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Nitrogen Application Rate Effect on Nitrate-Nitrogen Concentration and Loss in Subsurface Drainage for a Corn-Soybean Rotation

Peter A. Lawlor
Iowa State University

Matthew J. Helmers
Iowa State University, mhelmers@iastate.edu

James L. Baker
Iowa State University

Stewart W. Melvin
Iowa State University

Dean W. Lemke
Iowa Department of Agriculture and Land Stewardship

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Abstract

Excess precipitation in Midwest agricultural production areas is often removed artificially via subsurface drainage systems that intercept and divert it to surface waters. Nitrogen (N), either applied as fertilizer or manure or derived from soil organic matter, can be carried as nitrate with the excess water in quantities that may have deleterious effects downstream. A field study was initiated in 1989 in Pocahontas County, Iowa, on 0.05 ha plots of glacially derived clay loams. The objective of this three-phase study was to determine the effect of N application rate on NO3-N concentration and loss in a corn-soybean rotation over a wide range of weather conditions. Nitrogen-rate treatment phases with five seasons each (six for phase II) were imposed on subsurface-drained, continuous-flow-monitored plots over a 16-year period. Phase I N rates ranged from 0 to 168 kg N ha-1 in 56 kg N ha-1 increments. Separate plots were used for each crop in phase I, and significant NO3-N concentration differences were not observed between corn or soybean plots; this led to combining both crops in a split-plot configuration for phases II and III to study system effects. Phase II N rates ranged from 45 to 179 kg N ha-1 in 45 kg N ha-1 increments. Phase III was limited to two rates, 168 and 252 kg N ha-1. Average yearly flow-weighted NO3-N concentrations ranged from 3.9 mg L-1 (45 kg N ha-1, 1995) to 28.7 mg L-1 (252 kg N ha-1, 2001). Average flow-weighted NO3-N concentrations (in mg L-1) ranked by N rate were: 23.4 (252), 13.2 (179), 15.5 (168), 11.9 (134), 11.7 (112), 8.1 (90), 9.5 (56), 5.7 (45), and 8.9 (0). Losses were precipitation dependent and were reflective of individual seasons and rates imposed. Average flow-weighted NO3-N losses (kg ha-1) ranked by N rate and by phase were: 58 (168), 68 (112), 48 (56), 50 (no N) for phase I; 8 (179), 15 (134), 19 (90), 7 (45) for phase II; and 49 (252), 32 (168) for phase III. Results indicate that concentrations generally increased with rate; the effect on losses was variable due to disparity in drainage volumes among years. Corn yield during all periods showed a strong correlation between N rate and yield. As N rate increased, yield increased. It should be noted that at least 50% of the years showed limited yield response to N application above the next to the highest rates. To achieve average NO3-N concentrations less than 10 mg L-1 (USEPA drinking water standard) in subsurface drainage at this site, N application rates would need to be less than 112 kg N ha-1. Rates currently recommended for this area range from 112 to 168 kg N ha-1. Results from this study have significant implications for N fertilizer management and subsurface drainage NO3-N loss to surface waters in the state, the Mississippi River, and the Gulf of Mexico.

Keywords

Leaching, Nitrate, Nutrient management, Subsurface drainage, Water quality

Disciplines

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Comments

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P. A. Lawlor, M. J. Helmers, J. L. Baker, S. W. Melvin, D. W. Lemke

Abstract. *Excess precipitation in Midwest agricultural production areas is often removed artificially via subsurface drainage systems that intercept and divert it to surface waters. Nitrogen (N), either applied as fertilizer or manure or derived from soil organic matter, can be carried as nitrate with the excess water in quantities that may have deleterious effects downstream. A field study was initiated in 1989 in Pocahontas County, Iowa, on 0.05 ha plots of glacially derived clay loams. The objective of this three-phase study was to determine the effect of N application rate on NO_3-N concentration and loss in a corn-soybean rotation over a wide range of weather conditions. Nitrogen-rate treatment phases with five seasons each (six for phase II) were imposed on subsurface-drained, continuous-flow-monitored plots over a 16-year period. Phase I N rates ranged from 0 to 168 kg N ha^{-1} in 56 kg N ha^{-1} increments. Separate plots were used for each crop in phase I, and significant NO_3-N concentration differences were not observed between corn or soybean plots; this led to combining both crops in a split-plot configuration for phases II and III to study system effects. Phase II N rates ranged from 45 to 179 kg N ha^{-1} in 45 kg N ha^{-1} increments. Phase III was limited to two rates, 168 and 252 kg N ha^{-1}. Average yearly flow-weighted NO_3-N concentrations ranged from 3.9 mg L^{-1} (45 kg N ha^{-1}, 1995) to 28.7 mg L^{-1} (252 kg N ha^{-1}, 2001). Average flow-weighted NO_3-N concentrations (in mg L^{-1}) ranked by N rate were: 23.4 (252), 13.2 (179), 15.5 (168), 11.9 (134), 11.7 (112), 8.1 (90), 9.5 (56), 5.7 (45), and 8.9 (0). Losses were precipitation dependent and were reflective of individual seasons and rates imposed. Average flow-weighted NO_3-N losses (kg ha^{-1}) ranked by N rate and by phase were: 58 (168), 68 (112), 48 (56), 50 (no N) for phase I; 8 (179), 15 (134), 19 (90), 7 (45) for phase II; and 49 (252), 32 (168) for phase III. Results indicate that concentrations generally increased with rate; the effect on losses was variable due to disparity in drainage volumes among years. Corn yield during all periods showed a strong correlation between N rate and yield. As N rate increased, yield increased. It should be noted that at least 50% of the years showed limited yield response to N application above the next to the highest rates. To achieve average NO_3-N concentrations less than 10 mg L^{-1} (USEPA drinking water standard) in subsurface drainage at this site, N application rates would need to be less than 112 kg N ha^{-1}. Rates currently recommended for this area range from 112 to 168 kg N ha^{-1}. Results from this study have significant implications for N fertilizer management and subsurface drainage NO_3-N loss to surface waters in the state, the Mississippi River, and the Gulf of Mexico.*

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Water table management through the use of artificial subsurface drainage systems has resulted in very productive lands in humid zones with naturally poorly or somewhat naturally poorly drained soils. Subsurface drainage systems were predominately installed at the end of the 19th and during the first half of the 20th century and were necessary in the conversion of the prairie-wetlands landscape into agricultural production areas. Excess precipitation in these converted landscapes in Iowa and other Corn and Soybean Belt states in the Upper Mississippi/Ohio River watershed agricultural production states is removed artificially via subsurface drainage systems that intercept and divert it to surface waters. Agricultural drainage systems have been installed to allow timely seedbed preparation, planting, and harvesting, and to protect crops from extended periods of flooded soil and/or high water table conditions. In general, improved subsurface drainage also results in less surface runoff. Surface runoff generally has higher concentrations of sediment, phosphorus, ammonium-nitrogen (NH_4-N), bacteria, and some pesticides than does subsurface drainage. The tradeoff for improved subsurface drainage is a significant increase in nitrate-nitrogen (NO_3-N) leaching loss (Gilliam et al., 1999). A 1985 survey indicates that Illinois, Indiana, Iowa, Ohio, and Minnesota have a total of nearly 13.5 million hectares of agricultural land with artificial subsurface drainage (USDA, 1987). Nitrogen (N), either applied as fertilizer, manure, or derived from soil organic matter, can be carried as NO_3-N with the excess water in quantities that may have deleterious effects downstream. The movement of N from agricultural fields via subsurface drainage waters is a major factor in nonpoint-source

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The authors are **Peter A. Lawlor,** Research Associate, **Matthew J. Helmers, ASABE Member,** Assistant Professor, **James L. Baker, ASABE Fellow,** Professor Emeritus, and **Stewart W. Melvin, ASABE Fellow,** Professor Emeritus, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames Iowa; and **Dean W. Lemke, ASABE Member Engineer,** Iowa Department of Agriculture and Land Stewardship, Des Moines, Iowa. **Corresponding author:** Peter A. Lawlor, Department of Agricultural and Biosystems Engineering, 219C Davidson Hall, Iowa State University, Ames IA 50011; phone: 515-294-3232; fax: 515-294-6633; e-mail: palawlor@iastate.edu.

