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Nitrogen Rates

5

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In most crop rotations that include corn, nitrogen (N) applied to the corn phase is a proven and profitable practice. Corn in some rotations requires little to no N input, with first-year corn following established alfalfa as an example. Corn in other rotations requires substantial N input to meet plant requirements, with continuous corn (CC) typically requiring the greatest input. Other rotations or corn phases will be intermediate in N application requirement. With corn in the two most common crop sequences in the Corn Belt, corn following soybean (SC) and CC, if N is not applied, then yield will suffer. If N is not applied on an on-going basis, then over time corn yield will often average around 50 to 60 bu ac^{-1} in CC and 100 to 110 bu ac^{-1} in SC, or less. Consequently, the soil system typically cannot supply the full corn plant N requirement. On average, the yield with no N applied is around 70% in a SC rotation and 55% in CC of the yield obtained at an economic optimum rate. Therefore, supplemental N is needed to reach economic yield potential.

Research measuring corn response to N application has been on-going for over 50 years. Guidelines for suggested N rates based on that research have been derived using economic principles to determine the economic optimum N rate (EONR) rather than maximum yield. Therefore, recommendations are guided by economic return to N application through corn yield increase. The expectation by many is that simply applying N at economic optimum rates will “solve” the issue of nitrate movement from fields in subsurface drainage. However, nitrate losses occur in corn production systems even when no N is applied, and N application at optimum rates increases loss. To date, determination of EONR has not been modified to account for environmental costs resulting from increased nitrate loss to water systems when N is applied, largely due to lack of such cost information and societal decisions on where to partition those costs.

The objectives of this chapter are to review the effect of N application rate for corn on economic return, nitrate in subsurface drainage (tile flow), and potential nitrate reduction.

Economic N Application Rates

Producers should apply N rates that return the most profitable economic yield, where the yield gain from N application will more than pay for the invested N, rather than maximum yield. Nitrogen response trials are conducted where multiple rates of N are applied, and grain yield is measured at each rate. Analysis of that response data allows calculation of site EONR, the rate at which the grain yield increase just pays for the cost of the last increment of applied N (fig. 5-1). Economic net return is the

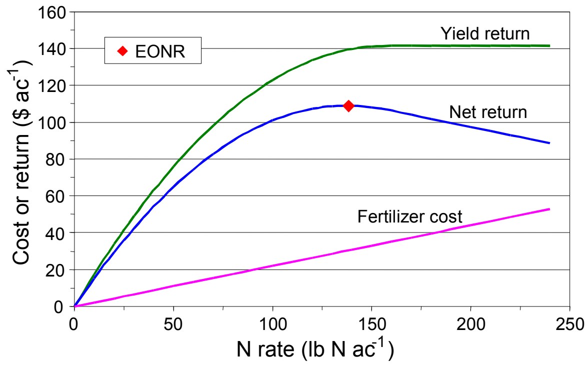

Figure 5-1. Example corn grain yield and fertilizer components of calculated economic net return across N rates from an N response trial, with the economic optimum N rate (EONR) at 0.10 N:corn price ratio ($0.22 lb^{-1} N : $2.20 bu^{-1} corn) indicated by the closed symbol.

difference between the yield gain and N cost. Analysis of response data from many sites is needed to account for typical variation in N response and optimum N across years (fig. 5-2) and locations (fig. 5-3) due to non-controllable factors and to improve determination of the point at which expected maximum economic net return to N (MRTN) occurs (the MRTN approach as described by Nafziger et al., 2004, and Sawyer et al., 2006). The MRTN approach incorporates the uncertainty in yield response to applied N from all sites, uses the diminishing yield increase and maximum response as N rate increases, and provides the point at which the economic net return is maximized across all sites (closed symbols in fig. 5-4). Since the net return is fairly constant at N rates near the MRTN, a range of N rates would be expected to provide similar economic profit (open symbols in fig. 5-4, which are within $1.00 ac^{-1} of the maximum return). This range can provide flexibility in decisions regarding application rate and should provide adequate yield across changing production conditions. Because of the small yield change within the N rate range for maximum profit, rates at the low end of the range will produce greater N use efficiency (more bushels per lb N) and leave less nitrate in the soil for potential loss than rates at the high end of the range. However, the risk of having inadequate N increases.

When N response trials are conducted with corn in different rotations, the MRTN can be calculated for each rotation. Examples are given in figure 5-4 for CC (56 sites) and SC (121 sites) in Iowa for trials conducted approximately the past ten years. In these Iowa trials, the MRTN rate for CC is approximately 175 lb N ac^{-1} and 125 lb N ac^{-1} for SC when the ratio of the N price to corn price is 0.10 ($0.22 lb^{-1} N:$2.20 bu^{-1}). This is a typical difference in economic N rate between these two rotations.

