NITROGEN MANAGEMENT AND ITS INFLUENCE ON N LOSSES TO SURFACE WATER THROUGH SUBSURFACE TILE LINES

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Abstract

Subsurface tile drainage from row-crop, agricultural production systems on high organic matter soils has been identified as a major source of nitrate entering surface waters in the Mississippi River Basin. Tile drainage studies have been conducted on three drainage research facilities at two locations in Minnesota since 1973. Nutrient and crop management systems including rate and time of N application, N sources (fertilizer, dairy manure and hog manure), nitrification inhibitors, cropping systems, and tillage systems have been evaluated to determine their agronomic and environmental characteristics. Results from these studies have been instrumental in the development of BMPs for nutrient management in Minnesota.

Precipitation (total annual amount and monthly distribution) and cropping system have the greatest impacts on nitrate losses from agricultural landscapes to surface waters. About two-thirds of the annual drainage and nitrate loading occur in April, May, and June when ET is low compared to precipitation. Fall application of N and residual soil nitrate are both highly susceptible to loss in this spring drainage. Dry and wet climatic cycles also greatly affect nitrate losses. Nitrate losses can be 30 to 50X greater for row crops (corn and soybeans) compared to perennial crops (alfalfa and CRP). Rate of N application is the nutrient management practice that most influences nitrate concentrations and losses in subsurface, tile drainage water. Time of N application and nitrification inhibitors play a significant role in minimizing nitrate losses to drainage, especially under wetter and warmer-than-normal late fall and early spring conditions. Tillage system and N placement appear to have very little impact on nitrate losses.

Results from these studies show that implementation of BMPs will be helpful to minimize nitrate losses to drainage water, but the question remains "will they be sufficiently effective to meet society's goals". Long-term drainage research conducted across a range of climatic and soil conditions is vital to improved N management and policy decision-making.

Introduction

Nitrogen (N) is a naturally occurring element that is essential to plant growth and crop production. Agriculture has been identified frequently as a major contributor of nitrate-nitrogen to surface water throughout the developed world. Omernik (1977) reported that total N

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concentrations were nearly nine times greater downstream from agricultural lands than downstream from forested areas with the highest concentrations being found in the Corn Belt States of the Upper Mississippi Basin. Nitrate-N is continually supplied to streams and rivers through mineralization of soil organic matter, particularly where tile drainage has exposed formerly wet soils to oxidation and through the application of fertilizer and animal manures to crop land.

Nitrate-N is mobile and, therefore, can be lost from the soil profile by leaching. Subsequent transport of nitrate-N to surface waters occurs primarily through subsurface drainage (tile lines) or base flow. Subsurface drainage is a common water management practice in highly productive agricultural areas of the Mississippi River Basin where poorly drained soils have seasonally perched water tables or shallow groundwater (Gast et al., 1978). Very little nitrate-N is lost from the agricultural landscape via surface runoff (Jackson et al., 1973; Logan et al., 1994).

Several long-term research studies on rivers of different stream order draining widely different scales of watershed basins all point to the fact that agricultural practices do affect the nitrate-N concentration in river water Nitrate-N concentrations in stream water collected from water years 1984 through 1993 for a portion of the Upper Mississippi River Basin were significantly greater (2 to 6 mg/L) from those rivers which drain a large percentage of agricultural land compared to those which drain a larger percentage of forested land (0.1 to 0.5 mg/L) (Kroening, 1996). In the Mississippi River, mean concentrations were significantly greater (1.8 to 2.5 mg/L) downstream of the confluence with the Minnesota River (an agricultural watershed) than upstream (0.2 to 0.9 mg/L). Keeney and DeLuca (1993) examined nitrate concentrations in the Des Moines River in 1945, 1955, 1976, and from 1980 through 1990 and found the average nitrate-N concentration to have changed little in the last 45 years (5.0 mg/L in 1945 to 5.6 mg/L in 1980-90). They concluded that intensive agricultural practices that enhance mineralization of soil N coupled with subsurface tile drainage are the major contributors of nitrate-N rather than solely fertilizer N.

Somewhat similar conclusions were drawn by David et al. (1997) who surmised that agricultural disturbance leading to high mineralization rates and N fertilization combined with subsurface tile drainage contributed significantly to nitrate export in the Embarras River in Illinois. In their 6-yr study, an average of 49% (range from 25 to 85%) of the large pool of nitrate remaining after harvest was leached through drain tiles and exported by the river. Precipitation exerted a large influence on drainage losses with a few days of high-flow events leading to most of the annual loss in some years. Rivers with higher concentrations of nitrates seem to be surrounded by landscapes with similar general characteristics. They are: 1) humid/high rainfall conditions, 2) high organic matter soils, 3) poorly drained, fine-textured soils needing artificial subsurface drainage for optimum crop production, and 4) domination by corn and soybean intensive agriculture.

The primary factors that influence the nitrate content of surface and subsurface waters draining agricultural landscapes can be divided into two categories – **uncontrollable and controllable**. Uncontrollable factors include precipitation, other climatic factors, and soil mineralization Controllable factors include those agricultural management practices that can be used by each crop producer to best fit the needs of his/her enterprise and include: 1) cropping system used, 2) rate of nitrogen applied, 3) time of nitrogen application, 4) placement method, 5) use of a nitrification inhibitor, and 6) tillage systems.

Objectives

This paper will summarize about 25 years of subsurface drainage results from research studies conducted in Minnesota. The influence of the above uncontrollable and controllable factors and their interactions on nitrate loss from the agricultural landscape to surface waters will be discussed.

