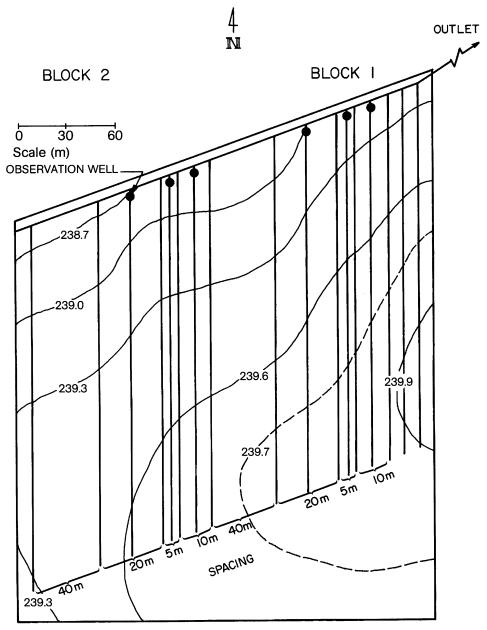
Fig. 1. Layout of subsurface drain spacing experiment on the Southeast Purdue Agricultural Center (SEPAC) experimental drainage field. Surface elevation contours are shown in meters.

(39°01′33″N, 85°32′24″W) in southeastern Indiana, USA. The site has been described in detail by Kladivko et al. (1991, 1999). The soil at the site is a Clermont silt loam (fine silty, mixed, superactive, mesic Typic Glossaqualf) and is typical of extensive areas of similar soils across southern Ohio, Indiana, and Illinois. The soil was formed in 50 to 120 cm of loess over glacial till. The surface soil at the study site is light gray, low organic carbon (0.7%) silt loam containing 66% silt, 22% sand, and 12% clay. The soil is slowly permeable, and has a borderline fragipan at the 120-cm depth that severely restricts further downward drainage. Although subsurface tile drainage had not traditionally been used on these soils due to concerns of siltation in the tiles and the slow permeability of the soil, the past few decades have seen an increase in use of modern, perforated plastic drain tubing in these soils, with good success. The field experimental site has drains (10-cm diameter) installed at spacings of 5, 10, and 20 m at an average depth of

75 cm and a slope of 0.4%. Three drain lines (225-m length) were installed at each spacing, with the outside drain lines on each spacing acting as common drains between treatments (Fig. 1). Each spacing was replicated in two blocks separated by a 40-m distance.

The center drains of the 5-, 10-, and 20-m plots discharged into observation wells at the bottom of the slope. Subsurface drainflow volumes were monitored continuously with tipping-bucket flow gauges connected to a datalogger, and flow-proportional samples were collected with automatic water samplers (Isco, Lincoln, NE) during all time periods in which there was flow. During 1991 to 1994 the datalogger system was not available, and daily flow volumes were obtained from cumulative tipping bucket data retrieved manually each week-day from the Isco samplers. Therefore, during 1991 to 1994 the flow recorded each Monday was the cumulative flow over the previous 3-d period. The Isco sampler daily data or other

Table 1. Field management practices and crop yields.

Year	Crop	Tillage	Preplant fertilizer N	Nitrapyrin	Starter N	Total N applied	Winter "trap crop"	Crop yield† 5 m	10 m	20 m
			kg ha^{-1}		——— kg ha^{-1} ———			——— Mg ha^{-1} ———		
1985	corn	chisel	285	yes	8	293	no	11.1	11.5	11.3
1986	corn	chisel	285	yes	21	306	no	8.1	8.3	8.5
1987	corn	chisel	285	yes	22	307	no	11.6	12.1	12.1
1988	corn	chisel	285	yes	11	296	no	8.0	8.4	7.7
1989	corn	chisel	228	yes	20	248	no	9.9	9.6	8.8
1990	corn	chisel	228	yes	28	256	no	8.3	7.6	7.7
1991	corn	chisel	228	yes	28	256	no	7.3	7.1	7.9
1992	corn	chisel	228	yes	28	256	no	10.7	10.6	10.1
1993	corn	chisel	228	yes	28	256	no	10.2	9.9	10.0
1994	soybean	no-till	0	NA	0	0	no	4.8	4.5	4.7
1995	corn	no-till	200	yes	28	228	yes	8.6	8.5	9.2
1996	soybean	no-till	0	NA	0	0	no	3.5	3.4	3.6
1997	corn	no-till	177	no	28	205	yes	8.9	8.6	8.8
1998	soybean	no-till	0	NA	0	0	no	3.5	3.4	3.5
1999	corn	no-till	177	no	28	205	yes	9.9	10.1	10.1

† Average of both blocks.

estimations were also used to patch gaps in datalogger data that occurred sporadically in other years. Water samples were frozen until subsequent laboratory analysis. Nitrate N mass losses were calculated as the product of water flow volumes and concentrations and were expressed on a per hectare basis, assuming that each drainline collects water from midplane to midplane. A linear interpolation of concentrations was used to estimate concentrations on days between measurement points, with a few exceptions where averages from other drains or adjacent time periods were used as estimates when there were limited measurement points. Rainfall was measured at the field site during 1985 to 1990 and in 1996 to 1997. Rainfall data from weather stations 10-km distant (North Vernon, 39°02′ N, 85°36′ W) or sometimes 32-km distant (Versailles, 39°04′ N, 85°15′ W, or Seymour, 38°59′ N, 85°59′ W) were used for time periods when on-site data were not available.

