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Nitrification Inhibitor and Nitrogen Application Timing Effects on Yields and Nitrate-Nitrogen Concentrations in Subsurface Drainage from a Corn-Soybean Rotation

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Abstract

Excess precipitation in Iowa and many other agricultural production areas is removed artificially via subsurface drainage systems that intercept and usually divert it to surface waters. Nitrogen, either applied as fertilizer or manure and derived from soil organic matter, can be carried as nitrate with the excess water in quantities that can cause deleterious effects downstream. A four-year, five-replication, field study was initiated in the fall of 1999 in Pocahontas County, Iowa on 0.05 ha plots that are predominantly Nicollet, Webster, and Canisteo clay loams with 3-5% organic matter. The objective was to determine the influence of seasonal N application and the use of nitrapyrin [inhibitor; 2-chloro-6 (trichloromethyl) pyridine] on flow-weighted nitrate-nitrogen concentrations and yields in a corn-soybean rotation, combined on single plots. Six aqua-ammonia nitrogen treatments (168 and 252 kg/ha at planting and in late fall, and 168 kg/ha at planting and late fall with nitrapyrin) were imposed on subsurface drained, continuous-flow-monitored plots. Combined fall 1999 and spring 2000 precipitation was 42% of normal average. Subsequently, normal precipitation was recorded for both fall and spring periods (after fall application, and before spring application) until spring and fall 2002 (51% and 73% of normal, respectively). Spring 2003 precipitation was again only 51% of normal average. Four-year average, flow-weighted nitrate-nitrogen concentrations ranked in highest to lowest order: spring-252(22.9 mg/L;a) > fall-252(18.1 mg/L;b) > spring-168 w/inhibitor(17.7 mg/L;bc) > fall-168 w/inhibitor(16.0 mg/L;bcd) > spring-168(14.8 mg/L;cd) > fall-168(14.2 mg/L;cd). Spring application plots had significantly greater soybean yield the following season compared to fall applications. Greatest corn yields were observed for the spring-252 and fall-168 rates, but were only significantly different than the spring-168 rate for yield. Therefore, under slightly dry to normal precipitation conditions, corn yields and nitrate-nitrogen concentrations in subsurface drainage were not significantly different between seasonal timing or inhibitor use treatments at the 168 kg/ha nitrogen rate.

Keywords

ammonia, crop production, drainage water, environmental impact, fertilizers, groundwater, hypoxic zone, inhibitor, leaching, nitrate, nitrification, nitrogen, nonpoint source pollution, nutrients, soil water pollution, subsurface drainage, water quality

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Introduction

Water table management through the use of artificial subsurface drainage systems is of primary importance in humid areas with poorly or somewhat poorly drained soils to optimize agricultural productivity. Excess precipitation in Iowa and many other Mississippi/Ohio River watershed agricultural production states is removed artificially via subsurface drainage systems that intercept and usually 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 conditions. The tradeoff of improved subsurface drainage is a significant increase in the losses of nitrate-nitrogen (NO_3-N) (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 drainage (USDA, 1987).

The movement of N from agricultural fields via drainage waters is a major factor in nonpoint source pollution of surface waters and ultimately the Gulf of Mexico where it has been implicated as a cause of the Hypoxic Zone (Mitsch et al., 2001; Rabalais et al., 1996). The environmental impacts downstream depend on the agronomic practices implemented, as well as the site, crops, soils and climatological factors. Ammonium based nitrogen fertilizers are commonly applied in the Cornbelt in either spring or fall. It is a general conclusion from research conducted over several decades that as a best management practice N should be applied at the correct amount nearest to the time it is needed by the crop. For corn produced in the Midwest, this would involve a sidedressed application several weeks after emergence, thus minimizing the time between application and crop utilization capabilities (Randall et al., 2003a). Unknown future weather conditions, limited equipment availability and labor constraints can make this practice unattainable. Application of N in the fall or early spring has its advantages for producers and fertilizer suppliers. Typically, soil conditions, fertilizer cost, equipment and labor favor fall or early spring application in Illinois, Iowa, Minnesota and Wisconsin (Dinnes et al., 2002; Randall and Schmitt, 1998). As a consequence, if precipitation exceeds the field capacity of the soil and the evapotranspiration needs of the crop system, N that was applied, can be lost as NO_3 in subsurface drainage. Conversely, soils with poor drainage may loose NO_3 via denitrification.

This leads to the conclusion that fall application of fertilizer N is agronomically, if not environmentally, risky. A review (Bundy, 1986) of research indicates that fall applications of ammonium (NH_4) based N fertilizers are usually 10-15% less effective than spring applications. Bundy states that while the use of nitrification inhibitors generally improves the effectiveness of fall applied N, it does not equal the management practice of delaying N fertilizer application until spring. Yield comparisons of fall and spring N applications have been mixed. In addition, the use of nitrification inhibitors has also had varying results. The response of corn to applications of inhibitors varies greatly throughout the US because of major differences in N loss potential from differing climate, soils and cropping systems (Nelson and Huber, 1992). Nitrification inhibitors function by retarding the activity and decreasing the population of *Nitrosomonas* bacteria that convert NH_4 to nitrite (NO_2), a precursor to the formation of highly leachable NO_3. They are expected to decrease nitrification thereby retaining NH_4, which is not susceptible to denitrification, and as a cation, can be soil absorbed and is less susceptible to leaching. In a Minnesota study, Randall et al. (2003b) noted that only one in seven years showed a significant difference ($P< 0.10$) in production when comparing spring and fall applications without an inhibitor. Precipitation in May during this year (1991) was above normal. When a fall inhibitor was used and compared, there was not a statistical difference in yield between spring and fall applications. Similar but more statistically significant results were reported in a separate study without an inhibitor (Vetsch and Randall, 2004), indicating that spring applications are superior to fall. Again, the impact of excessive spring precipitation was positively correlated to diminished yield for fall-applied N in individual years for a continuous corn system. Other research has also emphasized that March through May precipitation is a major cause of N loss from fertilized fields before rapid growth and N uptake begins in June (Balkcom et al., 2003). Nitrification inhibitor impacts on yields in the Eastern Cornbelt have been more positive.