Methods

Tile drainage studies have been conducted at the Southwest Research and Outreach Center at Lamberton since 1973 and at the Southern Research and Outreach Center at Waseca since 1975. Fifteen individually drained plots, each measuring 45' x 50' were installed at Lamberton in 1972. Eight plots of the same size were installed at Waseca in 1974 with another 36 plots, each measuring 20' x 30', installed in 1976. Each plot is surrounded by 12 mil plastic, which was trenched in to a depth of 6 feet, to minimize lateral flow from one plot to another. Plastic 4" tile installed at an average depth of about 3-1/2 feet and 5' from the plot edge drains each plot separately. Those installation dimensions simulate a tile spacing of 90' in the larger (45 x 50') plots and 50' in the smaller plots. Water discharge volumes have been measured daily (except weekends) but more frequently when major precipitation events occur. Samples were generally taken on a M-W-F basis except during major flow events or the initial flow period in a season when samples were taken daily. All samples have been analyzed for nitrate-N. Other constituents that have been measured include: ammonium-N, total phosphate, ortho-phosphate, chloride, sulfate-S, calcium, magnesium, atrazine, alachlor (Lasso), cyanazine (Bladex), metabolites of atrazine, and fecal coliform bacteria.

During the last 25 yrs, we have compared N rates, N sources, time of N application, nitrification inhibitors, cropping systems, and tillage systems at these two locations. These plots have allowed us to determine the cause and effect relationships between the crop and nutrient management factors cited above and crop production, residual NO_3 carryover, drainage volume, and nutrient and herbicide concentrations and losses in subsurface drainage water. This work has been conducted to develop best management practices (BMPs) for farmers that will lead to environmentally- and economically-sound crop production.

Results

Precipitation

Loading of nitrate-N into surface water is a function of transport volume (amount of water) and nitrate-N concentration in the transported water. The amount of drainage water leaving the landscape is largely a function of climate and soil properties, i.e., precipitation, texture, infiltration rate, etc. Drainage is further influenced by the temporal distribution of precipitation within a year and the amount of annual or growing season precipitation. For instance, a 3-inch rainfall in the spring, when evapotranspiration (ET) losses are low and soil moisture in the profile is likely near field capacity, will have a much greater effect on drainage volume than the same rainfall during the middle of the summer when daily ET losses are high and soil moisture is far short of field capacity. In the former scenario, storage capacity is minimal and drainage water carrying nitrates is plentiful. A significant storage reservoir can exist in the soil in the latter scenario, and subsurface drainage may or may not even occur.

Analysis of tile discharge data from research plots at Waseca, MN for the 13-yr period (1987-1999) clearly show the temporal effects of precipitation and ET on both drainage volume and nitrate-N losses. The 3-mo period of April, May, and June accounted for 63 to 68% of the annual drainage volume from continuous corn (Fig. 1), corn after soybean (Fig. 2), and soybean after corn (Fig. 3). Nitrate-N losses in the drainage water totaled 70% of the annual loss for this same 3-mo period for both corn after soybean (Fig. 4) and soybean after corn (Fig. 5). Only 15% of the annual nitrate discharge occurred after July. From December through February, when the soils were frozen, and September, following a 2-month period of high ET, drainage volume and nitrate-N lost totaled less than 3% of the annual loss. These data were somewhat similar to those obtained by Cambardella et al. (1999) in the Walnut Creek Watershed in Iowa where most of the nitrate-N in subsurface drainage was lost in November-May in 3 of 4 years. The absence of continuously frozen soils during the winter months at this location 150 miles south of Waseca likely was the primary reason for winter flow in central Iowa. In addition, nitrate-N loads leaving the fields in subsurface drainage were controlled primarily by the precipitation patterns that affected the amount of drainage.

This high proportion of annual flow occurring early in the spring (an uncontrollable factor), before substantial corn and soybean uptake of N, has a profound effect on N management, especially fall-applied N and residual NO_3 remaining in the soil profile after harvest. If fertilizer or manure N is applied too early in the fall or if the soil is too warm between the time N was fall-applied and significant percolation occurs in the spring, nitrification will convert much or most of the N to nitrate and the potential for nitrate leaching increases greatly. Residual soil NO_3 may be high in the fall if corn yields were lower-than-normal or if N was applied at higher-than-recommended rates. Under our precipitation/ET conditions, leaching of residual NO_3 is likely before June when uptake by the next corn or soybean crop becomes significant. Thus, the prevailing scenario of precipitation markedly exceeding ET before significant crop uptake of N occurs presents a major challenge to N management in much of the Corn Belt.

The effect of annual precipitation on subsurface drainage volume is also clear as shown in the following tile drainage studies. Annual tile drainage in an 11-yr study with continuous corn ranged from 1 to 24 in./yr with an average of 11.7 in./yr (Randall and Iragavarapu, 1995). Drainage was least in 1989 when growing season precipitation was 35% below normal and greatest in 1991 when growing season precipitation was 51% above normal. In addition, drainage in the 3-yr dry period (1987-89) averaged only 1.7 in./yr compared to the following 3-yr wet period (1990-92) when drainage averaged 21.6 in./yr. A 6-yr study conducted at Lamberton, MN showed no tile drainage in 1988 and 1989 when annual precipitation was 69 and 76% of normal, respectively (Randall, et al., 1997). Drainage from the corn and soybean row-crop systems averaged 0.9 in. in 1990, 8.8 in. in 1991, 5.6 in. in 1992, and 18.5 in. in 1993 (Table 3.4). Annual precipitation in those four years was 95, 125, 117, and 160% of normal, respectively. Data from these two studies clearly indicate the strong relationship between annual precipitation and volume of subsurface, tile drainage.

Nitrate-N concentrations in subsurface drainage water do not appear to vary consistently with daily drain flow volumes but do show seasonal and yearly variability (Kladivko et al., 1991). Factors affecting this variability include crop uptake of N, residual nitrate in the soil from the previous year, and amount and temporal distribution of rainfall. Goolsby et al. (1997) noted that the concentration and flux of nitrate in rivers of the Mississippi River Basin tend to be highest in the spring when stream flow is highest. Increased flows and elevated concentrations in agricultural tile drains were speculated as contributing to this relationship. Annual average nitrate-N concentrations in the Des Moines River from 1980 through 1990 ranged from 2.0 mg/L in 1989 to 9.1 mg/L in 1982 with an 11-yr average of 5.6 mg/L (Keeney and DeLuca, 1993).