Corn was planted each year from 1984 (one year before nitrate N measurements began) through 1993, using conventional tillage (chisel plow to a 20- to 25-cm depth in spring, followed by two passes with a disc or field cultivator). In 1994 a no-till, soybean–corn rotation was begun, with the addition of a winter wheat (*Triticum aestivum* L.) cover crop after corn as a "trap crop" for N in the soil profile. Fertilizer N rates were gradually reduced during the course of the 16-yr experiment, as new knowledge became available and fertilizer rate "philosophy" changed within the Purdue extension recommendations. Preplant fertilizer N rates were 285 kg N ha^{-1} for the first 5 yr of monoculture corn, 228 kg N ha^{-1} for the last 5 yr of monoculture corn, 200 kg N ha^{-1} in 1995, and 177 kg N ha^{-1} in 1997 and 1999, all preplant-applied as anhydrous ammonia. The nitrification inhibitor nitrapyrin [2-chloro-6-(trichloromethyl) pyridine] was used at a rate of 0.56 kg a.i. ha^{-1} with the anhydrous ammonia applications from 1984 through 1995 (excluding 1994 as soybean was grown and no N was applied in that year). A small amount (8–28 kg N ha^{-1}) of "starter" fertilizer N (as 18–15–0 of N–P–K in 1984–1989, and 19–7–0 liquid blend starting in 1990) was also applied during the planting operation for corn. Table 1 lists field management practices and crop yields for the 15-yr period of nitrate N measurements.

Statistical Analyses

An ANOVA approach was initially examined as the method for testing drain spacing effects on flow and load. However, results and diagnostics revealed problems and complications for unambiguous interpretation. Problems included

that the two blocks responded very differently, the concentration and load responses were time dependent, and the block × treatment interaction for load was a large effect and varied in magnitude over time. Alternative analyses that were better able to assess the treatment differences within each block were selected and are described in the following sections.

Flow

To test for differences in flow among drain spacings, values for annual flow were calculated for each drain. In each case, the annual drainflow record was reasonably stationary (without a long-term trend). Because the differences in flow between the two blocks were large, a simple paired observation comparison (*t* test) was used to test for significant differences in flow within each pair of spacings within each block (e.g., Steel and Torrie, 1980).

Concentration

To model the trend in each drain's concentration record over the 15-yr period, annual flow weighted mean concentrations (C in mg N L^{-1}) were calculated for each drain. Based on Emerson and Stoto's test (e.g., Chapter 4 in Hoagland et al., 1983), the concentration data were reasonably characterized by a lognormal distribution; hence the data were log-transformed. Time response (repeated measures) models were developed for the concentration vs. time behavior of each individual drain. At least two model forms including polynomial regressions were considered, but spline forms with segmented polynomials and/or rational polynomials were selected (e.g., Jaynes et al., 2001, 2004). A segmented polynomial is a function defined by a simple polynomial on each of two or more separate intervals of the independent variable (here, the time in years), and a rational polynomial is the quotient of two simple polynomials (Rivlin, 1969; Kimball, 1976). Robust regression methods using Ramsay's E_a robust weight, with $a = 0.3$ were employed in an iteratively reweighted nonlinear least squares regression procedure. Model selection and comparison were based on multiple performance statistics (including mean square error, prediction error sum of squares [PRESS] and their corresponding coefficients of determination, variance ratio, and Akaike Information Criterion [AIC]) and residual diagnostics (including autocorrelation tests). The final selected form of the regression was:

$$\ln(C) = a_0 + a_1 \, \text{seq}; \; \text{seq} \leq k t_1$$

$$\ln(C) = a_0 + a_1 kt_1 - a_1(\text{seq} - kt_1); \text{seq} > kt_1$$

where seq (sequence) is time in years past the start of the project (1985 equals Year 1); the parameters a_0, a_1, and kt_1 are all greater than or equal to zero; and kt_1 is the knot or fitted joint point where in our case the slope changes from positive to negative (change point between increasing and decreasing concentrations). When the 95% confidence interval of the slope parameter did not include zero, the trend with time was considered to be statistically significant. To test for differences in the regression parameters between spacings within each block, simple paired null hypothesis tests between model parameters for each pair of drain spacings were used.

Load

Two different types of analyses were used to assess the nitrate N loads over the 15-yr period. The first analysis was used to model the trend with time in nitrate N load for each drain, in a similar procedure as described for the concentration vs. time regressions. Annual total nitrate N load values (L in kg N ha^{-1}) were calculated for each drain. The 1985 data were excluded because the record was incomplete (9 mo only). Load values were rescaled with the square root transformation to improve normality. The final selected model form was:

$$\sqrt{(L)} = a_0 + a_1 \text{seq}^2; \qquad\qquad \text{seq} \leq kt_1$$

$$\sqrt{(L)} = a_0 + a_1 kt_1^2 - \sqrt{(a_1)} (\text{seq} - kt_1); \quad \text{seq} > kt_1$$

where seq is time in years past the start of the project; the parameters a_0, a_1, and kt_1 are all greater than or equal to zero; and kt_1 is the knot or fitted joint point where the slope changes.

The second type of analysis tested for significant differences in loads between drain spacings within each block. This was done by fitting a regression model to the measured *differences* in annual loads within each pair of drains. The 95% confidence interval of the fitted difference for each year was then calculated, and for periods when the confidence interval did not include zero, the differences between the two drains were considered statistically significant.