Early research in Iowa and other areas of the Midwest have shown that substantial amounts of NO_3-N can be lost in subsurface drainage that eventually returns to surface waters (Baker et al.,1975; Baker and Johnson, 1981; Hanway and Laflen, 1974; Kanwar et al.,1988). A common misconception regarding loss of N via subsurface drainage is that most of the loss is derived from applied fertilizer N which has had minimal interaction with soil-plant system. 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 cooler climates, it may take a year or more, depending on precipitation patterns, for added N to reach the drainage system. 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. Annual losses of 60-70 kg NO_3-N ha^{-1} were common using recommended fertilization practices (Randall, et al., 1997). Similar results were found in an Iowa drainage study (Baker and Melvin, 1994). Data from this study illustrates that significant N losses can occur even with no applied N and more so for soils in a fallow condition following two years of dry conditions and no drainage. At the other extreme, over application or ill-timed applications of either animal manure or commercial fertilizers can provide too much plant available N and increase the potential for NO_3-N leaching.

Objectives

Since there are practical advantages to the timing of N application depending on the producers operation, and despite the research that has been performed, there is a need to further the understanding of the environmental and production impacts of seasonal N application; also the impacts of nitrification inhibitors on N leaching and crop production in the upper Midwest need greater understanding. From this, the objectives of this study were to determine the influences of seasonal N application and an inhibitor on flow-weighted NO_3-N concentrations, losses and yields in a corn-soybean rotation.

Materials and Methods

Research Site and Monitoring Equipment

The field experimental site was located near Gilmore City in rural Pocahontas County, IA. It was in Garfield Township at SW 1/4, Section 27, T92N, and R3IW. 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 3-5% organic matter content. These are poorly to somewhat poorly drained glacial till soils with an average slope of 0.5 to 1.5 percent. Soil samples taken to a depth of 15 cm in April 2000 averaged 7.6 pH and 53 mg kg-1 Bray P1 (very high) (Sawyer et al., 2002). In 2003, Bray P1 was 31 mg kg-1 (very high) and pH was 7.7.

Total research area was 4.5 ha, of which 1.5 ha were used as plots for this study and the remainder as additional plot area (75 total plots), border and buffer. Each of the thirty plots were 0.05 ha (15.2 x 38.0 m) and established in 1989. Subsurface drainage lines 7.6 m apartwere installed parallel to the long dimension through the center of each plot and on the borders between plots at a depth of 1.06 m. Subsurface drains at plot borders were installed to help prevent lateral, subsurface drainage flow from adjacent plots. The border drain lines have an outlet to the surface at a remote location. The centerline subsurface drainage line position is illustrated in **Figure 1.** Only the center drainage line is monitored for drainage volume and nitrate nitrogen concentration. Corn (Zea mays L.) and soybean (Glycine max [L.] Merr.) were grown in rows on 0.762 m centers; this resulted in ten rows of each crop in each plot. Reasoning behind combining both crops in rotation within a single, monitored experimental plot stems from previous research and 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 (150-200 kg N ha-1) for corn production in a corn-soybean rotation, NO_3-N losses and concentrations were not significantly different in either the corn or soybean year.

Ten aluminum culverts, 1.2 m in diameter were buried vertically at the terminus of three drainage lines from individual plots to accommodate a water table dewatering sump and three sampling/monitoring configurations. The configuration is illustrated in **Figure 2**. Drainage lines, each from individual plots, terminated in the aluminum culvert and were directed to separate plastic sumps within the culvert and pumped by a Zoeller model M53 submersible pump (Zoeller Pump Co., Louisville, KY) through plastic plumbing fitted with a common plated sprayer orifice nozzle and a 16mm, Trident T-10 water meter (Neptune Technology Group, Inc., Tallassee, AL). Back pressure created by the meter forced a small constant fraction (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 recorded as dictated by flow patterns. Typically, after 13 mm of subsurface drainage, sample jars would contain 10 L of water available for sub-sampling. This rather unique configuration provided the infrastructure for continuously monitored flow volume measurement and sampling of subsurface drainage emanating from below the treated area. Sub-samples were collected at this point and over each flow period and represented the quality of water that was intercepted under the treated area. Sampled and metered drainage was then surface discharged some distance away. Samples collected were chilled and stored at 4°C until analyzed. Nitrate-nitrogen analyses were performed in the Agricultural and Biosytems Engineering Water Quality laboratory located on the campus of Iowa State University using a Lachet Quickchem 2000 Automated Ion Analyzer flow injection system (Lachet Instruments, Milwaukee, WI) and the cadmium reduction method. Statistical modeling was conducted using SAS Ver. 8.2 software (SAS Institute Inc., 1999).