Nitrate-N concentrations and losses are also greatly affected by dry and wet climatic cycles (Randall, 1998). In 1987 and 1988, when April through October rainfall was 8% and 33% below normal, respectively, subsurface drainage was <2 in./yr and nitrate-N concentrations ranged between 7 and 18 mg/L in a corn-soybean rotation receiving fall-applied anhydrous ammonia. Less than 0.1 in. of drainage occurred in 1989 when April-October rainfall was 35% below normal. Under these conditions during the 3-yr period, corn yields and N uptake were low, but residual soil nitrate (RSN) continued to increase in the soil profile. April-October precipitation in 1990 was 23% above normal, causing drainage volume to total 14 in. Moreover, the annual flow-weighted nitrate-N concentration in the corn plots averaged 35 mg/L – 2 times as high as during the dry years. Nitrate-N concentrations in the soil and drainage water returned to background levels in 1991 and 1992 when rainfall was 50 and 14% above normal, respectively. These data suggest that RSN can accumulate in the soil profile during dry climatic cycles because of soil mineralization, reduced crop uptake, and every-other-year N fertilization, even in a corn-soybean rotation. These elevated RSN levels are then poised for delivery to subsurface tile drainage when growing season precipitation returns to above-normal amounts.

In another set of drainage plots at Waseca, continuous corn was grown from 1985 through 1992. Fertilizer N was applied at a rate of 180 lb/A each spring. Annual flow-weighted nitrate-N concentrations in 1988 and 1989 averaged 15 and 12 mg/L, respectively, while drainage was 2 in. or less each year (Table 1). RSN totaled 201 lb/A in the 0 to 5-ft profile in October, 1989. In 1990 and 1991, April-October rainfall averaged 36% above normal and generated annual drainage volumes of 19 in. or greater. In addition, nitrate-N concentrations in the drainage water doubled from the previous two dry years to 24 mg/L in these two wet years. RSN at the end of 1991 was 50% lower than at the end of the dry years. In the third consecutive wet year (1992), 16 in. of water drained from the plots, nitrate-N concentrations in the drainage water returned to 14 mg/L, and RSN totaled only 45 lb/A. Annual losses of nitrate-N ranged from 2 lb/A in the dry years to 124 lb/A in the wet years. These data clearly indicate a buildup of RSN in the soil profile during dry years when drainage was limited. Much of the RSN buildup could likely be attributed to mineralization of soil organic matter, annual additions of fertilizer N, and limited uptake of N by the poor yielding corn. In the subsequent wet years, substantial losses of nitrate occurred via subsurface drainage due to high concentrations of nitrate-N and high drainage volumes.

The general effects of precipitation on nitrate losses can also be illustrated using basin-wide water quality monitoring data collected in the Minnesota River Basin, a 10 million acre agricultural basin draining to the Upper Mississippi River basin (Mulla, 1997). Mean annual precipitation in the Minnesota River basin varies from 22 in. on the western side of the basin to 32 in. on the eastern side. The basin is dominated by intensive row-crop agriculture, has soils that generally have organic matter levels greater than 3%, and has subsurface tile-drainage on over half of the farmed acreage. Water quality monitoring data from 1977 – 1994 show that nitrate-N concentrations range from 0.36 mg/L in the headwaters on the western side to 4.6 mg/L at the mouth of the river on the eastern end where it enters the Mississippi River. Mean annual precipitation increases by about 10 in. across this distance, which produces a corresponding and dramatic increase in the discharge from subsurface tile drains into ditches and streams that eventually flow into the Minnesota River. Fewer than 1% of the water quality samples collected since 1977 from the western portion of the basin have a nitrate-N concentration that exceeds 10 mg/L. About 10% of the water quality samples collected since 1977 exceed 10 mg/L on the eastern side of the basin.

Differences in nitrate-N contributions across the basin in response to a gradient in precipitation are even larger when nitrate-N loads are compared rather than nitrate-N concentrations. Four watersheds located in the wetter eastern portion of the basin account for 75% of the total nitrate-N load in the entire basin, yet they drain only 31% of the total basin area. Six watersheds on the drier western side of the basin collectively generate only 7% of the nitrate-N load. Median values for nitrate-N yields (load per unit area) for watersheds in the Minnesota River basin vary from about 3 to over 34 lb/mi^2/day, with the larger yields occurring in the watersheds on the wetter eastern side of the basin.

Mineralization

Mineralization, the conversion of organic forms of soil N to inorganic forms, i.e., NH_4^+, NO_3^-, etc, is a process that occurs throughout the agricultural landscape and is not controllable in a crop production system. Soils high in organic matter can mineralize a substantial amount of nitrate-N that is susceptible to loss in subsurface tile drainage, especially when wet years follow very dry years. Tile drainage from continuous corn plots that received only 18 lb N/A/yr at Lamberton contained annual flow-weighted nitrate-N concentrations of 13, 19, and 19 mg/L in 1973, 1974, and 1975, respectively (Gast et al., 1978). In a study at Waseca, four plots were fallowed (no crop grown and no N applied) with periodic tillage each year from 1987 through 1999. Nitrate-N concentration in the tile drainage water averaged 57 mg/L in 1990 following three dry years. Concentrations dropped to 38 and 25 mg/L in 1991 and 1992, respectively, and continued to average about 20 mg/L through 1999 (Fig. 6). Cambardella et al. (1999) found the temporal pattern of nitrate-N concentrations in subsurface drainage water to not be related to the timing of fertilizer N application or the amount of N applied and concluded that nitrate-N losses in drainage occur primarily as a result of asynchronous production and uptake of nitrate in the soil and the presence of large quantities of potentially mineralizable N in soil organic matter. In summary, elevated levels of nitrate-N will be lost to subsurface tile drainage water from row crops grown on these high organic matter soils regardless of fertilizer management practices, especially in wet years following dry years when crop production was limited.