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pollution of surface waters and ultimately the Gulf of Mexico, where it has been implicated as a primary contributor to the hypoxic zone (Mitsch et al., 2001; Rabalais et al., 1996). The environmental impacts of subsurface drainage depend on the agronomic practices implemented, as well as site, soils, and climatological factors.

Ammonium-N based fertilizers are commonly applied in the Corn Belt in either spring or fall. A general conclusion of research conducted over several decades is that as a best management practice N should be applied at the correct amount nearest to the time it is needed by the crop (Dinnes et al., 2002). Any time precipitation exceeds the field capacity of the soil and the evapotranspiration capacity of the crop system, NO_3-N in the soil profile may exit with subsurface drainage. Conversely, soils with poor drainage may lose NO_3-N via denitrification. Other research has also emphasized that March through May precipitation is a major cause of N loss from fertilized fields before rapid crop growth and crop uptake of water and N begins in June (Balkcom et al., 2003).

Some early research in Iowa and other areas in the Corn Belt have shown that substantial amounts of NO_3-N can be lost in subsurface drainage that eventually end up in surface waters (Baker et al., 1975; Baker and Johnson, 1981; Hanway and Laflen, 1974; Kanwar et al., 1988). Considering an N mass balance, Gilliam et al. (1999) noted that in warm humid climates most of the loss of N in drainage occurs during the winter and is a result of mineralization of organic N, followed by nitrification of NH_4-N. In contrast, in the cooler climates of the upper Midwest where the ground is usually frozen from December through late March, very little subsurface drainage and N loss occur during the winter months, but the period from April through June is a critical drainage period for NO_3-N loss (Randall, 2004).

A Minnesota study found that loss of NO_3-N from soybean fields in rotation with corn was not greatly different from fertilized corn fields. Average annual losses can range between 0 and 50 kg NO_3-N ha^{-1} using recommended fertilization practices (Randall et al., 1997, 2003; Randall and Vetsch, 2005). The same was found in an Iowa study, although the losses were somewhat lower at 11 to 14 kg N ha^{-1} over an 11-year period (Bahksh et al., 2005, 2006). A review by Dinnes et al. (2002) also cited many studies that have documented subsurface drainage losses from agricultural production areas. While it is well understood that subsurface drainage can export NO_3-N, there is a need to better understand and quantify how different N application rates affect NO_3-N concentrations and losses in subsurface drainage. In particular, it is important to evaluate this over a range of weather conditions. Thus, the objective of this study was to evaluate the effect of N fertilizer application rate on flow-weighted NO_3-N concentration and loss in subsurface drainage over a wide range of encountered precipitation patterns.

Materials and Methods

Research Site and Monitoring Equipment

The field experimental site was located near Gilmore City in Pocahontas County, Iowa. It was in Garfield Township at SW 1/4, Section 27, T92N, and R3lW. Predominant soils were Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) and Webster and Canisteo (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) clay loams with 3% to 5% organic matter. These are naturally poorly to naturally somewhat poorly drained glacial till soils with an average slope of 0.5% to 1.5%. Soil samples taken to a depth of 15 cm at the end of the study period indicated that Bray P_1 was 31 mg kg^{-1} (very high; Sawyer et al., 2002) and pH was 7.7.

The total research area was 4.5 ha, of which 3.8 ha were used as experimental plots for these studies and the remainder as border and buffer. Each of the 78 plots available was 0.05 ha (15 × 38 m long). The plots were established after the installation of drain lines in 1989 and are illustrated in figure 1. Subsurface drainage lines were installed parallel to the long dimension through the center of each plot and on the borders between plots (7.6 m spacing) at a depth of 1.06 m. The subsurface drains at plot borders were installed to isolate and prevent lateral, subsurface drainage from adjacent plots. The border drain lines had an outlet to the surface at a remote location. The plot configuration is illustrated in figure 2. Only the center drainage line was monitored for drainage volume and NO_3-N concentration. Corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) were grown on 0.762 m centers in all years, resulting in 20 rows of crop. From 1989 through 1993, whole plots were used for each crop. Beginning in 1994, plots were divided in half; ten rows of each crop were grown to study the combined effects of crops in rotation. The reasoning behind combining both crops in rotation within a single, monitored experimental plot stems from previous research and was bolstered by more current research. Weed and Kanwar (1996), Kanwar et al. (1997), Randall et al. (1997), and Zhu and Fox (2003) found that at close to recommended rates of N (112 to 168 kg ha^{-1}; Blackmer et al., 1997) for corn production in a corn-soybean rotation, NO_3-N losses and concentrations were not significantly different between the corn or soybean years.

Twenty-six aluminum culverts, 1.2 m in diameter, were buried vertically at the terminus of drainage lines from three individual plots to accommodate a water table dewatering sump and three sampling/monitoring systems. A single configuration is illustrated in figure 3. Drainage lines from individual plots were directed to separate sumps within the culvert, and drainage was pumped by a submersible pump (model M53, Zoeller Pump Co., Louisville, Ky.) through plastic plumbing fitted with a common plated sprayer orifice nozzle and a 16 mm, Trident T-10 water meter (Neptune Technology Group, Inc., Tallassee, Ala.). Back pressure created by the meter forced a small constant fraction (approx. 0.25%) of all drainage to be diverted through plastic tubing to a 20 L glass sampling bottle. Flow-weighted drainage samples were collected and volume measurements were recorded as dictated by drainage patterns. Typically, after 13 mm of subsurface drainage, the sample jars contained 10 L of water available for subsampling. This rather unique configuration provided the infrastructure for continuously monitored flow volume measurement and flow-integrated sampling of subsurface drainage emanating from below the treated area. Subsamples were collected at this point and over each drainage period and represented the quality of water that was intercepted under the treated area. Subsamples were chilled and stored at 4°C until analyzed. NO_3-N analyses were performed in the Agricultural and Biosytems

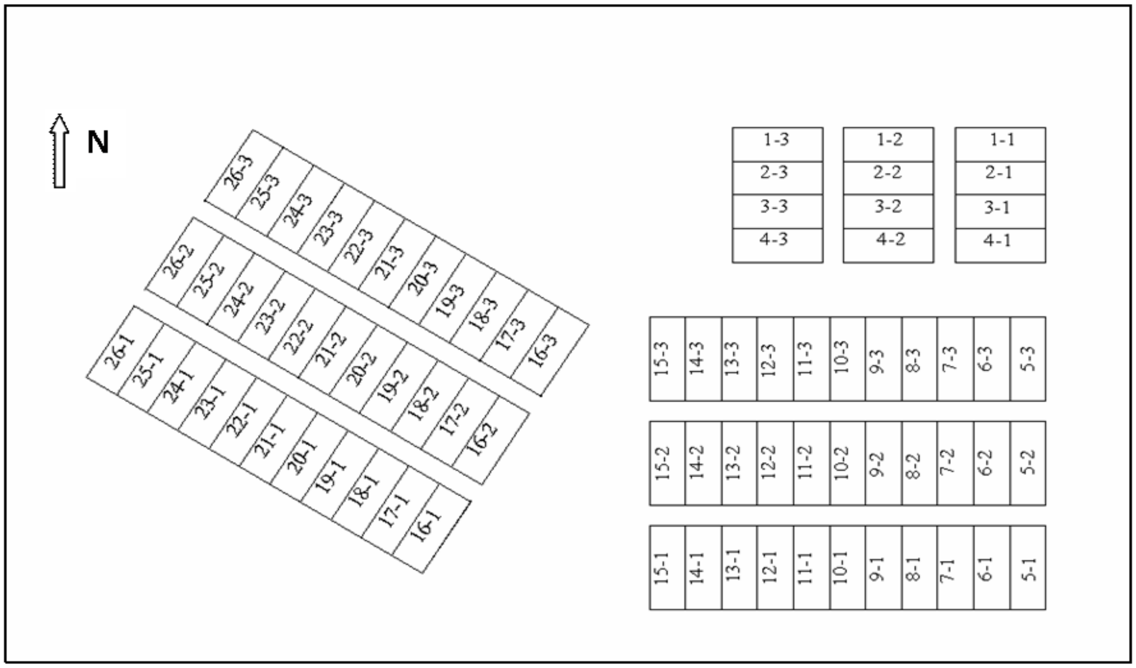

Figure 1. Experimental site map with corresponding plot numbers (table 1 lists individual plots used for treatments).