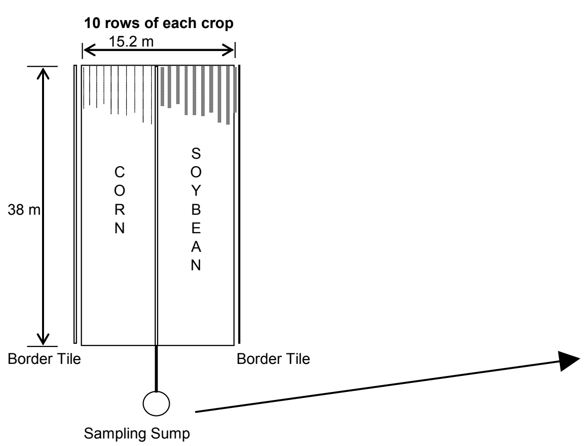

Figure 1. Subsurface drainage line configuration.

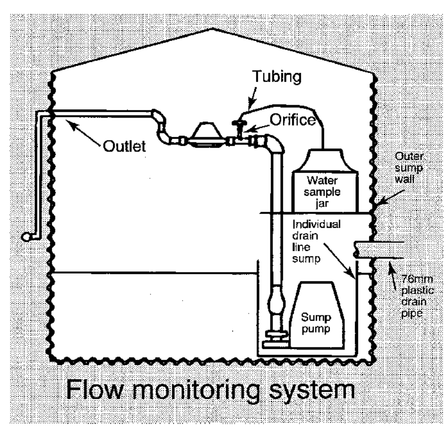

Figure 2. Flow monitoring system configuration.

Research Plot History

Between 1989 and 1999, the site was used for other NO3-N and herbicide leaching water quality studies. From 1994-1999, continuous corn, corn and soybean, and corn soybean oats (in rotation within the same plots), were grown with 45 kg/ha incremental rates ranging from 45-179 kg/ha applied as 28% urea ammonium nitrogen. For flow volume and NO_3-N nitrate loss purposes, annual drainage discharges for each of the six treatments from the previous ten years were used to selectively group the thirty plots into five replications according to the percentage of seasonal precipitation drained. Replication one was assigned to plots that had the lowest flow to seasonal precipitation ratio. The same procedure was used to assign plots to replications two through five; the next group of five plots with the lowest ratio was assigned to replication two. Replication five included those plots with the highest drainage to precipitation ratio. Six N treatments (168 kg fall N ha-1 with and without nitrification inhibitor, 168 kg spring N ha-1 with and without inhibitor, 252 kg spring and fall N ha-1 without inhibitor) were then randomly assigned to plots within each replication grouping. Plots were then split into halves and corn or soybeans were randomly assigned to each half the first year; thereafter, they were rotated. Nitrogen treatments were not re-randomized each year. Treatments remained the same on each plot and year during the study. This method insured that all treatments had replications that included all levels of flow volume and that treatments were not imposed on high or low flow volume plots exclusively.

Treatment Description and Crop Production

Six treatments, utilizing two N fertilizer rates, two timings and with and without a nitrification inhibitor with five replications each were initiated in the fall of 1999 and spring of 2000 at the experimental site described above. Commercial grade 28% (26 Baume) aqueous ammonia was applied midrow to the corn half of each plot with a conventional knife applicator at a rate of 168 or 252 kg N ha-1 in spring at or closely following emergence or late fall after soil temperatures were <10oC. The 168 kg N ha-1 rate is within the N fertilizer recommendations established by Iowa State University (Blackmer, et al., 1997) for a corn after soybean rotation. The 252 kg N ha-1 rate was used as a high rate comparison. Nitrapyrin (N-Serve; Dow AgroSciences, Indianapolis, IN), a nitrification inhibitor was added to two of the four 168 kg N ha-1 nitrogen rates, in the late spring or late fall at the maximum recommended label rate of 1.12 kg a.i. ha-1. Agronomic field procedures were carried out according to local practices and timetables. **Tables 2-4** include precipitation, temperature and fertilizer timing information. Planting dates were dictated by field conditions in the first two weeks of May each year and were typical for the area. Fertilizer application dates for the fall treatments ranged from 7 December 1999 to 12 November 2002. Soil temperatures at the 10 cm depth on the day of application for all years were less than 10oC and cooling and averaged between 0.1 to 8.7oC in the 10-d period following application. These temperatures and fall application periods closely follow general recommendations to delay applications until soil temperatures are <10oC (Keeney, 1982; Gomes and Loynachan, 1984; Sawyer, 2001). Soils remained frozen from late November or December through the winter. See **Table 3** for fall freeze and spring thaw timing. After planting fertilization dates in the spring ranged from 17 May 2000 to 12 June 2003. 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 either in late fall or early spring several weeks prior to planting. Metolachlor (Dual II Magnum; Syngenta Crop Protection, Greensboro, NC) was applied and incorporated to all plots pre-emerge at a rate of 2.34 L ha-1 and glyphosate (Roundup UltraMAX; Monsanto Co, St. Louis, MO) was applied post-emerge at a maximum rate of 2.04 L ha-1over the growing season for weed control. Pioneer 92B71 Roundup Ready soybean and Dekalb 545 Roundup Ready corn were used during the study.