Seasonal Patterns

To test whether concentrations varied consistently on a seasonal basis within years, several types of analyses were conducted. For each drain record, monthly flow-weighted mean concentrations were log-transformed for the same reasons discussed for the annual concentrations. The data for each drain were then examined for seasonal differences with several methods including graphical exploratory data analysis and ANOVA procedures that considered both long-term trend and autocorrelation structure. Unfortunately, diagnostics revealed violations of the usual error structure assumptions even after simple corrective procedures were applied (e.g., Littell et al., 1996). Because the purpose of the seasonal analysis was simply and briefly to compare with general trends found by other researchers, more complicated tests were not performed and exact probabilities are not reported. Instead, the tendency for the occurrence of seasonal patterns in concentration will be summarized.

Concentration versus Flow

To test whether there was a relationship between concentrations and flow rate, several different types of analyses were performed. Data for these analyses were from Tuesday through Friday only, since Saturday through Monday data represented a flow-weighted concentration from three days, rather than one day. Simple correlations of daily nitrate N concentration vs. daily flow were performed for each drain, for the overall record and by year, month, and quarter. An overall correlation for all drains and years was also calculated. In addition, a frequency analysis was performed to test for changes in concentration vs. changes in flow rate. Both flow and concentration data were grouped by whether they had increased or decreased since the previous measurement point. Both frequency analysis (e.g., Steel and Torrie, 1980) and simple correlation tests were performed with the resulting data set.

RESULTS AND DISCUSSION

Most results are presented first as annual averages with a discussion of trends over the 15-yr period. Results from a 3-yr period near the beginning of the experiment (1986 through 1988, the first three full calendar years of nitrate N measurements) are compared with results from a 3-yr period near the end of the experiment (1997 through 1999) to highlight the changes that have occurred over the long-term experiment. In addition, for the hydrology results, a comparison is made of the entire 9 yr in continuous corn vs. the entire 6 yr in the soybean–corn rotation. Finally, seasonal patterns and concentration behavior within individual flow events are discussed.

Hydrology

Annual rainfall over the 15-yr period ranged from a low of 800 mm for 1987 to a high of 1366 mm in 1995 (Table 2), with the 15-yr average (1118 mm) being nearly equal to the 30-yr "normal." Drainflow volumes varied among years as a result of the differences in annual rainfall and the timing of the rainfall within each year. Drainflow per unit area decreased as drain spacing became wider, as expected (Table 2). Averaged across both blocks, drainflow varied from a low of 6.7 cm (8% of annual rainfall) for the 20-m spacing in 1987, which was the driest year in the study (800 mm rainfall), to a high of 32.5 cm (26% of annual rainfall) for the 5-m spacing in 1985. A similarly wide range of drainflows between 0 and 40% of annual rainfall has been found across a range of studies in the humid regions of North America (Kladivko et al., 2001).

Drainflow from the west block was greater than from the east block, as has been the case since the beginning of the experiment. Averaged across the 15-yr period, the west block had 60% greater annual flow than the east block. Relationships among the three spacings in each of the blocks have been generally consistent, with greatest drainflow per area from the 5-m spacing and the lowest drainflow per area from the 20-m spacing (Table 2). Paired t tests showed significant differences ($P \leq 0.05$) in drainflow in all drain pairs (5 vs. 10, 10 vs. 20, 5 vs. 20 m) within each block, when considering the 15-yr period as a whole. Differences in flow between drain spacings occurred in most of the 15 yr for all drain pairs except the 10- vs. 20-m east plots, which had five years with similar drainflows and the first year of the study with greater flow in the 20-m plot than in the 10-m plot.

Table 2. Annual rainfall, percent of "normal" rainfall, and drainflow as affected by drain spacing.

	Rainfall		Drainflow								
			East block			West block			Average of both blocks		
Year	Amount	% of normal†	5 m	10 m	20 m	5 m	10 m	20 m	5 m	10 m	20 m
	mm	%					cm				
1985‡	1260	112	30.5	10.4	14.1	34.5	26.5	17.7	32.5	18.5	15.9
1986	1061	94	16.1	9.0	7.9	27.1	20.5	15.7	21.6	14.8	11.8
1987	800	71	10.1	5.8	4.4	15.0	11.8	9.0	12.5	8.8	6.7
1988	1001	89	23.0	10.8	8.3	25.7	21.8	15.3	24.4	16.3	11.8
1989	1231	109	25.5	12.9	12.3	35.0	29.2	21.0	30.3	21.1	16.6
1990	1255	111	24.9	10.6	10.1	29.8	24.9	21.6	27.4	17.7	15.8
1991	1101	97	16.4	7.6	7.4	23.2	18.4	16.0	19.8	13.0	11.7
1992	1120	99	11.2	6.8	5.4	21.7	16.5	17.0	16.4	11.7	11.2
1993	1323	117	21.6	11.4	11.4	27.4	25.7	16.6	24.5	18.5	14.0
1994	1035	92	18.1	8.2	8.1	29.1	15.9	12.6	23.6	12.1	10.4
1995	1366	121	19.8	13.3	9.9	24.5	20.0	15.3	22.1	16.6	12.6
1996	1152	102	24.2	15.7	14.4	32.3	29.3	22.2	28.2	22.5	18.3
1997	1040	92	20.8	14.5	12.1	26.2	29.9	21.7	23.5	22.2	16.9
1998	1154	102	18.5	14.0	13.6	26.5	28.1	20.4	22.5	21.0	17.0
1999	872	77	16.1	11.1	8.7	17.1	17.4	14.6	16.6	14.3	11.7
15-yr average	1118	99	19.8*	10.8*	9.9*	26.3*	22.4*	17.1*	23.1	16.6	13.5

† Thirty-year normal precipitation (1971–2000) from North Vernon, IN.
‡ Includes all 12 mo of 1985, even though nitrate N loads (Table 5) are only for 9 mo.
* Paired *t* tests showed significant differences at the 0.05 probability level in drainflow in all pairs of drains within each block (5 m E vs. 10 m E, 10 m E vs. 20 m E, 5 m E vs. 20 m E, 5 m W vs. 10 m W, 10 m W vs. 20 m W, 5 m W vs. 20 m W).