Cropping Systems

Nitrate-N concentrations in subsurface drainage water are related to cropping systems. Tile drainage water from row crop systems (continuous corn and a corn-soybean rotation) that were fertilized with N based on a spring soil nitrate test averaged between 22 and 28 mg NO_3-N/L for the 4-yr period (1990-93) at Lamberton (Table 2). In comparison, perennial crops (alfalfa and a CRP grass-alfalfa mix) gave nitrate-N concentrations ranging from 0.7 to 1.6 mg/L. Due to higher flow volumes from the plots planted to row crops, nitrate-N losses from the row crops ranged from 30 to 50 times higher than from the perennial crops (Randall et al.. 1997). The effect of a perennial grass on nitrate-N concentrations in tile drainage water was also demonstrated at Waseca. A grass mixture of bluegrass and fescue was established in August, 1999 on the fallowed plots described in the previous section. Nitrate-N concentrations in the drainage water in 2000 averaged 8 mg/L in May but declined to 2 mg/L in July for a season-average of 5 mg/L (Fig. 6). This rapid decline in nitrate-N concentration illustrates the capability of an unfertilized perennial grass to scavenge nitrate from the soil profile and reduce nitrate losses to drainage water.

Nitrate-N concentrations under alfalfa were also shown to be much lower compared to corn or soybeans in Iowa (Baker and Melvin, 1994). These findings are similar to those reported by Logan et al. (1980) who found highest nitrate-N losses with corn, intermediate with soybean or systems where other crops were in rotation, and lowest with alfalfa. Weed and Kanwar (1996) found higher nitrate-N losses from plots planted to continuous corn compared to a corn-soybean rotation in Iowa. A 4-yr field study on a poorly drained, fine textured soil in NW Ohio showed concentrations of nitrate-N with soybeans were as high or higher than with corn in a corn-soybean rotation, especially in the spring (Logan et al., 1994). They concluded that a significant portion of nitrate in tile drainage is due to N carried over from the previous corn crop. In summary, these studies show substantially higher nitrate-N concentrations in row crops, especially continuous corn, compared to perennial crops that have an extended period of greater root activity (water and nutrient uptake) and where cycling of N is optimized. However, even though alternative cropping systems containing perennial crops would reduce nitrate losses and environmental concerns, obtaining a market for these crops and satisfactory economic return are serious challenges facing farmers at this time.

Rate of Nitrogen Application

Applying the proper rate of N for a crop is a major management decision facing crop producers. Using too little N for a highly responsive crop such as corn or wheat results in lower yields, poorer grain quality, and reduced profits. When too much N is applied, crop yields and quality are not impacted, but profit can be reduced somewhat and negative environmental consequences likely will occur. Thus, many choose to error on the liberal side when making decisions on N rate. This "extra" N is often called "insurance" N.

University long-term research provides guidance necessary to make N rate decisions. The N rate recommendations provided via various extension bulletins and software venues are based on numerous field experiments conducted across a broad range of soils, cropping systems, and weather conditions. The N rate recommendations also include credits for N from other sources such as manure and N fixed by legumes. These N credits are then subtracted from the total amount of N required by the crop to provide a fertilizer N rate recommendation. Even though the examples used in the following discussion focus on fertilizer N, it should be remembered that these principles also relate to N supplied by manure and legume fixation.

The relationship between annual fertilizer N rate for continuous corn and annual flow-weighted nitrate-N concentration in tile drainage water is shown for 1977-1979 at Waseca (Fig. 7). The annual N rates were begun in 1975 but no drainage occurred in 1975 and 1976 due to very dry weather. Thus, at the beginning of 1977 increasingly high amounts of RSN remained in the soil profile with each added amount of N. Consequently, very high concentrations of nitrate-N were found in the 5 in. of drainage water in 1977 (Fig. 7). Nitrate-N concentrations in the drainage water were lower in 1978 and were reduced further in 1979 as drainage volume increased and yields improved. Annual flow-weighted nitrate-N concentrations from the 0-lb N plots ranged from 13 to 16 mg/L, again indicating the role that soil mineralization played during this dry to wet climatic cycle in this high organic matter soil. Averaged across the 3 years when tile flow occurred, nitrate-N concentrations in the drainage water were increased by 16 mg/L when the N rate was increased from 100 to 200 lb/A and by 20 mg/L when N rate was increased from 200 to 300 lb/A. If 170 lb N/A was the recommended N rate for a yield goal of 160 bu/A, but the grower decided to apply an additional 40 lb N/A for "insurance" purposes, based on these data, nitrate-N concentrations in the drainage water would be projected to increase about 7 mg/L. If an annual N credit of 90 lb/A from manure were ignored and a total of 260 lb N/A was applied annually, nitrate-N concentrations could be expected to increase by about 17 mg/L. On the other hand, if the N rate was reduced 10% to 150 lb/A, nitrate-N concentrations could be expected to decrease by about 3 mg/L with a yield reduction of about 5 to 6 bu/A.

Although abnormally dry conditions prevailed for portions of the above study, the results clearly show the effect of increasing N rate on the concentration of nitrate-N in tile drainage water. Nitrogen applied in excess of crop need leads to dramatic increases in nitrate-N concentration. A simple excess application of 40 lb N/A for "insurance" purposes can elevate NO_3-N concentrations by 6 to 20 mg/L, depending on the severity and length of the dry period and on crop yield.

Improved manure management, including uniform application of known nutrient amounts and immediate incorporation, is critical if the optimum N rate is to be achieved in livestock production systems. Altogether too often manure is applied with a disposal objective in mind rather than with a utilization objective. When this occurs, rates of N as manure tend to be high and are not distributed evenly across the field. Consequently, credit is not given for N in the manure and the total rate of N (fertilizer plus manure) becomes excessive. When the nutrient content of manure is known and best management practices are used in land application, manure does not lead to greater nitrate losses to subsurface, tile drainage than from commercial fertilizer (Randall et al., 2000). If manure is applied at greater than agronomic rates, elevated concentrations of nitrate will occur in the drainage water.