Results and Discussion

Growing Season Hydrology and Subsurface Drainage

Ambient precipitation was collected using a recording tipping bucket rain gauge (Campbell Scientific, Inc., Logan, UT) located near the center of the site area. Precipitation data are summarized in **Table 2**. Nitrogen application dates, temperatures, precipitation after fall N application and freeze/thaw dates during the study period are listed in **Table 3**. Precipitation amounts prior to and after spring fertilizer application during the study period are listed in **Table 4**. A dry fall preceded the first N application on 7 Dec 1999. The site only received 37% of normal rainfall in the three months prior to this time period. Soils thawed early in February 2000, approximately two months ahead of the norm. March and April 2000 rainfall was approximately half that normally received. Total within 60 days after N application, following a dry fall and spring was 347 mm. These conditions resulted in minimal subsurface drainage during the first full year of the study, 2000.

October and November 2000 precipitation patterns were normal and double the average normal, respectively. An early April 2001 thaw was followed by normal precipitation at the site. May brought nearly double the average normally expected. In the 60 days subsequent to spring application, 182 mm of precipitation was received. The second highest average monthly drainage volume during the study period, 165 mm, occurred in May 2001.

A normal to slightly dry summer and early fall period in 2001 was followed by an above average November/December precipitation pattern. After N application on 12 Nov 2001 and prior to freezing soil conditions encountered in late December, 80 mm of rainfall was recorded. This was not sufficient to cause any subsurface drainage. An early April 2002 thaw was followed by below normal precipitation in April, May, June and July. Total within 60 days following spring application was 95 mm.

Table 2. Precipitation at the research site just prior to (1999) and during the study period.

	1999	2000	2001	2002	2003	long term average*
Month			mm			
March	37	28	24	4	28	53
April	212	34	78	61	36	72
May	115	93	171	77	109	94
June	83	113	79	51	222	107
July	70	152	117	87	126	108
August	57	92	72	279	42	108
September	24	35	42	35	46	88
October	15	61	51	77	12	56
November	21	67	56	3	0	33
Total (Mar-Nov)	632	675	691	674	623	722
Yearly precipitation	743	816	766	766	679	784

***from Climatological Data for Iowa, National Climate Data Center for Pocahontas, Iowa 1961-90.**

Table 3. N application dates, temperatures, precipitation after fall N application and freeze/thaw dates during the study period.

application period	application date	10-cm soil temperature (°C)	precipitation (mm) before freezing	10-cm freeze date	10-cm thaw date
Fall 1999	7-Dec-99	2	0	10-Dec-99	-
Spring 2000	17-May-00	16	-	-	2-Feb-00
Fall 2000	14-Nov-00	2	5	24-Nov-00	-
Spring 2001	4-Jun-01	16	-	-	5-Apr-01
Fall 2001	12-Nov-01	8*	80	24-Dec-01	-
Spring 2002	20-May-02	15	-	-	4-Apr-02
Fall 2002	13-Nov-02	3.3	0	8-Nov-02	-
Spring 2003	5-Jun-03	18	-	-	15-Mar-03

* slightly warming to 12.6°C then proceeded to drop to below 10°C two days later.

August 2002 had the largest monthly precipitation total during the study period and only resulted in an average of 1mm of subsurface drainage. September and November 2002 precipitation was well below normal; Spring of 2003 was again drier than average.

May 2003 precipitation was slightly above average and June rainfall was twice the normal average and the highest drainage volume period during the study. Total precipitation within 60 days following spring 2003 application was 398 mm.

Table 4. Precipitation amounts prior to and after spring fertilizer application during the study period.

plant date	N application date	precipitation period: 10 days prior	day 1-10 after	day 11-30 after	day 31-60 after	total 60 days after
		mm				
5-May-00	17-May-00	25.9	68.8	145.3	132.8	346.9
11-May-01	4-Jun-01	44.5	63.5	1.5	117.1	182.1
9-May-02	21-May-02	39.4	9.1	48.5	37.6	95.2
8-May-03	5-Jun-03	14.0	53.9	218.4	125.7	398.0

In summary, precipitation during the drainage season (March-November) was slightly below the long term norm for all years in the study period and ranged from 623 mm in 2003 (86% of normal) to 691 mm (96% of normal) in 2001. Monthly norms were highly variable and subsurface drainage, or the lack thereof, mimicked the precipitation patterns observed. April precipitation for three of the four years, 2000, 2002 and 2003 was 83% or less than the norm. May precipitation for these three years was nearly normal. Precipitation recorded in May of 2001 was nearly double (179%) the average and resulted in significant drainage volumes. June 2003 was the wettest drainage period recorded during the study with 193% of average precipitation. Precipitation in the fall (September-November) of 2000 and 2001 was nearly normal but on a monthly basis November in both years received over 175% of the norm; no drainage was recorded until the following spring for these years, due to low summer soil moisture. Years 1999, 2002 and 2003 each had drier than normal falls and again no drainage was available for monitoring during these periods.

Timely precipitation amounts and patterns during this study resulted in decreased subsurface drainage. Overall, and with such a dynamic biological system being monitored, drainage volumes between treatments are fairly balanced and are a reflection of selective replication grouping as described in **Research Plot History** section. Average subsurface drainage volumes by year and treatment with statistical significance using LSD modeling are presented in **Table 5.** Yearly variation in subsurface drainage volumes is to be expected when studying modified natural systems under ambient rainfall conditions. Average annual subsurface drainage volumes were significantly different between all four years during the study period. As an example, a comparison of year 2000 and 2002, years with nearly equal drainage season (Mar-Nov) precipitation totals, resulted in statistically different subsurface drainage volumes. The year 2000 had a treatment average subsurface drainage volume of 13 mm, whereas 2002 had an average volume fifteen times higher. Drainage volumes are directly related to ambient soil moisture conditions (as affected by the previous year), individual storm timing and totals and crop water demand during the drainage season. Year 2003 had the lowest total drainage season precipitation resulting in the highest subsurface drainage volumes and drainage to precipitation ratios during the study period. June precipitation was double the normal precipitation, resulting in 183 mm of drainage recorded.