Drainflow as a percent of annual rainfall ("drainage efficiency") was calculated for each year and each drain and averaged over the various time periods of interest. Averaged over the 15-yr period, drainage efficiencies were 20.6, 14.9, and 12.1% for the 5-, 10-, and 20-m spacings, respectively. A comparison was made between the two different cropping systems used in different time periods of the study, namely continuous corn with chisel tillage in 1985–1993 vs. the 1994–1999 system of soybean–corn rotation with no-till and a winter wheat cover crop after corn. Due to the lack of on-site rainfall data during the 1991–1995 and 1998–1999 time periods, however, the calculated drainage efficiency values for those years are not as certain as the other time periods. The actual measured drainflow (cm) is not affected by the inaccuracies of the rainfall data and is discussed at the same time.

Average annual drainage efficiencies were 20.4, 13.7, and 11.2% (23.3, 15.6, and 12.8 cm flow) for the 5-, 10-, and 20-m spacings, respectively, for the 1985–1993 continuous corn years, and 20.8, 16.5, and 13.2% (22.8, 18.1, and 14.5 cm flow), respectively, during the 1994–1999 soybean–corn years. The data suggest that the drainage efficiency did not change over time for the 5-m spacing, but that the 10- and 20-m spacings showed an increased efficiency during the later time period. This increased efficiency for the wider spacings may reflect a maturation of the drainage system over time, with flow paths to the drains developing from greater distances over the years after drain tiles were installed. Detailed analysis of individual storm hydrographs would be needed to further evaluate this hypothesis and is beyond the scope of this paper. Because the 5-m spacing showed no evidence for a change in drainage efficiency with time, it suggests that the changes for the 10- and 20-m plots were not due to evapotranspiration differences resulting from the new cropping system. We cannot separate the effects of changes in tillage (chisel to no-till), crop (continuous corn to soybean–corn rotation), and winter cover crop (none to winter wheat) in

this experiment, but the combination of changes apparently caused no major change in drainage efficiency for this field.

Within the six years of soybean–corn rotation, there were no apparent trends in drainflow or drainage efficiency between the corn years and the soybean years. Each year had a different combination of rainfall timing, intensity, and amount, and so it was not possible to discern any consistent effects between the two crops because they were not both grown in the same year.

Nitrate Nitrogen Concentrations

Nitrate N concentrations in drainflow decreased considerably over the 15-yr period. Concentrations were consistently in the 20 to 30 mg L^{-1} range in the 1985 to 1988 period and in the 7 to 10 mg L^{-1} range in the 1996 to 1999 period (Table 3). Concentrations did not vary with block or drain spacing.

Table 3. Annual flow-weighted mean nitrate N concentrations as affected by drain spacing.

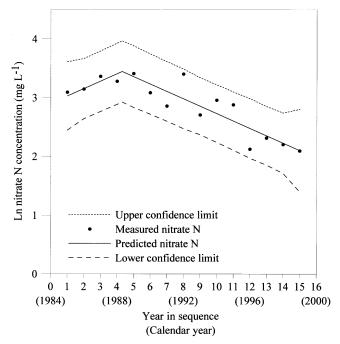| | | Concentration† | | |
		Drain spacing		
Year	Crop	5 m	10 m	20 m
		mg L^{-1}		
1985	corn	19.9	20.0	20.3
1986	corn	22.4	25.0	23.4
1987	corn	31.6	33.5	30.5
1988	corn	26.8	29.0	27.4
1989	corn	32.6	34.5	30.1
1990	corn	24.1	22.5	20.7
1991	corn	13.3	15.6	15.7
1992	corn	27.7	30.1	28.0
1993	corn	16.9	17.1	15.3
1994	soybean	19.8	17.4	18.2
1995	corn	17.8	15.1	15.9
1996	soybean	6.9	7.1	7.1
1997	corn	9.6	10.7	10.3
1998	soybean	6.5	7.0	7.2
1999	corn	6.6	6.4	6.9

† Averaged across both blocks.

Fig. 2. Measured flow-weighted mean annual nitrate N concentrations in drainflow, and regression predictions with 95% confidence limits, for the 20-m west plot over the 15-yr study. The regression model is listed in Table 4.

Regression analyses, as described in the Materials and Methods section, were used to test whether the trends with time were statistically significant. An example regression for the 20-m west drain (Fig. 2) shows that concentrations trended upward over the first 4.3 yr (knot point value) and then downward over the last 10.7 yr. Table 4 shows values of starting concentration (intercept), knot (joint point between increasing and decreasing concentrations), and slope for all six drains. Slopes ranged from 0.126 to 0.178 ln(mg L^{-1}) yr^{-1}. The 95%

Table 4. Regression parameters† for flow-weighted annual mean nitrate N concentrations vs. time for all six drains.