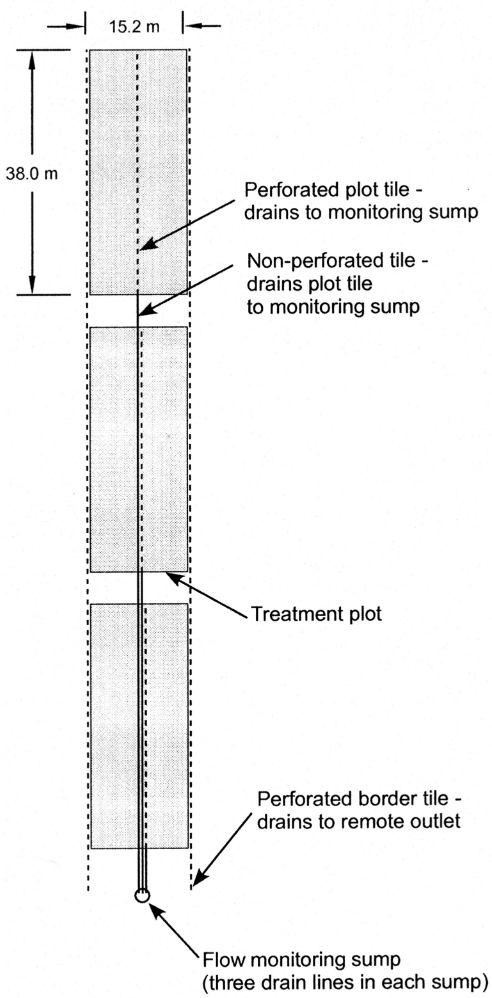

Figure 2. Example subsurface drainage layout for three treatment plots.

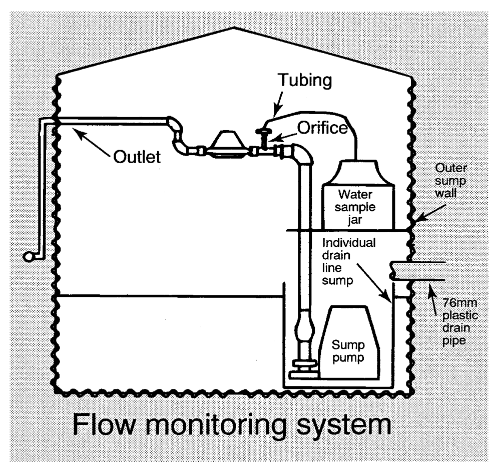

Figure 3. Drainage monitoring sump configuration (three individual drain line sumps in each flow monitoring sump).

Engineering Water Quality Laboratory located on the campus of Iowa State University using a Quickchem 2000 Automated Ion Analyzer flow injection system (Lachet Instruments, Milwaukee, Wisc.) and the cadmium reduction method.

Ambient precipitation was collected using a recording tipping-bucket rain gauge (Campbell Scientific, Inc., Logan, Utah) located near the center of the site area. Normal precipitation for Pocahontas, Iowa, located 15 km west of the research site, was used for comparative purposes with precipitation received at the research site. A 30-year average for Pocahontas, from 1961 to 1990, was considered the long-term norm and provided a base for monthly, growing and drainage season, and annual precipitation comparisons.

Treatment Description

Plot studies were conducted from 1989 to 2004 to determine NO_3-N concentrations in subsurface drainage water in response to various N fertilization rates in a corn-soybean rotation. Nitrogen application rates ranged from 0 to 252 kg ha^{-1} on corn and were zero on soybean. N application rates were held constant for five-year periods (except phase II, six years). Table 1 lists the N rate treatments imposed on specific plots at the experimental site (see fig. 1 for plot locations). Not all the plots shown in figure 1 were used for the N-rate studies described here; other treatments and studies were being conducted on the remaining plots. Treatments were assigned randomly to plots in replicates of three from 1989 to 1999. After assessing eleven years of drainage volume data (1989-1999), the 75 plots (plots 5-1, 5-2, and 5-3 were decommissioned in 1994 due to excessive drainage) were blocked by their drainage volume to drainage season precipitation ratios into replicates of five in 2000. Block 1 included plots that had the lowest drainage to drainage season precipitation ratios. The same procedure was used to assign plots to blocks 2 through 5; the next group of five plots with the lowest ratios was assigned to block 2. Block 5 included those plots with the highest drainage to precipitation ratios. Treatments were then randomly assigned within each drainage volume block, resulting in five replications per treatment. This method ensured that treatments (2000-2004) had replications that included all levels of drainage volume and that treatments were not imposed on high- or low-drainage volume plots exclusively. Phase III only used ten of the 75 available blocked plots; the remainder were used for other studies.

In all years, a conventional cropping system was used. Chisel-plow tillage of corn residue after stalk chopping in the fall was followed by spring disking of corn and soybean plots with additional seedbed preparation using a field cultivator. N fertilizer was applied mid-row to corn, at planting or as an early season sidedress, with a conventional knife applicator. A two-pass cultivation procedure was used, in addition to herbicides, for weed control. Planting dates were dictated by field conditions and ranged from 29 April in 1993 to 2 June in 1996. Fertilization dates in the spring ranged from 30 April in 1992 to 23 June in 1998.

N application rates during phase I (1989-1993) ranged from 0 to 168 kg ha^{-1} in 56 kg N ha^{-1} increments for corn in rotation with soybean. Liquid 28% urea ammonium nitrate (UAN) was the fertilizer source. Rates were selected to determine what effect a wide range of N fertilization levels would have on subsurface drainage concentrations. Phase changes were made to accommodate the changing research intentions of the various phases. From 1994 to 1999 (phase II), corn in rotation with soybean was grown with 45 kg N ha^{-1} incremental N rates ranging from 45 to 179 kg N ha^{-1}, again applied as liquid 28% UAN. These rates were selected to "fine tune" the range selected in phase I. Phase III (2000-2004) included two N fertilizer rates. Commercial-grade 28% aqueous ammonia-N was applied at rates of 168 or 252 kg N ha^{-1} in spring at or closely following corn emergence. The lower rate was selected to continue a recommended application rate both for the area and as used previously. The higher rate was used to obtain data outside the normal application rate. Recommended rates for the study area are 112 to 168 kg N ha^{-1} (Blackmer et al., 1997). Although not typical for the area, the spring fertilizer application timings represent a best management practice recommended by numerous researchers (Blackmer et al., 1997; Jaynes et al., 2004; Randall and Mulla, 2001; Dinnes et al., 2002). Locally, most N fertilizer is applied in late fall or in early spring several weeks prior to planting.

Yields, drainage volumes, NO_3-N concentrations, and NO_3-N losses were analyzed as a completely randomized design using PROC GLM procedures (SAS, 2003), and means were separated using a least significant difference test at $p = 0.05$ ($LSD_{0.05}$). The first year of phases II and III were not included in overall phase averages and statistical analyses, as the first year of the phase change was considered a "calibration or transition" year. However, for completeness, the drainage, NO_3-N concentrations and losses, and crop yields for these "calibration or transition" years were included in the tables. These analyses were used to study treatment effects on water quality and crop yield using SAS version 9.1 (SAS, 2003).