Table 5. Average subsurface drainage volumes by treatment within years and among years and drainage/precipitation ratios.

treatment	2000	2001	2002	2003	average
	average drainage volume, mm				
Fall 168 w/inhibitor	9b	292a*	196ab	327a	206a
Fall 168	8b	208ab	216ab	296a	182a
Fall 252	12b	284a	160ab	336a	198a
Spring 168 w/inhibitor	9b	177b	119b	344a	162a
Spring 168	31a	234ab	230ab	327a	206a
Spring 252	7b	293a	264a	324a	222a
average drainage, mm	13d**	247b	197c	326a	196
drainage/precipitation ratio	0.02	0.36	0.29	0.52	0.26

****means with the same letter within a column are not significantly different at p=0.05.**
****means with the same letter within this row are not significantly different at p =0.05.**

Drainage volumes by year and month, indicative of drainage sampling periods encountered during the study period, are listed in **Table 6**. Most drainage occurred between April and June of each year for two of the four years monitored. In 2000, a year with a dry spring and very little drainage, 85% occurred in July following a heavy precipitation period. In 2001, 99% of drainage was measured between April and June. Drainage was not typical in 2002; 45% occurred in the April-June period and 55% occurred in the August-October period. Seventy-four percent of drainage in 2003, a more typical period, was measured in the April through June months.

Table 6. Average subsurface drainage volumes by year and month prior to (1999) and during (2000-03) the study period.

	April	May	June	July	August	September	October
year	drainage volume, mm						
1999	0	67	12	0	0	0	0
2000	0	0	2	11	0	0	0
2001	39	164	43	0	2	0	0
2002	7	57	23	0	85	14	11
2003	21	68	154	82	0	0	0

In summary, hydrologically the study period was marked by only one of the four years having substantial drainage periods in the early spring when it is expected that most drainage and N losses would occur, especially for N placement the previous fall. Only 2002 had end of the season subsurface drainage. A dryer than normal fall through spring period was encountered in 1999-2000, and 2001-2002 and during the spring of 2003. Only May of 2001 had greater than normal spring precipitation, resulting in substantial drainage, with this drainage period occurring prior to spring N application. Overall, precipitation and drainage patterns during the study period were optimum or nearly optimum agronomically and environmentally for both fall and spring N applications when considering N concentration and loss.

Nitrate-Nitrogen Concentrations in Subsurface Drainage

During the four years of study, average yearly flow-weighted NO_3-N concentrations ranged from 11.0 (spring ammonia 168 kg N/ha, no inhibitor, in 2002) to 28.7 mg L^{-1} (spring ammonia 252 kg N/ha, in 2001) (**Table 7**). Statistical differences (p= 0.05) of flow-weighted NO_3-N concentrations in subsurface drainage are presented in **Table 7.** Four-year average, flow-weighted NO_3-N concentrations ranked in highest to lowest order: spring-252 > fall-252 > spring-168 w/inhibitor > fall-168 w/inhibitor > spring-168 > fall-168. Lowest levels were recorded for all three fall application treatments, in 2000. In 2001, spring ammonia 252 kg N ha-1 treatment (28.7 mg L^{-1}) was significantly different from all treatments except spring ammonia 168 kg N ha^{-1} with inhibitor treatment. In 2002, both fall and spring applications at 168 kg N ha^{-1} rate with no inhibitor had the lowest concentrations, but were only significantly different from the highest spring and fall application rates. This pattern was repeated in 2003. Four-year average flow-weighted concentrations ranged from 14.2 for the fall low rate without inhibitor plots to 24.4 mg NO_3-N L^{-1} for the spring high rate treatment. Monthly concentrations, when there was flow, are shown in **Figure 3.** Data showing highest concentrations (2001) were preceded by above normal precipitation after a dry period; both 1999 and 2000 were dryer than the norm. Lowest concentrations during the study were measured in a below normal precipitation period (2002) following above normal precipitation the previous year. It should also be noted that the highest concentrations recorded among the 168 kg N ha-1 treatments (spring applied, with inhibitor, 2001) were collected prior to the N application date and could be attributed to previous applications and N mineralization. In three out of four years, for this N rate, no significant differences were noted when comparing spring and fall application periods with or without nitrification inhibitor.

Table 7. Flow-weighted nitrate-nitrogen concentrations.

treatment	2000	2001	2002	2003	average
	nitrate-nitrogen concentration mg L^{-1}				
fall with inhibitor, 168	16.7a*	19.1b	13.6bc	15.4c	16.2bc
fall 168	16.3a	14.8b	11.7c	14.7c	14.2c
fall 252	16.6a	19.5b	17.4ab	19.7ab	18.1b
spring with inhibitor, 168	17.9a	22.5ab	14.2bc	16.2bc	17.7b
spring 168	17.8a	18.0b	11.0c	14.7c	15.4bc
spring 252	26.8a	28.7a	19.3a	23.0a	24.4a
Least Significant Difference	11.0	8.1	4.0	4.2	3.0

*means within years with the same letter are not significantly different at p= 0.05

When comparing the low application rate and no inhibitor treatments concentrations, no differences were observed under these weather conditions at this site between fall and spring application periods. All fall applications, when compared directly, i.e. spring versus fall with no inhibitor, even though not significantly different from each other, were observed to have lower or nearly equal concentrations in three out of four years. The late fall ammonia with inhibitor treatment resulted in nearly equal or higher concentrations in two of the four years. Using inhibitor in the late spring resulted in higher NO_3-N concentrations three out four years when compared to the no inhibitor treatment.