Drain	R^2	Parameter	Estimate	Standard error	95% Confidence limits	
5 m east	0.83	a_0	2.889	0.157	2.548	3.231
		a_1	0.178	0.027	0.119	0.238
		kt_1	4.302	0.541	3.122	5.481
10 m east	0.85	a_0	2.914	0.140	2.610	3.219
		a_1	0.168	0.024	0.116	0.221
		kt_1	4.276	0.513	3.158	5.393
20 m east	0.81	a_0	2.830	0.153	2.497	3.163
		a_1	0.158	0.027	0.100	0.216
		kt_1	4.117	0.612	2.782	5.451
5 m west	0.68	a_0	2.742	0.165	2.382	3.101
		a_1	0.129	0.029	0.067	0.191
		kt_1	4.688	0.746	3.063	6.312
10 m west	0.80	a_0	2.859	0.140	2.554	3.164
		a_1	0.141	0.024	0.088	0.194
		kt_1	4.319	0.611	2.989	5.650
20 m west	0.81	a_0	2.902	0.121	2.638	3.166
		a_1	0.126	0.021	0.080	0.171
		kt_1	4.305	0.593	3.012	5.598

† Regression is in the form of two linear segments, joined at point kt_1 (yr), with slope a_1[ln(mg L^{-1}) yr^{-1}] for the rising limb and $-a_1$ for the descending limb, with intercept a_0[ln(mg L^{-1})], and y = ln(annual mean concentration in mg L^{-1}), and yr is year in sequence past the beginning of the experiment (1984 equals year zero). Example regression for the 10-m east plot is as follows: $y = 2.914 + 0.168(yr)$ for years ≤4.276 and $y = 3.634 − 0.168(yr − 4.276)$ for years >4.276.

confidence intervals of the slopes did not include zero, thus lending support to the observation that the concentrations have declined with time since 1989. Paired t tests showed no differences ($P \leq 0.05$) between spacings within each block, in any of the three regression parameters. Thus, the conclusion is that drain spacing does not affect the rate of change of concentrations resulting from a field management change, within the range of spacings studied here.

The large decrease in nitrate N concentrations with time is probably due to a combination of several factors that have changed over the 15-yr period, and the original design of the drainage experiment did not allow for testing these different factors individually. Although we have no "control" plots that remained unchanged throughout the 15 yr, it is unlikely that the concentration changes are a result of a long-term regional trend in climate or similar factors. We performed a time-series analysis of stream concentration data from Sugar Creek, Indiana (USGS Station no. 03361650; USGS, 2004), a stream within the same agroecoregion as the study site. Concentrations had been measured two to five times monthly during April through August and monthly during September through March over the years 1992 to 2001, and our time series analysis of the data found that the concentrations and loads were stationary over the period of record. The stream is about 85-km distant (39°42′51″N, 85°53′08″ W) from our study site and should indicate if regional concentrations had changed appreciably during this time period. This analysis lends support to the conclusion that the large changes in concentration we measured at our site are due primarily to changes in management practices implemented over the 15-yr period.

The 71% decrease in nitrate N concentrations from the 1986 to 1988 period (28 mg L^{-1}) to the 1997 to 1999 period (8 mg L^{-1}) is probably a result of a combination of the management practice effects along with yearly weather and crop yield variations. Reduction of fertilizer N rates (Baker and Johnson, 1981; Randall and Goss, 2001; Jaynes et al., 2004) and the growth of a winter "trap crop" after corn (Owens et al., 1995; Dinnes et al., 2002; Strock et al., 2004) have both been shown to reduce nitrate N concentration in drainage and are probably the major factors in our study. A corn–soybean rotation compared with continuous corn (Randall et al., 1997) or the soybean phase compared with the corn phase of a corn–soybean rotation (Jaynes et al., 2001; Randall et al., 2003) have sometimes shown lower nitrate N concentrations and may also be a factor at our site. Conversion from spring chisel tillage to no-till on this field probably had minor influence on nitrate leaching, since most of the annual drainage during the "tilled" years occurred before the tillage operation was performed. Tillage systems have generally been found to not have much impact on nitrate losses except for fall tillage followed by warm and wet conditions (Randall and Goss, 2001).

In addition to management practice changes, the weather and resulting crop yields had an impact on year-to-year variations in nitrate N concentrations (and load, as discussed later). During the first 5 yr of the drainage

study (beginning in 1984, one year before the nitrate measurements began), preplant fertilizer N rates were 285 kg ha^{-1}, which was the recommended application rate at that time for a yield goal of 12.5 Mg ha^{-1}. Several years of poor crop yields (1986, 1988; see Table 1) probably resulted in high residual soil N and contributed to the increasing trend in concentrations over the 1985 to 1989 period. Preplant fertilizer N rates were reduced from 285 to 228 kg N ha^{-1} in the 5-yr period from 1989 to 1993, and concentrations started to show a decrease in 1990, in the first "flow season" after the reduction in fertilizer application. A rise in concentrations in 1992 probably reflects the poor crop yield in 1991, but concentrations decreased again in 1993 following a high crop yield in 1992. These relatively rapid responses to low crop yield, during the next flow season, have also been observed by others (Randall and Mulla, 2001). The 1994 change to a soybean–corn rotation and lower fertilizer N rates for the corn did not result in an immediate decrease in concentration, but by 1996 the concentrations had declined again. The lower concentrations are probably a result of both the winter wheat "trap crop" after the corn and the lower fertilizer N rates.