Results

Precipitation and Subsurface Drainage

Research Site Precipitation

Long-term normal precipitation for Pocahontas, Iowa, was 784 mm. During the 16 years of study from 1989 to 2004, average annual precipitation at the research site was 729 mm, or 7% below the long-term normal for the area. Annual precipitation ranged from 507 mm in 1989, 35% below normal, to 944 mm, 21% above normal, in 1991(table 2). Only four of the 16 years were wetter than normal, with between 6% to 21% higher than normal amounts. Six of the 16 years had precipitation totals within 10% of the normal.

The drainage season, a period when the ground is usually not frozen and capable of releasing excess water as drainage, was considered to be from March through November. Drainage season precipitation ranged from 457 to 886 mm, with the lowest in 1997 and the highest in 1991. Drainage season precipitation as a percentage of annual totals ranged from 81% in 1994 to 97% in 2002. Fifteen of the 16 years received at least 85% of their precipitation within the drainage season months. Average drainage season

Table 1. Nitrogen application rates used on corn in corn-soybean rotation and plots used during the three phases of the study. Refer to figure 1 for plot locations within the experimental site.

Phase I (1989-1993)			Phase II (1994-1999)		Phase III (2000-2004)	
Rate (kg N ha^{-1})	Plots Used: Even Years	Plots Used: Odd Years	Rate (kg N ha^{-1})	Plots Used Each Year	Rate (kg N ha^{-1})	Plots Used Each Year
0	4-1, 14-2, 24-3	10-1, 23-2, 9-3	45	2-1, 12-2, 10-3	168	11-1, 14-1, 23-1, 9-2, 12-3
56	6-1, 20-2, 25-3	2-1, 12-2, 10-3	90	25-1, 10-2, 7-3	252	9-1, 20-1, 1-3, 16-3, 17-3
112	5-1, 26-2, 3-3	25-1, 10-2, 7-3	134	8-1, 24-2, 19-3	--	
168	18-1, 8-2, 2-3	8-1, 24-2, 19-3	179	18-1, 15-2, 18-3	--	

Table 2. Precipitation at the research site during the study period (all values in mm).

Year	Month									Growing Season[a]	Drainage Season[a]	Annual Total
	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.			
1989	34	55	56	63	114	52	83	12	5	368	474	507
1990	98	35	127	242	145	80	50	24	13	644	814	884
1991	109	131	168	131	76	65	50	38	118	490	886	944
1992	53	61	50	90	229	80	16	77	53	465	709	815
1993	51	113	125	179	138	160	28	31	12	630	837	942
1994	2	52	41	179	89	51	37	48	30	397	529	654
1995	79	102	108	93	54	127	39	54	7	421	680	722
1996	34	13	113	115	81	180	51	46	53	540	686	764
1997	35	60	55	82	86	15	78	40	6	316	457	526
1998	57	120	100	108	105	43	21	77	18	377	649	713
1999	37	113	142	106	98	47	19	14	21	412	597	675
2000	28	35	78	79	137	74	30	56	67	398	584	687
2001	16	89	143	68	90	72	40	42	54	413	614	702
2002	7	65	77	51	77	262	30	87	1	497	657	680
2003	28	79	109	218	147	42	0	0	0	516	623	689
2004	97	80	168	98	80	13	88	14	68	447	706	767
Average	48	75	104	119	109	85	41	41	33	458	655	729
Normal[b]	53	72	94	107	108	108	88	56	36	505	722	784

[a] Growing season was May through September, and drainage season was March through November.
[b] Source: Climatological Data for Iowa, National Climate Data Center for Pocahontas, Iowa, 1961-1990.

precipitation for the site was 9% below the 1961-1990 normal drainage season precipitation. Seven of the 16 years had drainage season precipitation totals within 10% of the norm.

Overall averages for the months of May and June during the study period at the site surpassed the long-term averages for the area (10 and 12 mm higher, respectively); all other months exhibited equal or below normal amounts. September had the greatest average deficiency of 47 mm..

Growing season precipitation (May through September) is also included in table 2. As a percentage of annual precipitation, it ranged from 52% in 1991 (490 mm) to 75% in 2003 (687 mm); the average for the 16-year period was 63% and was nearly equal to the 30-year normal. Five of the 16 years had growing season precipitation totals within 10% of the norm.

Research Site Subsurface Drainage

Precipitation was highly variable during the study period, and subsurface drainage volume mimicked the precipitation patterns observed. Comparisons of the average subsurface drainage volumes by year are presented in table 3 along with drainage/precipitation ratios (D/P) for the drainage year. The drainage year was October and November precipitation of the previous year combined with the March through September precipitation of the comparison year. Using the drainage year time period accounted for soil water recharge in October and November of the previous year after the growing season and before soils froze. These ratios were used to compare drainage volumes between time periods and treatments more effectively because a wet or dry fall could influence subsequent drainage volumes in the spring. It was determined through direct observation and soil temperature monitoring that spring snowmelt had minimal influence on subsoil water recharge and subsurface drainage. Average subsurface drainage volumes within years and by treatment with statistical significance ($LSD_{0.05}$) are also shown in table 3. Average drainage volume LSDs were comparable to those reported by Bakhsh et al. (2005, 2006), Randall et al. (1997), and Randall and Vetsch (2005).

Drainage volumes for treatments ranged from 0 mm in 1989 for all N rate treatments to 666 mm for the 168 kg N ha^{-1} treatment in 1993 (drainage ratio of 0.72). Only three years exhibited statistically significant differences in volumes between treatments (1998-2000). Average D/P ratios ranged from 0 in 1989 to 0.72 in 1992, with an average of 0.36. Approximately 38% of all years had average drainage values within 25% of the overall average volume, indicating highly variable drainage volume patterns encountered during the period.

Yearly variation in subsurface drainage volumes is to be expected when studying artificial drainage systems under ambient rainfall conditions. As an example, a comparison of 1996 and 1999, years with nearly equal drainage year (Oct.-Nov. and Mar.-Sept.) precipitation totals, resulted in statistically different (data not presented between years) subsurface drainage volumes. The year 1999 had an overall average subsurface drainage volume of 98 mm, whereas 1996 had an average volume 3.1 times higher. Drainage volumes are directly related to ambient soil moisture conditions, individual storm timing and totals, and crop water demand during the drainage season. As an example, 1992 had below-average drainage year precipitation but had the highest D/P ratio during the study period.

On average, 86% of subsurface drainage occurred between April and July (table 4). For these months, the range was 0 to 277 mm of drainage. Specifically, the months of April and July had approximately 13% each, and the months of May and June each had 30% of the total. In the majority of years, little if any drainage occurred in March or in the September through November period. Freezing conditions in the winter did not allow monitoring equipment operation during the months of December to March, so no drainage was

Table 3. Average subsurface drainage (D, mm) volumes by nitrogen treatment rate and year.[a]

Year	N-rate (kg N ha^{-1})										$LSD_{0.05}$	Drainage Year[b]	
	0	45	56	90	112	134	168	179	252	Average		Precip. (P)	Ratio (D/P)
1989	0	--	0	--	0	--	0	--	--	0	--	516	0.00
1990	469 a	--	450 a	--	443 a	--	417 a	--	--	444	306	794	0.56
1991	602 a	--	603 a	--	470 a	--	535 a	--	--	552	463	767	0.72
1992	516 a	--	352 a	--	609 a	--	370 a	--	--	462	412	735	0.63
1993	498 a	--	625 a	--	--[c]	--	666 a	--	--	596	453	924	0.65
1994	--	72 a	--	180 a	--	0 a	--	45 a	--	74	198	494	0.15
1995	--	245 a	--	244 a	--	139 a	--	29 a	--	164	315	680	0.24
1996	--	281 a	--	618 a	--	280 a	--	54 a	--	308	793	665	0.46
1997	--	58 a	--	60 a	--	22 a	--	9 a	--	37	118	510	0.07
1998	--	84 b	--	420 a	--	228 ab	--	184 ab	--	229	313	600	0.38
1999	--	82 bc	--	149 a	--	108 b	--	51 c	--	98	33	657	0.15
2000	--	--	--	--	--	--	31 a	--	7 b	19	24	496	0.04
2001	--	--	--	--	--	--	234 a	--	294 a	264	172	641	0.41
2002	--	--	--	--	--	--	231 a	--	264 a	248	172	665	0.37
2003	--	--	--	--	--	--	327 a	--	324 a	326	433	711	0.46
2004	--	--	--	--	--	--	377 a	--	202 a	290	350	624	0.46
Average										257		655	0.36

[a] Average of separate corn and soybean plots from 1989-1993. Means within years and on average (i.e., within rows) followed by the same letter are not significantly different at $p = 0.05$.
[b] October and November of the previous growing season, and March through September of the current growing season.
[c] Drainage volume data were in error.

drainage was recorded for these months. However, since the soils were either lacking available moisture for drainage or were frozen, it was expected that little drainage would occur in the winter for these plots.