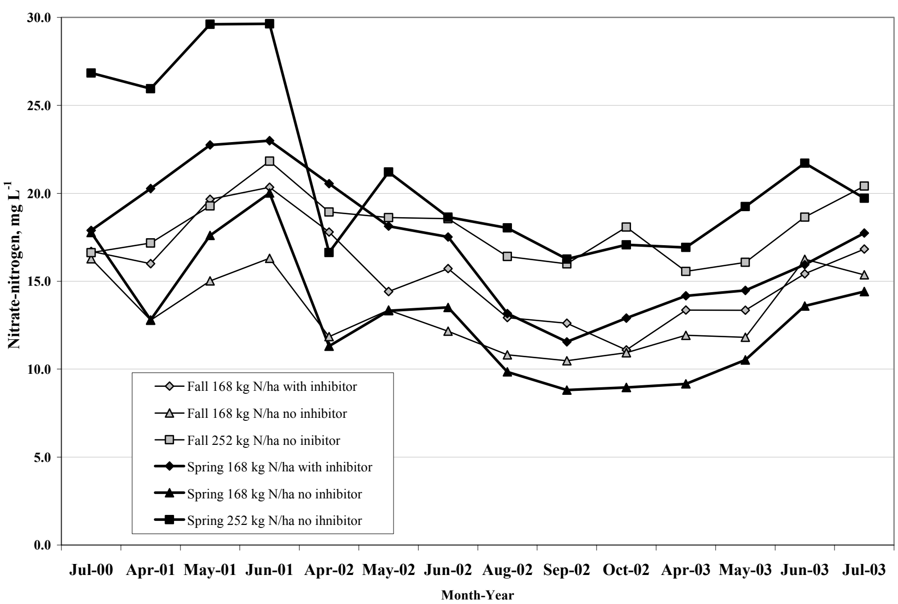

Figure 3. Monthly flow-weighted NO_3-N concentrations in subsurface drainage, when it occurred, for 168 and 252 kg N ha^{-1} for spring and fall treatments with and without inhibitor, 2000-03.

Nitrate-Nitrogen Losses in Subsurface Drainage

Nitrate-nitrogen losses for each year and the overall treatment averages with statistical differences are presented in **Table 8**. Annual losses are the product of subsurface drainage volume and NO_3-N concentrations, and results mirror those for concentrations described in a previous section. Losses ranged from less than 2 to nearly 86 kg ha^{-1} during the study period. Again, loss, and NO_3-N concentrations are predominantly affected by drainage season precipitation timing and application rate, organic matter mineralization and less so by timing of N application or nitrification inhibitor treatment. Although above average total precipitation was recorded in 2000, drainage season precipitation (Mar-Nov) was approximately 7% less than average and well distributed temporally, resulting in minimal subsurface drainage and N loss. It should be noted however, that within 60 days of fertilizer application on 17 May, nearly half of the total drainage season precipitation was received, and all the subsurface drainage. Drainage season precipitation in 2001, which was only 16 mm greater than 2000, resulted in nearly 20 times the drainage volume and N loss, even though precipitation in the 60 days following N application was only half that received in 2000. Approximately 80% percent of the N losses that occurred in 2001 were prior to spring N fertilizer application on 4 June and were likely derived from organic matter N mineralization and previous fall and spring applications made in a minimal drainage year (2000), suggesting a “banking” and N loss lag from the previous season. Both spring and fall applications without inhibitor exhibited less loss than their inhibitor counterparts. N losses in 2001 were the highest recorded in most part because of high flows. Inhibitor treatments in both seasons had higher losses then the non-inhibitor plots. In 2002 losses were less than those recorded in 2001 and 2003; more than half the losses occurred between August and October 2002, a rather atypical loss period. Fall ammonia treatments with and without inhibitor had equal losses (27 kg ha^{-1}), whereas, the spring inhibitor treatment had 8 kg ha^{-1} less loss than its non-inhibitor equivalent and 10 kg ha^{-1} less than fall treatments, possibly indicating that the inhibitor decreased losses late in the growing season. Precipitation and drainage volume patterns in May/June 2003 were the highest recorded during the study, although total seasonal losses were second to those in 2001. Overall treatment averages presented in **Table 8** exhibit no significant differences among the low N treatments.

Table 8. Nitrate-nitrogen losses for treatments in 2000-2003 and statistical significance at p = 0.05*.