The precise fertilizer N rate and crop management system needed for optimal crop growth and environmental quality is region specific and varies from year to year, and this remains a major challenge for agriculturalists worldwide. The results from this site in southeastern Indiana suggest that it is possible to decrease average annual nitrate N concentrations to below 10 mg L^{-1} (drinking water standard), while still growing corn and soybean, on soils similar to the Clermont silt loam. The Clermont has a much lower organic matter content (approximately 1.3%) than many of the more productive, high organic matter (approximately 4–5%) soils of the U.S. Midwest. Research on higher organic matter soils suggests that it may not be possible to grow corn and soybean on those soils while consistently maintaining concentrations below 10 mg L^{-1}, even with the best management practices currently available (Jaynes et al., 2001; Randall and Mulla, 2001). The results of all these types of studies underscore the necessity for long-term field experiments in different regions and on different soils, to understand the impacts of yearly weather variations, long-term climate, soils, and management on nitrate N leaching.

Nitrate Nitrogen Load

Annual nitrate N loads to drainage water decreased significantly over the 15-yr experimental period (Table 5), due to the large decrease in nitrate N concentrations over the same time period. Annual nitrate N loads averaged 38 kg N ha^{-1} in the 1986 to 1988 period and 15 kg N ha^{-1} in the 1997 to 1999 period. This 60% reduction in load occurred in spite of the fact that drainflow was 29% greater in the 1997 to 1999 period (18.4 cm) than in the 1986 to 1988 period (14.3 cm). The 71% decrease in concentrations, from 28 mg N L^{-1} in the 1986 to 1988 period, to 8 mg N L^{-1} in the 1997 to 1999 period, resulted in a large decrease in loads even with a moderate increase in flow in those years. Regression analysis was used to test the significance of the decline in loads with time, in a similar manner as was done for concentrations. The 95% confidence interval of the regression slopes did not include zero, again suggesting a significant decrease in loads over the last 10 to 11 yr.

In addition to the long-term trends in nitrate N loads, year-to-year variations in loads occurred as a result of variation in weather and crop yields. Loads were particularly high in 1989 after the low corn yields in the 1988 drought year. The higher residual nitrate that was probably remaining in the soil profile in autumn 1988, coupled with the high drainflow volumes in 1989, led to the highest nitrate N loads of the 15-yr study. Logan et al. (1994) and Randall et al. (1997) have also found greater N losses to drains in years following a drought due to greater residual N in the soil profile.

Nitrate N mass loads per unit area varied similarly to drainflow volumes, with a tendency for greater losses from the narrower spacings (Table 5). Annual nitrate N losses were 50, 37, and 27 kg ha^{-1} for the 5-, 10-, and 20-m spacings, respectively, in the 1986–1988 period and 16, 16, and 13 kg ha^{-1} in the 1997–1999 period. The differences in loads between spacings were significant in some but not all years. As described in the Materials and Methods section, years with significant load differences were identified by fitting a regression to the *difference* in loads within each pair of drains within each block. When the 95% (or 90%) confidence interval of the modeled difference for a given year did not include zero, the difference in loads between the two drains was considered to be statistically significant. The pair of drains with the greatest number of years of significant differences in modeled N loads was the 5- and 20-m east plots, and the regression analysis is illustrated in Fig. 3. The figure shows significant ($P \leq 0.05$) differences between the two spacings in the 1986 through 1993 period. Significant differences between drains were more common in the east block than in the west block. Significant periods of difference for all pairs of drains at both the $P \leq 0.05$ and the $P \leq 0.10$ levels are shown in Table 5.

As can be expected, differences in loads were larger in years with overall higher loads, and statistically significant differences were more prevalent in those years. The significant differences (Table 5) occurred almost exclusively in the time period with continuous corn, higher N fertilizer rates, and no winter cover crop (1985–1993), whereas both absolute loads and the differences in loads between drains were smaller in the period with the winter cover crop, lower fertilizer N rates, and soybean–corn rotation (1994–1999). The total 15-yr nitrate N load was 559, 298, and 232 kg ha^{-1} for the 5-, 10-, and 20-m east drains, respectively, and 675, 587, and 463 kg ha^{-1} for the 5-, 10-, and 20-m west drains. The greater total loads from the narrower spacings compared with the wider spacings are consistent with the annual differences in loads discussed previously.

Table 5. Annual nitrate N loads in drainflow as affected by drain spacing.

Year	Crop	East block 5 m	East block 10 m	East block 20 m	West block 5 m	West block 10 m	West block 20 m	Average of both blocks 5 m	Average of both blocks 10 m	Average of both blocks 20 m
							kg ha^{-1}			
1985	corn, 9 mo†	35.3	18.5	16.1	37.6	31.7	24.2	36.5	25.1	20.2
1986	corn	40.5	23.3	18.6	53.4	50.0	36.5	47.0	36.6	27.6
1987	corn	37.1	22.1	14.0	39.6	34.2	25.9	38.3	28.1	19.9
1988	corn	73.6	33.1	23.4	55.8	59.7	40.7	64.7	46.4	32.0
1989	corn	95.8	47.0	36.8	96.8	95.3	63.5	96.3	71.1	50.1
1990	corn	62.1	25.6	19.8	69.1	51.7	47.1	65.6	38.6	33.4
1991	corn	25.1	13.5	10.4	26.4	24.9	27.9	25.7	19.2	19.1
1992	corn	31.8	20.4	14.0	58.2	50.2	50.9	45.0	35.3	32.5
1993	corn	37.5	20.2	17.9	45.0	42.1	24.8	41.2	31.1	21.3
1994	soybean	29.1	13.0	13.9	68.7	30.1	24.2	48.9	21.6	19.0
1995	corn	35.3	18.9	13.8	43.3	31.8	27.2	39.3	25.3	20.5
1996	soybean	14.6	9.4	8.4	25.1	23.9	18.5	19.8	16.6	13.4
1997	corn	21.4	16.6	12.8	23.5	29.8	21.9	22.4	23.2	17.3
1998	soybean	9.8	9.6	7.2	20.1	20.1	18.4	15.0	14.8	12.8
1999	corn	9.9	6.8	4.9	11.9	11.6	11.8	10.9	9.2	8.4
Total		559.0	297.9	231.8	674.6	587.0	463.4	616.8	442.4	347.6