Regression lines for the relationship between mean growing season precipitation (April – August) and predicted nitrate-N losses in tile drainage at Waseca for various N rates are shown in Fig. 8. These relationships were obtained by running the ADAPT model for 82 years of precipitation data and plotting predicted drainage losses of nitrate-N versus precipitation (Davis et al., 2000). As expected, the predicted nitrate-N losses in wet years were much greater than in dry years for a given rate of applied N, and the magnitude of nitrate-N losses increased as N application rate increased. In dry years, nitrate-N losses through tile drainage were quite low for all N application rates, because of a lack of precipitation to drive nitrate leaching. During normal years (25 in. of precipitation), nitrate-N losses were reduced from about 45 lb/A to about 5 lb/A when N fertilizer application rates were reduced from 200 lb/A to 110 lb/A. Thus, during normal precipitation years, about half of the N fertilizer applied in excess of University of Minnesota recommendations was predicted to be lost by leaching to tile drains.

Time of Nitrogen Application

Time of N application is another management decision that crop producers make each year. Agronomically and environmentally speaking, spring application is frequently superior to fall application because less loss of N occurs in the 2 to 3-month period between application and N uptake by the crop. However, many corn growers, especially in the northern part of the Corn Belt, desire to apply N in the fall because they usually have more time in the fall and field conditions are better. In the spring, early planting of corn as soon as soils are fit is desirable for highest yields and profit. Consequently, the window of opportunity for spring N application becomes very narrow (Randall and Schmitt, 1998). Soil compaction can also be a deterrent to spring application of N.

Nitrogen was applied as 15-N depleted ammonium sulfate in the fall and spring for continuous corn during a 6-yr period at Waseca. Corn yields from the late fall application (early November) of 120 and 180 lb N/A averaged 8% lower than with spring (late April) application (Table 3). In addition, annual losses of nitrate-N in the tile drainage water averaged 36% higher (8 lb/A/yr) with fall application compared to spring application. Averaged across time of application, yields and nitrate-N losses in the drainage water were 17 and 30% higher, respectively, for the 180-lb rate compared to the 120-lb rate. At the end of the study, 65% of the N being lost in the drainage from the 240-lb fall treatment was derived from the fertilizer, whereas only 15% of the N in the drainage water lost from the 120-lb spring treatment was derived from the fertilizer (Buzicky et al., 1983). Based on these data, obtained during a climatic period without very dry years, a 40-lb application of "insurance" N above the recommended 170-lb N rate would increase nitrate-N losses in tile drainage water by about 5 lb/A/yr.

Time of Nitrogen Application and Nitrapyrin (N-Serve)

Anhydrous ammonia (AA) was applied in four treatments [late fall, late fall + nitrapyrin, spring pre-plant, and split (40% preplant + 60% side-dress)] to drainage plots at Waseca from 1987 through 1993 (Randall et al., 2001a). Flow-weighted nitrate-N concentrations across the 4-yr flow period (1990-93) for the corn plots averaged 20, 17, 16, and 16 mg/L for the four treatments, respectively (Table 4). Although nitrate-N concentrations in the drainage water from soybean were lower compared to corn, the split and spring applications of N resulted in somewhat greater nitrate-N concentrations than the fall applications. Averaged across four cycles of the corn-soybean rotation, nitrate-N losses were greatest for fall N without N-Serve (3.8 lb/A-in.) with very little difference among the other three N treatments. Corn grain yield averaged across all 7 years was increased 8 bu/A by the fall N + N-Serve and spring N treatments and 14 bu/A for the split N treatment compared to fall N without N-Serve (Randall et al., 2001b). Apparent N recovery in the corn was also lowest for fall N without N-Serve and greatest for the split N treatment. These data obtained from poorly drained, fine-textured soils during wetter than normal years suggest that application of AA in the spring or in late fall along with a nitrification inhibitor (N-Serve) would: (a) reduce nitrate-N concentration by about 3 to 4 mg/L, (b) reduce nitrate-N flux by about 8 to 16 lb/A/yr. and (c) increase corn yields about 8 bu/A compared to late fall application of AA without a nitrification inhibitor. Earlier fall applications of AA, when soil temperatures are warmer and conversion to nitrate (nitrification) is faster, would be expected to produce even greater losses of nitrate to drainage water and poorer yields.

Split application of N does not always result in increased N efficiency and reduced nitrate losses. Baker and Melvin (1994) reported losses of nitrate-N to be higher for split application compared to a preplant application for continuous corn in Iowa. Losses with split application for the corn-soybean rotation were lower in the year of application but tended to be higher in the following year when soybean followed corn.

Tillage

Studies conducted in Iowa showed that tillage methods have less effect on nitrate-N loss to drainage water than do crop rotations (Bjorneberg et al., 1996; Weed and Kanwar, 1996). Moldboard plowing gave the lowest flow volumes while ridge tillage and no tillage had the lowest nitrate-N concentrations. A 11-yr study with continuous corn at Waseca showed similar results (Randall and Iragavarapu, 1995). Although slightly more water drained from the no-till plots, nitrate-N concentrations were slightly lower compared to moldboard plow plots (Table 5). Thus, nitrate-N flux in subsurface drainage was not influenced by tillage system. Drain flow from continuous corn grown on a loam soil in Ontario was significantly greater for no tillage compared to conventional tillage (CT) while nitrate-N concentrations tended to be greater with CT (Patini et al., 1996). During the 40-month period, nitrate-N loss in tile effluent was not significantly different for the two tillage treatments. In summary, tillage systems appear to have little influence on nitrate-N losses from agricultural fields.