Nitrate-Nitrogen Concentrations in Subsurface Drainage

During the 16 years of study, average yearly flow-weighted NO_3-N concentrations ranged from 3.9 mg L^{-1} (at 45 kg N ha^{-1}, 1995) to 28.7 mg L^{-1} (at 252 kg N ha^{-1}, 2001). Statistical differences ($LSD_{0.05}$) of flow-weighted NO_3-N concentrations in subsurface drainage are presented in tables 5 through 8. Concentrations and $LSD_{0.05}$ values are comparable to those reported by Bakhsh et al. (2005, 2006), Randall et al. (1997), and Randall and Vetsch (2005).

Only in 1989 did below-average precipitation result in no subsurface drainage. This was the first year of the study and was actually an advantage, allowing one growing season for treatment establishment before drainage and concentration data were collected.

Phase I (1990-1993) four-year average, flow-weighted NO_3-N concentrations for soybean ranged from 7.8 to 11.7 mg L^{-1} (table 5). Concentration values for individual years ranged from 4.3 mg L^{-1} (at 0 kg N ha^{-1}, 1993) to 17.7 mg L^{-1} (at 168 kg N ha^{-1}, 1990). Significant differences were noted when comparing four-year average NO_3-N concentrations between the highest rate (168 kg N ha^{-1}), the lowest rate (56 kg N ha^{-1}), and plots with no applied N.

Phase I (1990-1993) four-year average, flow-weighted NO_3-N concentrations for corn ranged from 9.9 to 13.1 mg

Table 4. Average subsurface drainage volumes over all rate treatments by year and month during the study period (all values in mm).

Year	March	April	May	June	July	August	September	October	November	Total
1989	0	0	0	0	0	0	0	0	0	0
1990	2	19	67	277	77	3	0	0	0	444
1991	0	109	185	149	3	2	9	6	81	552
1992	0	98	13	70	189	4	0	38	49	462
1993	0	173	139	94	81	90	0	9	10	596
1994	0	1	0	61	9	0	2	0	0	74
1995	0	0	100	28	0	0	0	0	35	163
1996	0	0	109	108	23	68	0	6	0	308
1997	0	3	17	9	9	0	0	0	0	38
1998	0	0	123	82	18	0	0	0	0	224
1999	0	0	84	12	1	0	0	0	0	97
2000	0	0	0	5	15	0	0	0	0	20
2001	0	37	180	47	0	3	0	0	0	267
2002	0	11	67	33	0	105	25	9	0	250
2003	0	19	76	113	121	0	0	0	0	329
2004	0	38	144	87	17	4	0	0	0	291
Average	0	32	82	68	35	17	2	4	11	256

Table 5. Flow-weighted NO_3-N concentrations for a comparison of corn and soybean in rotation (1990-1993).

	N rate[a] (kg N ha^{-1})	NO_3-N Concentration (mg L^{-1})[b]				
		1990	1991	1992	1993	Average
Corn	0	13.2 ab	12.2 ab	7.1 a	6.0 ab	9.9 bc
	56	17.1 ab	10.5 ab	9.6 a	5.5 b	11.1 ab
	112	16.0 ab	15.2 a	9.7 a	10.7 a	13.1 a
	168	18.1 a	13.2 ab	8.8 a	7.8 ab	12.0 ab
Soybean	0	9.7 b	9.4 ab	7.9 a	4.3 b	7.8 c
	56	9.7 b	9.1 b	5.7 a	6.1 ab	7.8 c
	112	12.4 ab	12.1 ab	8.5 a	7.2 ab	10.3 abc
	168	17.7 ab	14.7 ab	8.5 a	5.8 ab	11.7 ab
$LSD_{0.05}$		8.1	5.8	4.7	5.1	3.0

[a] N application in the corn year only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05.

L^{-1} (table 5). Concentration values for individual years ranged from 5.5 mg L^{-1} (at 56 kg ha^{-1}, 1993) to 18.1 mg L^{-1} (at 168 kg N ha^{-1}, 1990). Individual annual average NO_3-N values for the no N applied treatment ranged from 6.0 to 13.2 mg L^{-1}, and the overall average, 9.9 mg L^{-1}, was the lowest, but these values were still quite high (i.e., over 80% of the fertilized plot concentrations).When comparing NO_3-N concentrations between the corn and soybean plots within the same year, significant differences were not noted within years. The corn year (when fertilizer was applied) was higher, but not significantly so, 81% of the time (range of 0.4 to 7.4 mg L^{-1} higher). Whole system values (averages for corn and soybean combined) for the same period are presented in table 6. Statistical differences were noted between the no applied N treatment and the 112 and 168 kg N ha^{-1} rates.

Concentrations generally decreased over time for each rate during this phase and could be mostly attributed to above-average precipitation, which resulted in large drainage volumes removing NO_3-N; this phase was preceded by below-normal precipitation in 1988 and 1989, which provided conditions conducive to accumulation of NO_3-N in the soil profile above the subsurface drain lines. Overall, the highest concentrations were recorded in 1990, and the lowest were recorded in 1993.

In phase II (1994-1999), the plots were planted to half corn and half soybean in rotation, and four N rates were imposed on the corn half of the plots. Average, flow-weighted NO_3-N concentrations by rate ranged from 5.7 to 13.2 mg L^{-1} (table 7). Concentration values for individual years ranged

Table 6. Flow-weighted NO_3-N concentrations for the corn-soybean rotation combined (1990-1993).

N Rate[a] (kg N ha^{-1})	NO_3-N Concentration (mg L^{-1})[b]				
	1990	1991	1992	1993	Average
0	11.4 b	9.8 b	7.5 a	5.0 b	8.9 b
56	13.4 ab	10.8 ab	7.6 a	5.8 ab	9.5 ab
112	14.2 ab	13.7 ab	9.1 a	9.0 a	11.7 a
168	17.9 a	14.0 a	8.6 a	6.8 ab	11.8 a
$LSD_{0.05}$	5.9	3.9	3.2	3.5	2.1

[a] N application in the corn year only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05.

Table 7. Flow-weighted NO_3-N concentrations for the corn-soybean rotation combined (1994-1999).

N Rate[a] (kg N ha^{-1})	NO_3-N Concentration (mg L^{-1})[b]						
	1994	1995	1996	1997	1998	1999	Average (95-99)
45	4.9 a	3.9 c	4.4 d	4.9 d	5.8 c	10.4 c	5.9 d
90	7.9 a	5.5 bc	6.9 c	7.4 c	7.9 c	12.9 bc	8.1 c
134	--[c]	7.9 ab	9.9 b	14.6 a	11.0 b	17.3 ab	11.9 b
179	7.5 a	9.4 a	12.5 a	11.8 b	14.4 a	20.2 a	14.6 a
$LSD_{0.05}$	5.9	2.5	2.4	1.2	2.5	4.6	1.5

[a] Corn and soybean grown on the same plot; N application in the corn half only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 1994, was considered a "calibration or transition" year and was not included in the overall average.
[c] No drainage for this treatment.

from 3.9 mg L^{-1} (at 45 kg ha^{-1}, 1995) to 20.2 mg L^{-1} (at 179 kg ha^{-1}, 1999). All years (1995-1999) exhibited significant differences ($LSD_{0.05}$) among the N rates tested for NO_3-N concentration (table 7). Significant differences were noted when comparing five-year average NO_3-N concentrations between the higher N rates (134 and 179 kg ha^{-1}), the mid-rate (90 kg ha^{-1}), and the lowest rate (45 kg ha^{-1}). Precipitation during this phase was normal to below normal and was preceded by an excessive precipitation period with decreasing concentrations in phase I. This resulted in a general increase in concentration for each N rate over time, suggesting an accumulation of NO_3-N in the soil profile above the subsurface drain lines. Generally, the lowest concentrations were in 1994, and the highest were in 1999. In this phase, the overall average of 5.7 mg L^{-1} for the lowest N rate (45 kg N ha^{-1}) was much lower than the 8.9 mg L^{-1} for the corn-soybean rotation in phase I with no applied N.