Periods of significant differences based on regression model

Block	Drain pairs	$P \le 0.05$	$P \le 0.10$
East	5 vs. 10 m	1987–1991	1987–1993
	5 vs. 20 m	1986–1993	1985–1995
	10 vs. 20 m	1986–1989	1986–1992
West	5 vs. 10 m	1994	1994
	5 vs. 20 m	1988–1989, 1994	1987–1989, 1994–1995
	10 vs. 20 m	1985, 1988–1989, 1993	1985–1986, 1988–1989, 1993

† Mass loads calculated only for April through December, 1985, because sampling did not begin until April.

Seasonal Effects on Drainflow, Loads, and Concentrations

Loads to the drains exhibit a clear seasonal cycle related to the timing of drainflow in this system. The majority of the drainflow and nitrate N loads occur
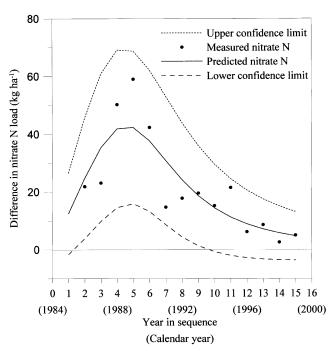

Fig. 3. Measured annual nitrate N load differences between the 5- and 20-m east plots, and regression predictions with 95% confidence limits, over the 15-yr study. Loads from the two plots are significantly different when the confidence limits do not include the 0 difference line. Regression: $y = (yr)/(0.0799 + 0.000061yr^4)$; $R^2 = 0.78$.

during the fallow season of November through March, as discussed in previous reports about this site (Kladivko et al., 1991, 1999). Rainfall is relatively uniformly distributed throughout the year, with the driest month (October) receiving 6.0% of the annual rainfall and the wettest two months (July and April) receiving 10.5 and 10.4%, respectively (Fig. 4). However, drainflow varies much more over the year, due to higher evapotranspiration during the growing season. Drains typically begin to flow in November or December at this site, after the soil profile has rewetted following the growing season, although in some years there is no flow until January. Drainflow continues throughout the winter during most years, although in some years the drainflow ceased during parts of January or February. This site thus differs from sites further north in the Midwest, where flow ceases most of the winter and occurs primarily in April through June (Randall and Goss, 2001). Flow at this site usually ceases in May or early June, but occasionally there will be some small flow events in July through October. The 14-yr (1985 was omitted because it was a partial year for nitrate analyses) distribution of the fraction of flow and nitrate N load occurring in each month is shown in Fig. 4 for the 20-m west drain. In climates where the soil does not freeze all winter, most of the drainage and nitrogen loss occurs in the late fall, winter, and early spring (Goss et al., 1993; Drury et al., 1996; Gilliam et al., 1999). The differences in the seasonal distribution of flow must be considered when comparing studies from different regions and when designing and evaluating management strategies for decreasing nitrate loads to drainage water.

Visual observation of the data from individual drains did not reveal a strong seasonal pattern in monthly
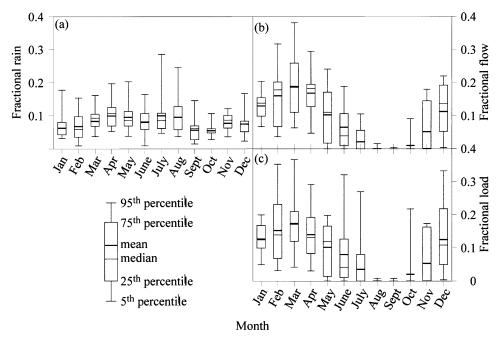
Fig. 4. Box plot diagrams of monthly fraction of annual (a) rainfall, (b) drainflow (20-m west plot), and (c) nitrate N load (20-m west plot), for 1986 through 1999 (1985 nitrate measurements did not begin until April, see text).

nitrate N concentrations for the 15-yr period, because of temporal variability. The close correspondence of percent of annual flow and load in each month (Fig. 4) also indicates a relatively stable concentration throughout the year. The analysis of variance on the 15-yr de-trended data for each drain did show a weak tendency in most of the drains for March–April to have lower concentrations than May–June–July or January–February, and for July concentrations to be the highest, but the effects were inconsistent among drains and often small. In contrast, Jaynes et al. (2001) found a large increase in concentrations in May–June in one of the two corn years in a 4-yr study, while the other corn year showed only a small effect. Cambardella et al. (1999) found a tendency for higher concentrations in April through July in some years.

At our site, the tendency for slightly higher nitrate concentrations in May–June–July has minimal impact when considering total nitrate loads for the year. On average only 8.2% of the annual load and 7.1% of the annual flow occurred in June. Both flow and load were minimal in July through October. On average 64% of the annual flow and 63% of the annual nitrate load occurred in the fallow season of November through March. Another 17% of the flow and 15% of the nitrate load occurred in April, much of which was before any field operations for the next crop. Thus, nearly 80% of the annual drainflow and annual nitrate load occurs in the winter and early spring before fertilization for the next crop. These results underscore the potential importance of cropping systems that would use some of the nitrogen and water during late fall or early spring, such as winter cover crops or perennials that grow later in the fall and earlier in the spring than the typical corn–soybean rotation. Perennial crops generally produce much lower nitrate N concentrations and loads in drain-

flow than annual row crop systems, but lack of a suitable market limits widespread adoption of such systems (Randall and Mulla, 2001). Winter cover crops may be able to provide some of the benefits of perennials in the midst of an annual cropping system, if sufficient growth of the cover crop can be obtained under the cool conditions of the Midwest.