Edge of Field Losses vs. Nitrate-N in Rivers

Questions frequently arise regarding the relationship between edge-of-field losses of nitrate as determined from subsurface drainage research conducted on small plots and nitrate levels in rivers located within areas dominated by tile drainage. Figure 9 illustrates the cumulative loading of nitrate-N in drainage water in 1999 from small plots located within the LeSueur River drainage basin that received 120 lb N/A as AA either on Oct. 20, 1998 or April 28,1999 and nitrate-N concentrations in the LeSueur River 30 miles from the research plots. (All nitrate-N data from the LeSueur River were collected and provided by Mike Meyer, environmental soil scientist, Metropolitan Council.) A couple of points are illustrated very clearly. First, nitrate-N losses in 1999 from fall-applied AA were 25 lb/A greater than from spring-applied AA. Second, four primary rain events/periods (about Apr. 10, May 15, May 25, and June 10) were responsible for most of the nitrate losses. Third, most of the AA applied on April 28 likely would not have leached into the tile drainage until at least late-May. Thus, a significant portion of the nitrate loss can be attributed to residual and mineralized N following the 1998 soybean crop. Fourth, nitrate-N concentrations in the LeSueur River varied considerably in the 3-mo. period and appeared to be closely synchronized with the major drainage events. Prior to initiation of subsurface drainage, nitrate-N concentrations in the river averaged only 7.4 mg/L. The concentrations more than doubled to 16.6 and 15.7 mg/L during the first major drainage event and then declined to 10.8 mg/L about three weeks later when subsurface drainage had largely subsided. Nitrate-N concentrations spiked again to 16.2 and 15.2 mg/L during the May 15 to 25 drainage events before declining to 12.7 mg/L in early June. The next major drainage event resulted in another spike to 15.6 mg/L before nitrate-N concentrations declined to 11.6 mg/L as subsurface drainage in the river basin slowed greatly and stopped in our plots. These data suggest a strong relationship between edge-of-field nitrate losses and nitrate concentrations in rivers receiving drainage from these poorly drained soils.

Summary

Numerous studies conducted on subsurface, tile drainage plots at Waseca and Lamberton, MN have provided an excellent set of data which show:

- Distribution and amount of annual precipitation greatly affects drainage volume, nitrate concentrations, and nitrate losses. Approximately 65% of southern Minnesota's annual subsurface drainage volume and 70% of the annual nitrate-N losses in drainage occur in April, May, and June. Drainage volume is greatest in April, whereas nitrate-N losses are greatest in May. Nitrate-N concentrations and losses are greatly affected by dry and wet climatic cycles with greatest losses occurring in wet years following abnormally dry years.

- Nitrate losses from the landscape are highly related to cropping system. Row crops, i.e., corn and soybean, yield much greater drainage volumes and nitrate-N concentrations in the drainage water than do perennial crops, i.e., alfalfa and CRP. Nitrate-N losses can be 30 to 50X higher from these row crops compared to perennial crops.

- Nitrate losses to subsurface drainage are greatly influenced by rate of N application and moderately influenced by time of N application. A 40-lb over-application of N in excess of crop needs can be expected to increase nitrate-N concentrations in the drainage by 6 to 20 mg/L depending on the severity and length of the preceding dry year(s). Nitrate-N losses increase as N rate increases with the magnitude of loss being much greater in wet years compared to dry years. Late fall applications of AA with N-Serve or spring application of AA can reduce nitrate-N concentrations by 3 to 4 mg/L and losses by 8 to 16 lb/A/yr compared to fall application of AA without N-Serve. Early fall application increases the potential for greater nitrate-N concentrations and losses in drainage water, especially since the majority of leaching occurs early in the spring.

- Placement method of N and tillage have minimal effects on nitrate losses in drainage. Drainage volume tends to increase with reductions in tillage while nitrate-N concentrations are generally higher for conventional moldboard plow systems. As a result, nitrate-N losses are generally similar for no-till and moldboard plow systems. Recent modeling research, however, indicates nitrate-N losses could be somewhat greater for chisel plow systems than moldboard systems because of more leaching (less surface runoff) but similar nitrate-N concentrations (D. J. Mulla, personal communication, 2000).

- Use of best management practices (BMPs) by farmers will reduce nitrate losses to subsurface drainage. But, will these practices be sufficient to reduce nitrate losses to meet the environmental goals of society? If not, will policies be developed to effect changes in land use, cropping systems, N application practices, subsurface drainage systems, or will other mitigating practices be required.

- Long-term drainage research, which integrates the effect of climatic variability, is vital to our understanding of nitrate losses to subsurface drainage. Educators and policy makers must consider this research as they deal with the occurrence of nitrates in surface waters from agricultural production systems.

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Table 1. Effect of PRECIPITATION on drainage volume, annual flow-weighted nitrate-N concentration, and nitrate-N losses in subsurface tile drainage in MN.

Year	April-October Rainfall[1]	Total Drainage	Nitrate-N Concentration	Nitrate-N Loss
	inches	inches	ppm	lb/A
1988	17	2	15	5
1989	16	1	12	2
1990	31	19	24	100
1991	38	24	24	124
1992	29	16	14	49

[1] 1961-90 Normal = 25.2 inches

Table 2. Effect of CROPPING SYSTEM on drainage volume, average flow-weighted nitrate-N concentration, and nitrate-N losses in subsurface tile drainage during a 4-yr period (1990-93) in MN.

Cropping System	Total Drainage	Nitrate-N Concentration	Nitrate-N Loss
	inches	ppm	lb/A
Cont. Corn	30.4	28	194
<u>Corn</u>-Sb	35.5	23	182
<u>Soybean</u>-C	35.4	22	180
Alfalfa	16.4	1.6	6
CRP	25.2	0.7	4

Table 3. Effect of N RATE and TIME OF APPLICATION on nitrate-N losses and corn grain yield in MN.