In phase III (2000-2004), only two rates were used for rate comparison as part of a separate seasonal N application timing study (table 8). For two of the four years (2001-2004), there was a significant ($LSD_{0.05}$) difference between rates. The lower rate always exhibited lower concentrations. Phase III data showed the highest concentrations in 2001, a year preceded by a dry period with both 1999 and 2000 dryer than normal. The lowest concentrations during the study were

Table 8. Flow-weighted NO_3-N concentrations for the corn-soybean rotation combined (2000-2004).

N Rate[a] (kg N ha^{-1})	NO_3-N Concentration (mg L^{-1})[b]					
	2000	2001	2002	2003	2004	Average (2001-04)
168	17.8	17.9 b	10.9 b	15.0 a	15.7 a	14.9b
252	26.8	28.7 a	19.3 a	23.0 a	22.0 a	23.3a
$LSD_{0.05}$	--[c]	5.4	5.4	12.4	6.8	3.3

[a] Corn and soybean grown on the same plot; N application in the corn half only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 2000, was considered a "calibration or transition" year and was not included in the overall average.
[c] Lack of drainage limited samples, preventing LSD comparisons.

measured in a below-normal precipitation period (2002) after an above-normal precipitation period (2001).

Nitrate-Nitrogen Losses in Subsurface Drainage

Annual NO_3-N losses are the product of subsurface drainage volumes, which are intimately connected with precipitation patterns, and NO_3-N concentrations. Results generally mirror those for concentrations described in the previous section. Losses ranged from 0 (no or low-drainage periods, respectively, for 1989 and 1994) to nearly 109 kg N ha^{-1} (at 112 kg N ha^{-1}, 1991) during the study period (tables 9 through 12). Losses and $LSD_{0.05}$ values are comparable to those reported by Bakhsh et al. (2005, 2006), Randall et al. (1997), and Randall and Vetsch (2005). Again, losses and NO_3-N concentrations are predominantly affected by precipitation and drainage volume, application rate, and organic matter mineralization combined with crop yields that affect the overall N balance in the soil profile. Phase I was marked by three of five years with above-normal precipitation, and average drainage volume across both the corn and soybean systems was 48% of drainage year precipitation (October and November of the previous growing season and March through September of the current growing season). Phase II was somewhat drier, with drainage values 26% of drainage year precipitation. Phase III was intermediate, with 34% of drainage year precipitation being removed by the subsurface drainage system.

Phase I losses for soybean ranged from 23 to 83 kg N ha^{-1} (table 9). Losses for the corn in rotation with soybean ranged from 21 (at 0 kg N ha^{-1}; 1993) to 109 kg N ha^{-1} (at 112 kg N ha^{-1}; 1991). Overall, there were no significant differences in NO_3-N losses with varying application rates. Table 10 presents the losses for the combined corn and soybean plots for this period. Lack of statistical significance when comparing losses is not unusual since variability in both concentration and drainage volume is compounded when calculating losses (Randall and Vetsch, 2005).

Phase II NO_3-N losses followed a similar trend as concentrations; both were lower than phase I values when above-average precipitation created substantial losses. Corn-soybean rotation losses in individual years (table 11) ranged from 0 (at 134 kg N ha^{-1} in 1994, a low drainage period) to 40 kg N ha^{-1} (at 90 kg N ha^{-1} in 1996). In one of five years, there was a statistically significant difference among rates. Averaged over five years, NO_3-N losses ranged from 7 to 19 kg N ha^{-1} for the four N rates. Losses did not linearly follow the application rate, mostly due to drainage volume variability.

Table 9. NO_3-N losses by system and within years for a comparison of corn-soybean rotation (1990-1993).

	N Rate[a] (kg N ha^{-1})	NO_3-N Losses (kg ha^{-1})[b]				
		1990	1991	1992	1993	Average
Corn	0	45 a	91 a	27 a	21 a	48 a
	56	63 a	72 a	31 a	49 a	54 a
	112	36 a	109 a	40 a	62 a	74 a
	168	80 a	64 a	33 a	59 a	59 a
Soybean	0	60 a	43 a	65 a	34 a	52 a
	56	48 a	46 a	23 a	52 a	41 a
	112	82 a	28 a	58 a	--[c]	64 a
	168	70 a	83 a	32 a	36 a	57 a
$LSD_{0.05}$		75	97	74	81	37

[a] N application in the corn year only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05.
[c] Drainage volume data were in error.

Table 10. NO_3-N losses for the corn-soybean rotation combined (1990-1993).

N Rate[a] (kg N ha^{-1})	NO_3-N Losses (kg ha^{-1})[b]				
	1990	1991	1992	1993	Average
0	53 a	67 a	46 a	28 a	50 a
56	56 a	59 a	27 a	50 a	48 a
112	70 a	88 a	51 a	--[c]	68 a
168	75 a	74 a	33 a	50 a	58 a
$LSD_{0.05}$	44	76	47	43	25

[a] N application in the corn year only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05.
[c] Drainage volume data were in error.

Above-average total precipitation was recorded in 2000, and drainage season precipitation (March-November) was approximately 7% less than average, resulting in minimal subsurface drainage and NO_3-N loss (average of 19 mm and 4 kg N ha^{-1} for the two N rates) (table 12). It should be noted that within 60 days of N application on 17 May, nearly half of the total drainage season precipitation was received, and all the subsurface drainage. Drainage season precipitation in 2001 was only 16 mm greater than 2000 but resulted in nearly 14 times the drainage volume and NO_3-N loss. Precipitation in the 60 days following fertilizer application was only half that received in 2000. Approximately 80% of the NO_3-N losses that occurred in 2001 were prior to spring N application on 4 June and were likely derived from organic matter N mineralization and previous spring applications made in a minimal drainage year (2000).

Crop Production

All years, when rates were compared within years, exhibited significant corn yield differences ($LSD_{0.05}$) between low rates and the close to optimum N rates for each phase, as shown in tables 13 through 15. These tables also include the average corn yields by year for Pocahontas County for comparison of site yields, although the average N rate for the county is unknown. Corn yield during all periods

Table 11. NO_3-N losses for the corn-soybean rotation combined (1994-1999).

N Rate[a] (kg N ha^{-1})	NO_3-N Losses (kg ha^{-1})[b]						
	1994	1995	1996	1997	1998	1999	Average (95-99)
45	3 ab	10 a	13 a	3 a	5 a	8 a	7 c
90	11 a	14 a	40 a	5 a	35 a	20 a	21 a
134	0 b	12 a	28 a	3 a	27 a	19 a	18 ab
179	3 ab	3 a	7 a	1 a	25 a	11 b	9 bc
$LSD_{0.05}$	10	22	62	10	37	6	10

[a] Corn and soybean grown on the same plot; N application in the corn half only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 1994, was considered a "calibration or transition" year and was not included in the overall average.

Table 12. NO_3-N losses for corn-soybean rotation combined (2000-2004).

N Rate[a] (kg N ha^{-1})	NO_3-N Losses (kg ha^{-1})[b] 2000	2001	2002	2003	2004	Average (2001-04)
168	5 a	37 a	25 b	49 a	58 a	39 b
252	2 a	86 a	47 a	74 a	39 a	63 a
$LSD_{0.05}$	7	50	20	271	63	22

[a] Corn and soybean grown on the same plot; N application in the corn half only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 2000, was considered a "calibration or transition" year and was not included in the overall average.

showed a strong correlation between N rate and yield. As N rate increased, yield increased. It should be noted that at least 50% of the years showed limited yield response to N application above the next to the highest rates. Of these, the wettest years had the closest yields at the top two increments of N (1990, 1991, 1993, 1996, 1998, 2001, 2002, and 2004).