Concentrations versus Flow Rates

Exploratory graphical analysis of concentration and flow data revealed some periods where concentration declined rapidly as the flow increased rapidly. An example from the 20-m west plot in 1998 (Fig. 5) shows that
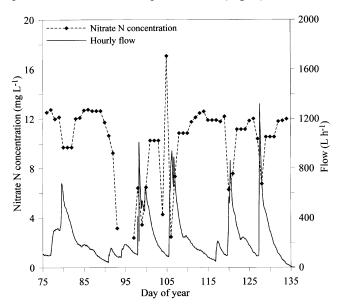

Fig. 5. Plot of drainflow and nitrate N concentration over a 2-mo period in March to May of 1998 for the 20-m west plot.

on Days 99, 106, 120, and 127, the flow peaked while the concentration dropped. This behavior is opposite of the typical preferential flow behavior of pesticides (Kladivko et al., 1991, 1999) or newly applied tracers (Kung et al., 2000), which tend to move with the water in the preferential flow paths and have higher concentrations as the hydrograph rises. Nitrate and other chemicals that are well distributed in the soil matrix tend to move more by matrix flow, however, and therefore drain concentrations are diluted by the relatively clean water flowing in the preferential pathways (Smettem et al., 1983; Hallberg et al., 1986). This behavior does not occur consistently in our drains, however, and we do not know why it occurs sometimes but not all the time.

To test for the prevalence of a negative relationship between concentration and flow, correlation and frequency analysis tests were conducted. The simple correlation analysis using data from all drains and years showed a significant ($P \leq 0.01$) but weak negative correlation of -0.0614 between daily concentration and daily flow rate (Saturday through Monday excluded; see the Materials and Methods section). Correlations run on subsets of the data found significant negative correlations for some years, months, or quarters in each drain with an occasional positive correlation. The frequency analysis of change in concentration vs. change in flow highlights changes within events and also gave a similar general result, with a significance level of $P = 0.012$ across all drains. These weak relationships were similar to the results of Jaynes et al. (1999), who found a weak negative correlation between change in nitrate N concentration and change in flow in a stream site in Iowa but inconsistent trends for the tile drains.

CONCLUSIONS

Subsurface drainage is an important water management practice in many humid regions of the world, but it also has potential negative effects of increased nitrate leaching through soils. Long-term studies that include year-to-year weather variability are needed to better evaluate field management practices for reducing nitrate leaching. Our 15-yr study on a loess-derived soil in southeastern Indiana provides an important data set for assessments of nitrate leaching into tile drains in the Mississippi River basin. The primary findings from our site are:

- Nitrate N concentrations and mass losses were significantly decreased over the 15-yr period of study, by a combination of reductions in N fertilizer rates, change in rotation and tillage, and growth of a winter cover crop as a "trap crop" after corn. Nitrate N concentrations and loads decreased from 28 mg L^{-1} and 38 kg ha^{-1} yr^{-1}, respectively, in the 1986–1988 period, to 8 mg L^{-1} and 15 kg ha^{-1} yr^{-1} in the 1997–1999 period, while drainflow was 29% higher in the latter period.
- Both drainflow volumes and nitrate N leaching losses were greater with more intensive drain spacing. Drainflow was affected by spacing throughout the 15-yr study, whereas differences in nitrate N loads with spacing occurred primarily during the years with continuous corn, high fertilizer N rates, and no cover crop.
- The majority of the drainflow occurs in the fallow season. About 64% of the annual drainflow occurs in November through March, and 81% in November through April.
- The majority of the N loads occur in the fallow season. About 63% of the annual N load occurs in November through March, and 78% in November through April.
- Concentrations did not vary greatly by month within a year, but loads did vary due to the seasonal distributions of drainflow.

Current concerns about hypoxia in the Gulf of Mexico have focused attention on nitrate N loads from tile-drained soils of the U.S. Midwest. As researchers and policymakers evaluate the current nitrate N loads from these systems and explore options for reducing the loads, past and current studies from different Midwest locations should be carefully compared and contrasted. Some key points from our current study that should be kept in context when comparing results across the region are highlighted here:

- The relatively shallow (0.75 m) drain depth at our site may affect concentrations and drainflow volumes, compared with sites where drains are installed at deeper depths (1.2 m).
- The low organic matter content of this soil (approximately 1.3%) contrasts with the Mollisols of much of the upper Midwest. The nitrate N concentrations of less than 10 mg L^{-1} achieved in the last four years of our soybean–corn rotation with winter cover crop after the corn may not be achievable on high organic matter soils growing the same rotation, due to higher mineralization rates.
- Drainage occurs all winter (usually) at our site. This contrasts with many Midwest drainage research sites (Minnesota, Iowa) where drainflow ceases during January, February, and part of March.
- Fertilizer N is applied as spring preplant anhydrous ammonia, in the second half of April. This contrasts with sites receiving fall N applications or nitrate-containing fertilizers.

Additional research comparing the low organic matter soils represented here and the high organic matter soils of much of the U.S. Midwest is essential for understanding the system and designing appropriate management practices for different regions.

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