	2000	2001	2002	2003	average
treatment	**nitrate-nitrogen loss kg ha^{-1}**				
fall with inhibitor, 168	1.3b	56.4b	27.6b	40.8b	31.5b
fall 168	1.3b	31.8b	27.4b	43.8ab	26.0b
fall 252	1.9ab	52.6b	32.7ab	64.3ab	37.9b
spring with inhibitor, 168	1.6ab	41.6b	17.6b	39.9b	25.2b
spring168	4.5a	37.3b	25.4b	33.8b	25.3b
spring 252	1.9ab	85.8a	46.6a	74.1a	52.1a
Least Significant Difference	3.1	24.8	16.8	32.6	12.0

* means within years with the same latter are not significantly different at p = 0.05

Even though losses are not significantly different (for 168 rate treatments) when comparing timing and inhibitor treatments, any decrease in loss is preferable, both economically and environmentally. Four-year average kg ha^{-1} N losses in decreasing order among all treatments are as follows: spring 252 > fall 252 > fall 168 with inhibitor > fall 168 > spring 168 = spring 168 with inhibitor. If this criterion is used for determining treatment success in minimizing losses, these data would suggest that the use of an inhibitor in the fall at the 168 kg N ha^{-1} rate would decrease losses slightly over the practice of not using a fall inhibitor, one in four years under the experimental conditions encountered. Fifty percent of the time, losses would be nearly equal using an inhibitor. The use of an inhibitor in the low rate spring N treatment decreased loss in two of the four years when compared to no spring inhibitor. A fall application of N alone would be preferable 50% of the time in all years studied, but a spring application would be most effective in wet springs, and for these conditions, losses would diminish by between 2-10 kg N ha^{-1}. Overall averages suggest that a spring application with or without the inhibitor had less loss than the fall inhibitor treatment and nearly equal loss as fall without an inhibitor, and a fall application without inhibitor had less loss then when an inhibitor was used in the fall.

Crop Production

Corn and soybean yield data and Pocahontas County Iowa averages are presented in **Tables 9 and 10**. Highest yield among corn treatments was recorded during the first year for the fall ammonia 168 kg N/ha^{-1} without inhibitor. This treatment continued to have some of the highest yields among these treatments. Lowest yield was for the spring ammonia 168 kg N/ha^{-1} without inhibitor treatment during the last year of the study. Among these lower rate N treatments, this spring timing treatment produced the lowest yields in three of the four years. In 2001, weather delayed spring N application following a major N loss period earlier in the spring, may have allowed the spring treatments to take advantage of the lateness of the application as all spring application yields surpassed those that received fall applications in this year. Although not significant, the fall inhibitor treatment in this year may have also kept N in place as yield was higher than the same treatment rate without inhibitor. The fall ammonia treatment without inhibitor had the highest yields in three of four years at the low rate.

Table 9. Corn yield for treatments in 2000-03.

	2000	2001	2002	2003	average
treatment			**yield, kg ha^{-1}**		
fall with inhibitor, 168	9698a*	8560a	8194a	7991ab	8613ab
fall no inhibitor ,168	9971a	8199a	8707a	8293ab	8792a
fall no inhibitor, 252	9700a	8277a	7973a	7945ab	8474ab
spring with inhibitor, 168	9057ab	8640a	8457a	7500b	8360ab
spring no inhibitor,168	8342b	8871a	8364a	7477b	8232b
spring no inhibitor, 252	9353a	8967a	8474a	8450a	8830a
Least Significant Difference	976	1337	1164	916	516
Pocahontas county average yield	9758	8485	10046	10542	9708

* means within years with the same latter are not significantly different at p = 0.05

The highest overall average yield for corn during the study was recorded for the spring 252 kg N ha^{-1} treatment but was only statistically higher than the low spring rate without inhibitor. This significance over other treatments was also true for the fall low rate without inhibitor, which had only 38 kg ha^{-1} less yield than the spring high rate. Only in the high drainage/N loss year of 2001 did spring application treatment yields surpass those that received fall applications.

Soybean yields were greatly affected by N timing and less so by application rate and inhibitor (**Table 10**). Fall 168 kg ha^{-1} without inhibitor had significantly lower yields in the first two years of the study when compared to all other treatments, but still surpassed the county averages. In the second year, the high rate of fall ammonia also had significantly lower yield. In 2002, only the latter treatment had significantly lower yields than any other treatment, and yield also dropped below the county average. During the last year no significant differences were realized among the treatments; although, all spring applied N treatment yields had higher yields than for those applied in the previous fall. When yields are averaged over all four years, the three fall N treatment yields were significantly lower than spring applied plots, possibly indicative that nitrogen applied 18 months prior to utilization by a soybean crop was missing or diminished to a level that affected production. N applied one season prior to the soybean crop apparently remained at levels to benefit the succeeding crop.

Table 10. Soybean yield for treatments in 2000-03.

	2000	2001	2002	2003	average
treatment	yield, kg ha^{-1}				
fall with inhibitor, 168	3606bc	3111abc	2785ab	1747a	2812b
fall no inhibitor, 168	3547c	2895c	2829ab	2020a	2869b
fall no inhibitor, 252	3742bc	3006c	2580b	1874a	2849b
spring with inhibitor, 168	3893ab	3242abc	3306a	2189a	3158a
spring no inhibitor, 168	4080a	3530ab	3459a	2222a	3323a
spring no inhibitor, 252	4163a	3670a	3362a	2287a	3370a
Least Significant Difference	335	601	677	589	242
Pocahontas county average yield	2896	2856	3286	2251	2822

* means within years with the same latter are not significantly different at p = 0.05