During the first phase (1989-1993), yields within individual years ranged from 4056 kg ha^{-1} (0 kg N rate, 1990) to 9541 kg ha^{-1} (168 kg N rate, 1991) (table 13). The lowest yield year for all rates was 1993, an above-average precipitation and subsurface drainage period. During the first phase, the site yield surpassed county averages in 3 of 5 years and on average. During the second phase (1994-1999), a mostly normal or slightly dry period, yields ranged from 4396 kg ha^{-1} using 45 kg N ha^{-1} to 9440 kg ha^{-1} at the 179 kg ha^{-1} rate (table 14). One of the driest years, 1997, with very limited N movement through the soil profile, also had some of the highest yields across all rates, even surpassing the county average. Corn yield data for phase III, with statistical differences, are presented in table 15. Only two of five years and the overall average had yields that were statistically significant ($LSD_{0.05}$). The higher application rate N treatment in the corn year always had higher yield. Yields ranged from 8343 kg ha^{-1} in 2000 (168 kg N ha^{-1}) to 11,147 kg ha^{-1} in 2004 (252 kg N ha^{-1}). The yield at the 168 kg N ha^{-1} rate surpassed the county average during an above-normal precipitation year (2001), possibly a result of the extensive site drainage system. As shown in tables 16 through 18, in some years a correlation between increasing N application rate in the previous corn year and soybean yield was noted. Four of the 16 years had significant yield differences, possibly related to N rate. One-half of the all years showed a minor soybean yield depression at the highest corn N rate; in these years, the treatment with the next to highest increment of N applied the previous season on corn had the highest soybean yield.

In summary, soybean and corn yields in some years were slightly below the county averages, although nearly equal or above in most years. Wet years saw a yield increase over county averages, possibly because of the site's closely spaced drainage system. N rate and yield were positively correlated; as rate was increased, corn yield also increased, quite often up to the second to the last increment of N. Soybean yield was sometimes affected positively by previous N applications to corn in rotation.

Table 13. Corn yield for corn-soybean rotation nitrogen rate treatments (1989-1993).

N rate[a] (kg N ha^{-1})	Corn Yield (kg ha^{-1})[b] 1989	1990	1991	1992	1993	Average (90-93)
0	5205 b	5550 b	5379 c	5184 c	4056 b	5042 c
56	6710 ab	6417 b	7197 b	6626 b	5934 a	6544 b
112	7839 a	8706 a	9369 a	8549 a	6568 a	8298 a
168	7901 a	8706 a	9541 a	9344 a	6517 a	8527 a
$LSD_{0.05}$	1831	1817	1510	1127	940	921
Pocahontas County average	8817	7732	7431	10040	4678	7470

[a] N application in the corn year only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 1989, was considered a "calibration or transition" year and was not included in the overall average.

Table 14. Corn yield for corn-soybean rotation nitrogen rate treatments (1994-1999).

N Rate[a] (kg N ha^{-1})	Corn Yield (kg ha^{-1})[b] 1994	1995	1996	1997	1998	1999	Average (95-99)
45	4396 b	6587 c	6479 a	7720 c	5758 a	6439 b	6597 c
90	6175 ab	7932 b	6867 a	8646 b	6315 a	7051 ab	7362 b
134	6461 a	8002 b	7310 a	9116 ab	7222 a	7551 ab	7840 ab
179	7122 a	8691 a	7172 a	9440 a	7152 a	8209 a	8133 a
$LSD_{0.05}$	1842	561	979	675	1737	1661	689
Pocahontas County average	10203	8761	9425	9294	8547	9889	9183

[a] Corn and soybean grown on the same plot; N application in the corn half only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 1994, was considered a "calibration or transition" year and was not included in the overall average.

Table 15. Corn yield for corn-soybean nitrogen rate treatments (2000-2004).

N Rate[a] (kg N ha^{-1})	Corn Yield (kg ha^{-1})[b] 2000	2001	2002	2003	2004	Average
168	8343 a	8871 a	8364 a	7477 b	10273 b	8740 a
252	9352 a	8967 a	8474 a	8450 a	11147 a	9302 a
$LSD_{0.05}$	1174	1321	1457	801	581	887
Pocahontas County average	9758	8485	10510	10542	12260	10449

[a] Corn and soybean grown on the same plot; N application in the corn half only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 2000, was considered a "calibration or transition" year and was not included in the overall average.

Table 16. Soybean yield for corn-soybean nitrogen rate treatments (1989-1993).

N Rate[a] (kg N ha^{-1})	Soybean Yield (kg ha^{-1})[b]					
	1989	1990	1991	1992	1993	Average (90-93)
0	2330 a	1613 ab	1311 a	3015 a	2147 a	2010 a
56	1900 a	1120 b	1271 a	2499 a	2049 a	1706 a
112	2558 a	2016 a	1420 a	3126 a	1813 a	2101 a
168	1936 a	1635 ab	1253 a	2680 a	2122 a	1922 a
$LSD_{0.05}$	1568	704	405	673	431	591
Pocahontas County average	2896	2520	2399	3017	1693	2407

[a] N application in the corn year only.
[b] Means within years and on average (i.e. within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 1989, was considered a "calibration or transition" year and was not included in the overall average.

Table 17. Soybean yield for corn-soybean nitrogen rate treatments (1994-1999).

N Rate[a] (kg N ha^{-1})	Soybean Yield (kg ha^{-1})[b]						
	1994	1995	1996	1997	1998	1999	Average (95-99)
45	3489 a	3341 a	2515 b	2690 a	3272 a	2404 b	2845 a
90	3552 a	3330 a	2661 ab	2999 a	3247 a	2988 a	3345 a
134	3599 a	3203 a	2880 a	3010 a	3163 a	3104 a	3072 a
179	3113 b	2996 a	2943 a	3042 a	3252 a	2743 ab	2995 a
$LSD_{0.05}$	370	542	361	627	421	499	245
Pocahontas County average	3366	3245	3118	3158	3138	2842	3100

[a] Corn and soybean grown on the same plot; N application in the corn half only.
[b] Means within years and on average (i.e. within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 1994, was considered a "calibration or transition" year and was not included in the overall average.

Table 18. Soybean yield for corn-soybean nitrogen rate treatments (2000-2004).

N Rate[a] (kg N ha^{-1})	Soybean Yield (kg ha^{-1})[b]					
	2000	2001	2002	2003	2004	Average (2001-04)
168	4080 a	3530 a	3459 a	2221 a	3082 a	3073 a
252	4162 a	3671 a	3362 a	2287 a	3253 a	3143 a
$LSD_{0.05}$	346	417	333	701	597	395
Pocahontas County average	2896	2856	3286	2251	3084	2869

[a] Corn and soybean grown on the same plot; N application in the corn half only.
[b] Means within years and on average (i.e., within columns) followed by the same letter are not significantly different at p = 0.05. The first year in this phase, 2000, was considered a "calibration or transition" year and was not included in the overall average.

Discussion

This three-phase study was initiated to better quantify how different N application rates affect NO_3-N concentrations and losses in subsurface drainage. In particular, it was important to evaluate this over a wide range of weather conditions in Iowa. Although the volumes varied considerably, drainage occurred in each year except 1989.

While the average annual flow-weighted NO_3-N concentrations varied from year to year even within similar N application rates, overall there was a general trend that as N application rates increased, NO_3-N concentrations in the subsurface drainage increased (fig. 4). Based on multiple years of data from the three phases studied at this site, the N application rate would need to be less than 112 kg N ha^{-1} to achieve an average level of approximately 10 mg L^{-1}, the drinking water standard. While subsurface drainage is not required to meet this standard, water quality criteria for N that are being considered by the state may require a value this low or lower. Based on these data, if the N application rate were reduced from 168 to 134 kg N ha^{-1} there would be approximately a 20% reduction of NO_3-N concentration in subsurface drainage, and a reduction in N application rate from 134 to 112 would result in approximately a 10% reduction. Corn yield during the study responded to N application rate, and N application rates below recommended rates may decrease corn yield.