Nitrogen Trt.[1] Rate	Nitrogen Trt.[1] Time	Annual Loss of NO_3-N in Drainage	5-Yr Yield Average
lb/A		lb/A /yr	bu/A
0	----	7	66
120	Fall	27	131
120	Spring	19	150
180	Fall	34	160
180	Spring	26	168

[1] Ammonium sulfate applied about 1 Nov. or 1 May.

Table 4. Effect of TIME OF APPLICATION and N-SERVE for corn following soybeans on corn yield, N recovery, and nitrate-N losses in subsurface tile drainage in MN from 1987-1994.

Nitrogen Trt[1]		Grain[2]	Apparent Recovery	Avg. NO_3-N[3] Concentration		Nitrate[4] Lost in
Time	N-Serve	Yield	In Plant	Corn	Soybean	Drainage
		bu/A	%	- - - - mg/L - - - -		lb/A-in.
Fall	No	131	31	19.8	9.2	3.8
Fall	Yes	139	37	17.2	8.8	3.1
Spring	No	139	40	15.8	10.0	3.1
Split	No	145	44	15.8	11.2	3.3

[1] Anhydrous ammonia was applied about 23 Oct. (fall) and 1 May (spring). Split treatment consisted of 40% spring preplant and 60% sidedress at V8 stage.

[2] Seven-yr (1987-93) average.

[3] Flow-weighted concentrations in corn plots (1990-93) and soybean plots (1991-94).

[4] Average across four cycles of the corn-soybean rotation.

Table 5. Effect of TILLAGE for continuous corn on nitrate-N losses in subsurface tile drainage in MN.

	Tillage System[1]	
Parameter	Moldboard Plow	No Tillage
Drainage volume (inches)	11.0	12.4
Nitrate-N concentration (mg/L)	15	13
Nitrate-N lost (lb/A)	38	37
N lost as a percent of applied N	21	20

[1] Eleven year (1982-92) average.

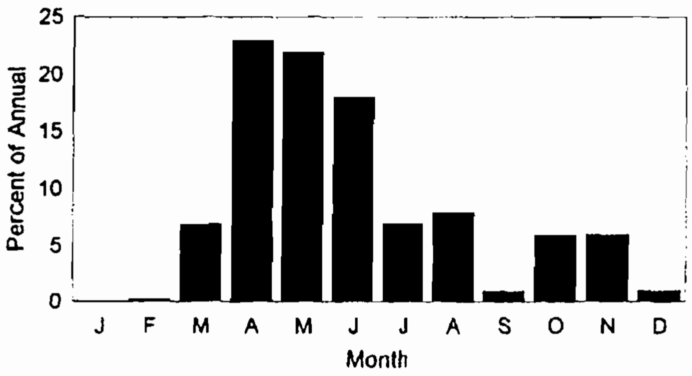

Fig. 1. Monthly distribution of annual subsurface tile discharge averaged across a 13-yr (1987-99) period for continuous corn.

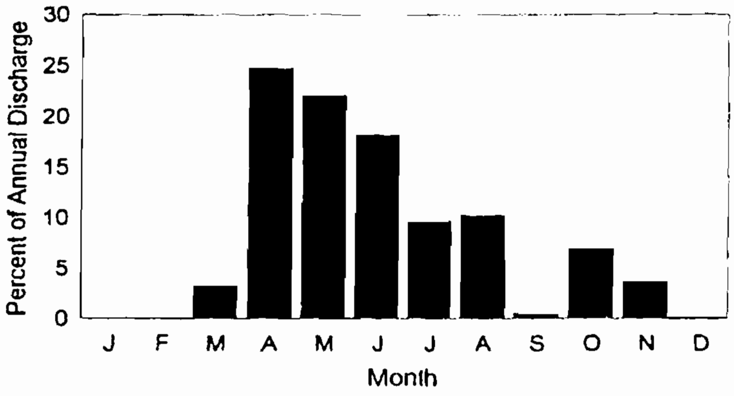

Fig. 2. Monthly distribution of subsurface tile drain discharge averaged across a 13-yr (1987-99) period for <u>corn</u>.

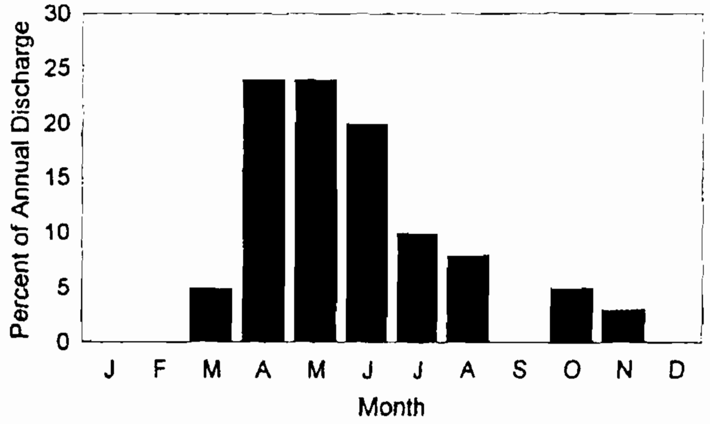

Fig. 3. Monthly distribution of subsurface tile drain discharge averaged across a 13-yr (1987-99) period for <u>soybean</u>.

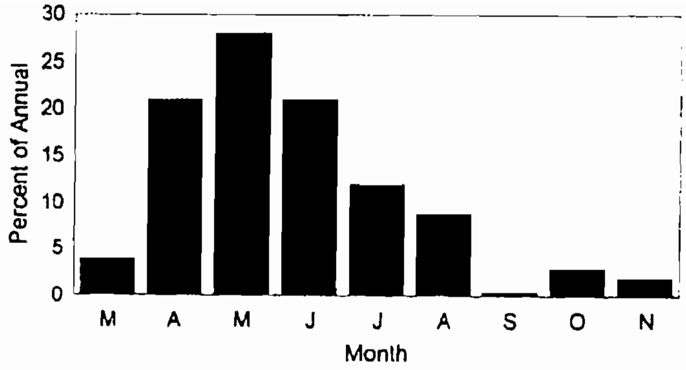

Fig. 4. Monthly distribution of nitrate lost in subsurface tile drainage water during the corn phase when averaged across a 13-yr (1987-99) period.