Summary and Conclusions

Water table management through the use of artificial subsurface drainage systems is of primary importance in humid areas with poorly or somewhat poorly drained soils to maximize agricultural productivity. Drainage systems have been installed to allow timely seedbed preparation, planting and harvesting and to protect crops from extended periods of flooded soil conditions. The tradeoff of improved subsurface drainage is a significant increase in the leaching losses of NO_3-N. Nitrogen, either applied as fertilizer, or manure and derived from soil organic matter, can be carried as NO_3-N with the excess water in quantities that can cause deleterious effects downstream. It is a general conclusion among research conducted over several decades that as a best management practice N should be applied at the correct amount nearest to the time it is needed by the crop. Typically, soil conditions, fertilizer cost, equipment and labor favor fall or early spring application over a later application in the spring or summer in Illinois, Iowa, Minnesota and Wisconsin. This leads to a widely held conclusion that fall application of fertilizer N is agronomically, if not environmentally, risky. In this study, spring and fall N application effects on crop production, subsurface drainage NO_3-N concentrations and losses were compared. A nitrification inhibitor was also examined to determine its effectiveness in retaining applied N fertilizer in the spring and fall. An established, five replication, drainage volume balanced plot treatment monitoring system was configured to measure and sample intercepted subsurface drainage from the treated area on a continual basis during the drainage seasons each year.

Precipitation patterns and subsurface drainage volumes were directly related. During the four years of this study, drainage season precipitation (March-November) was slightly below the long term norm for all years in the study period and ranged from 623 mm in 2003 (86% of normal) to 691 mm (96% of normal) in 2001. Years 1999, 2002 and 2003 each had drier than normal falls and again no drainage was available for monitoring during these periods. Most drainage occurred between April and June of each year for two of the four years monitored. Hydrologically, the study period was marked by only one of the four years having substantial drainage periods in the early spring when it is expected that most drainage and N losses would occur, especially for N placement the previous fall. Only May of 2001 had greater than normal spring precipitation, resulting in substantial drainage, although this drainage period occurred prior to spring N application. Overall, precipitation and drainage patterns during the study period were optimum or nearly optimum agronomically and environmentally for both fall and spring N applications when considering NO_3-N concentrations and losses.

Average yearly flow-weighted NO_3-N concentrations ranged from 11.0 (spring ammonia 168 kg N/ha, no inhibitor, in 2002) to 28.7 mg L^{-1} (spring ammonia 252 kg N/ha, in 2001). Four-year average flow-weighted nitrate-nitrogen concentrations ranked in highest to lowest order: spring-252(24.4 mg L^{-1};a) > fall-252(18.3 mg L^{-1};b) > spring-168 w/inhibitor(17.7 mg L^{-1};bcd) > fall-168 w/inhibitor(16.2 mg L^{-1};bcd) > spring-168(15.4 mg L^{-1};cd) > fall-168 (14.2 mg L^{-1};d). Data show highest concentrations (2001) were preceded by above normal precipitation following a dry period; both 1999 and 2000 were dryer than the norm. Lowest concentrations during the study were measured in a below normal precipitation period (2002) following above normal precipitation the previous year. It should also be noted that the highest concentrations recorded among the 168 kg N ha^{-1} treatments (spring applied, with inhibitor, 2001) were collected prior to the N application date and could be attributed to previous applications and N mineralization. In three out of four years, for this N rate, no significant differences were noted for concentration, when comparing spring and fall application periods with or without nitrification inhibitor. Although timing, method of N application and accounting for mineralizable soil N are important for reducing potential NO_3-N leaching, this research would tend to support conclusions reached by Power and Schepers (1989) that perhaps the most important factor was to apply the correct amount of N.

Losses ranged from less than 2 to nearly 86 kg ha^{-1}. Losses and NO_3-N concentrations are predominantly affected by drainage season precipitation timing and application rate, organic matter mineralization and less so by N application timing or nitrification inhibitor treatment. Four-year average kg ha^{-1} N losses in decreasing order among all treatments with statistical significance at p=0.05 are as follows: spring 252 (52.1a) > fall 252 (37.9b) > fall 168 with inhibitor (31.5b) fall 168 (26.0b) > spring 168 (25.3b) = spring 168 with inhibitor (25.2b). Even though losses are not significantly different (for 168 treatments) when comparing timing and inhibitor treatments, any decrease in loss is preferable, both economically and environmentally. Data suggests that the use of an inhibitor in the fall at the 168 kg N ha^{-1} rate would decrease losses slightly over the practice of not using a fall inhibitor, one in four years for the conditions encountered. A fall application of N alone would be preferable 50% of the time in all years studied, but a spring application would be most effective in wet springs, and for these conditions, losses would diminish by between 2-10 kg N ha^{-1}. Overall averages suggest that a spring application with or without the inhibitor had less loss than the fall inhibitor treatment and nearly equal loss as fall without an inhibitor, and a fall application without inhibitor had less loss then when an inhibitor was used in the fall. The fall ammonia treatment at the low rate without inhibitor had the highest yields in three of four years. The highest overall average yield for corn during the study was recorded for the spring 252 kg N ha-1 treatment but was only statistically higher than the low spring rate without inhibitor. Only in the high drainage/N loss year of 2001 did spring application treatment yields surpass those that received fall applications. Soybean yields were greatly affected by N timing and less so by application rate and inhibitor. When soybean yields are averaged over all four years, the three fall N treatment yields were significantly lower than spring applied plots, possibly indicating that nitrogen applied 18 months prior to utilization by a soybean crop was missing or diminished to a level that affected production. N applied one season prior to the soybean crop apparently remained at levels to benefit the succeeding crop.

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