As previously discussed, the annual flow-weighted NO_3-N concentrations in phase I decreased over time during a period characterized by above-normal precipitation. This observation was an indication that there seems to be some flushing of stored NO_3-N from the system during a wetter period. In contrast, during phase II, a period characterized by below-normal precipitation, a general trend of increasing annual flow-weighted NO_3-N concentrations was observed through the phase, which is an indication of NO_3-N storage within the soil system.

Although a strictly constant N application rate was not used throughout the 16 years of this study, the most consistent application rates used were 168 to 179 kg N ha^{-1}. These treatments were combined to compare year-to-year NO_3-N concentration and loss data over the study period (fig. 5). The average NO_3-N concentration for this N application range was 13.5 mg L^{-1}, with an average loss of 35 kg N ha^{-1}. NO_3-N loss as a percentage of that applied as N fertilizer was approximately 21%. Review of the 16 years at this similar application rate emphasizes the large variability between years and the flushing and storage of N inherent in the system. Specifically, NO_3-N concentrations ranged from a low of 6.8 mg L^{-1} in 1993, a year preceded by three years of relatively large volumes of subsurface drainage, to 20.2 mg L^{-1} in 1999, a year preceded by a lower subsurface drainage period (1997 and 1998). In addition, the years preceding 1993 had fairly high corn yields. In addition, when a "large pool" of N seemingly exists, as was the case at the beginning of the study, the NO_3-N concentration from a no applied N treatment (as in phase I) can be high and the effect of rate can be less evident.

Conclusions

This multi-year experiment indicates that the N application rate affects concentration and losses, and even at constant rates, these can be highly variable depending on precipitation patterns, N mineralization/denitrification processes, and crop utilization in a given season. It was observed that an increase in N application rates results in an

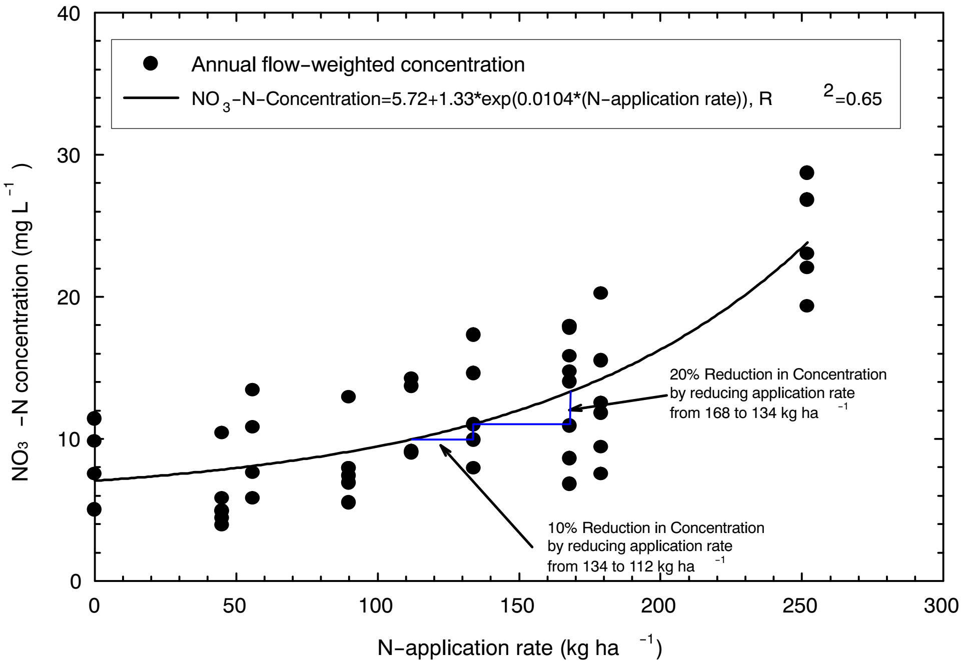

Figure 4. Overall nitrogen application rate effect on annual flow-weighted NO_3-N concentration.

increase in NO_3-N concentrations and losses. However, even when no N is applied, NO_3-N concentrations were greater than zero in subsurface drainage, and the four-year average was 8.9 mg L^{-1}. In Iowa, subsurface drainage can occur anytime the soil is not frozen and moisture exceeds the soil storage capacity. Typically, subsurface drainage begins in late March and ends in July, although it may continue into late November. On average, nearly 63% of subsurface drainage occurs in May and June, while April and July together account for 25%. Approximately one-third of annual precipitation may become subsurface drainage. With no N fertilizer applied in a corn-soybean rotation (phase I), it was noted that concentrations did not diminish substantially until two seasons with substantial drainage had passed. Growing seasons with adequate or below-normal precipitation for crop production but with little or no drainage seemingly resulted

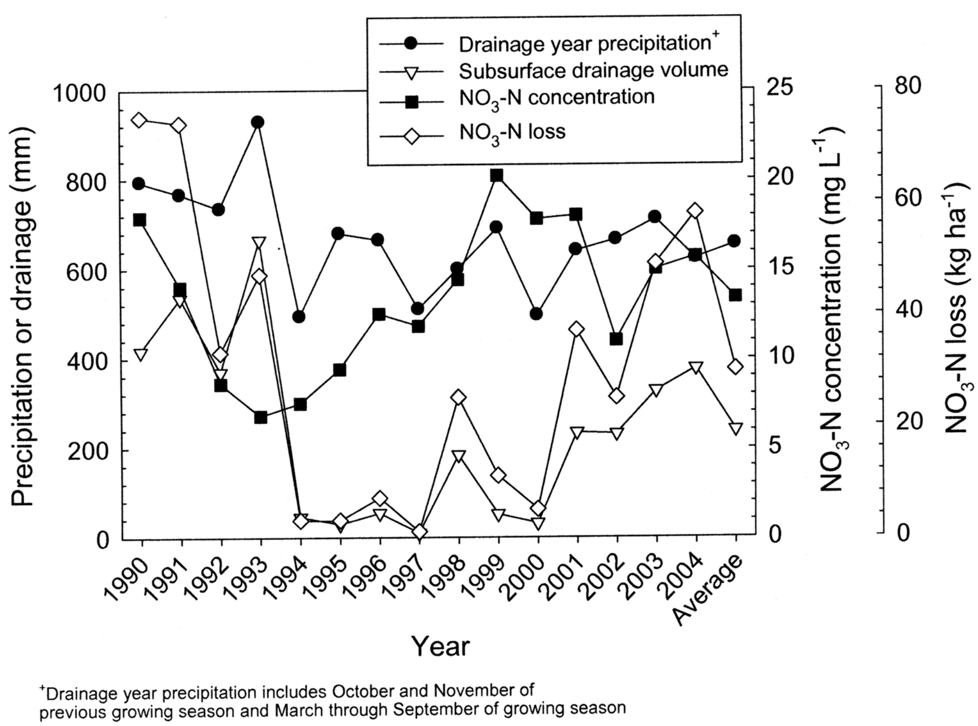

Figure 5. Comparison of drainage year precipitation, drainage volume, NO_3-N concentration, and NO_3-N loss for the 168 to 179 kg N ha^{-1} application rates during the study period.

in N storage/carryover within the soil profile for subsequent crop usage or loss through subsurface drainage systems. Thus, after dry periods, drainage that occurs may have higher NO_3-N concentrations. Excessive precipitation and drainage periods may result in lower concentrations for several seasons until N soil levels are amended with fertilizer. Wet and dry periods result in N withdrawal and storage, respectively. Based on the information collected at this study site, the recommended N application rates for corn in a corn-soybean rotation in Iowa (112 to 168 kg ha^{-1}) commonly resulted in NO_3-N concentrations in subsurface drainage above 10 mg L^{-1}.

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