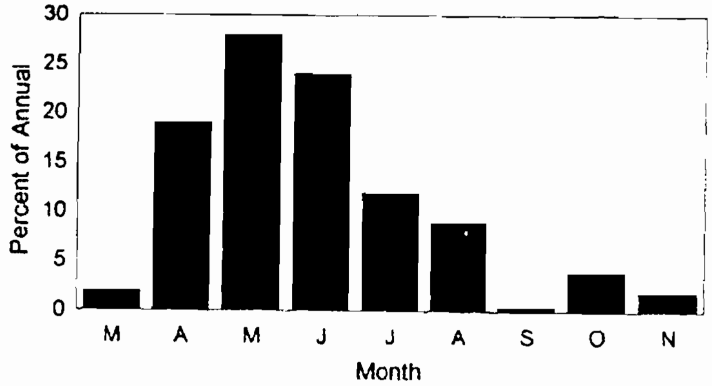

Fig. 5. Monthly distribution of nitrate lost in subsurface tile drainage water during the soybean phase when averaged across a 13-yr (1987-99) period.

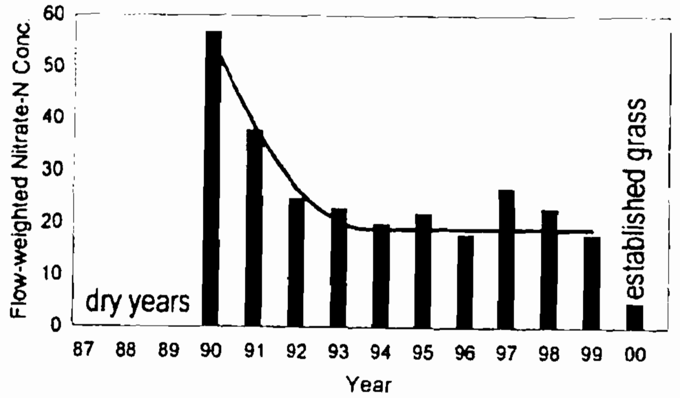

Fig. 6. Nitrate losses in tile drainage water from soil mineralization.

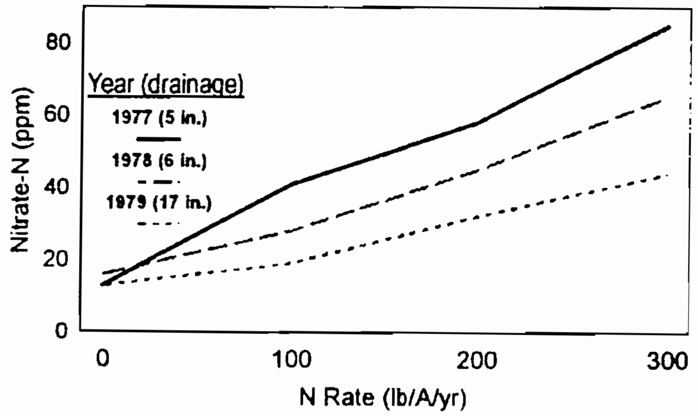

Fig. 7. Nitrate-N concentration in tile drainage water as affected by N rate for continuous corn at Waseca.

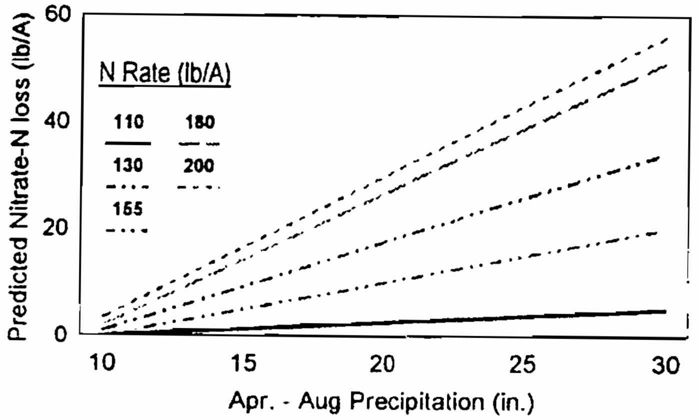

Fig. 8. Predicted nitrate-N loss via tile drainage water as affected by N rate and precipitation.

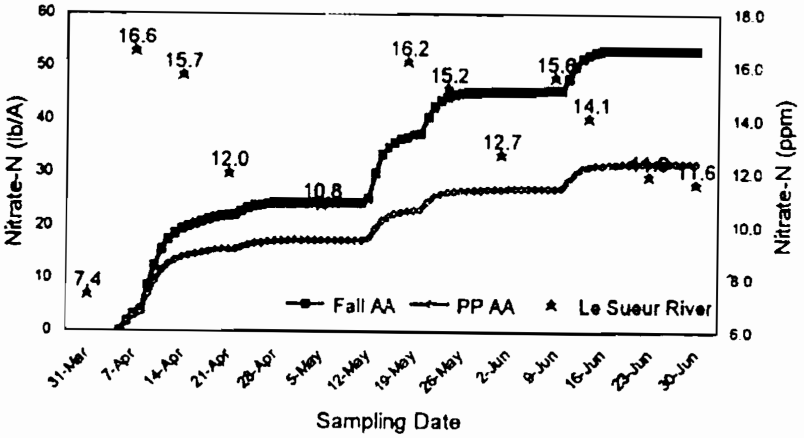

Fig. 9. Cumulative loading of nitrate-N in tile water leaving plots at Waseca and NO_3-N concentrations in the LeSueur River in 1999.

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