Economic N rates are not necessarily the same across the Corn Belt. Figure 5-5 shows the MRTN rate for CC and SC from recent N response trials conducted in Iowa, Illinois (82 CC sites and 172 SC sites), and Minnesota (68 CC sites and 50 SC sites). Differences can be due to variation in soils, climate, management, and interaction of these factors. These differences must be taken into account as evaluations are made regarding suggested N rates and potential to affect nitrate in drainage water leaving fields.

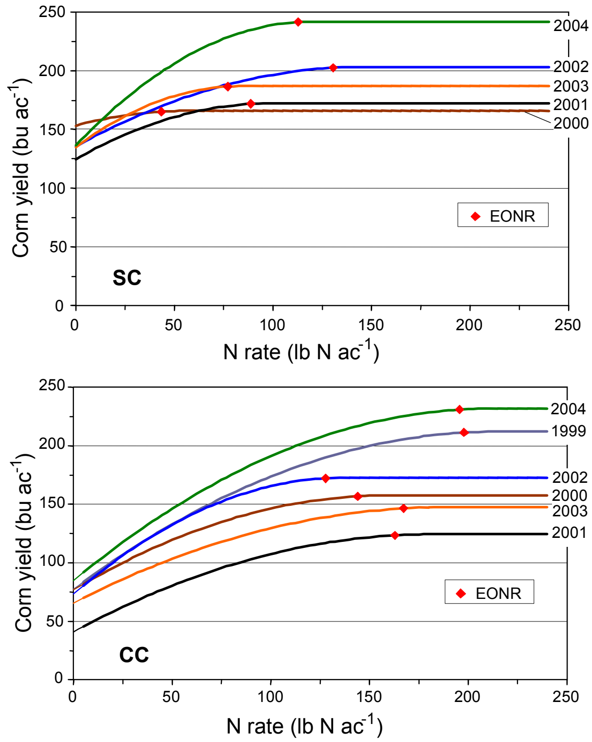

Figure 5-2. Variation in EONR (0.10 price ratio) and yield across years for SC and CC at the same site, Ames, Iowa.

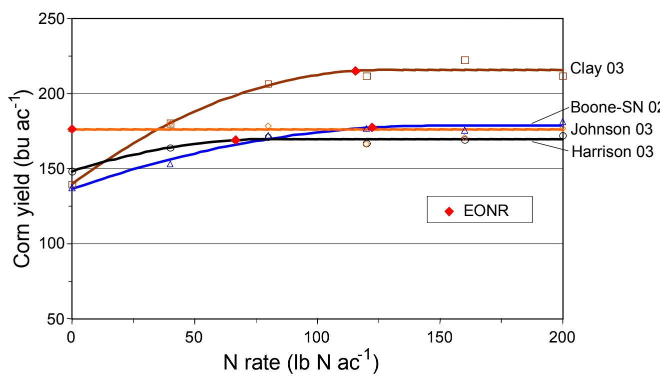

Figure 5-3. Example of variation in response to N and EONR (0.10 price ratio) at different sites in Iowa. Open symbols are measured yield for each N rate.

Economic N rates also change with different relationships between N price and corn price (i.e., the N:corn price ratio, \$ lb^{-1} N : \$ bu^{-1} corn). As shown in figure 5-4, as the N price becomes higher relative to the corn price (i.e., the ratio gets larger), the net return and MRTN rate decrease. In addition, the economic penalty to high N rates

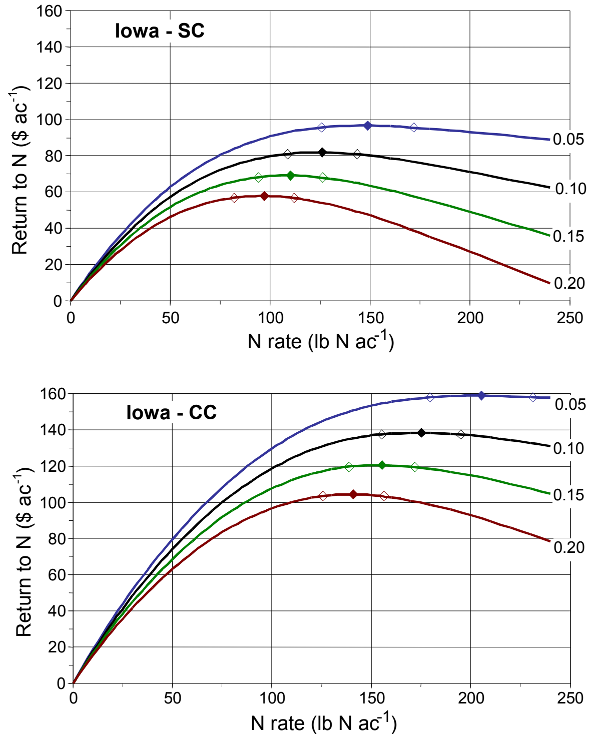

Figure 5-4. Effect of fertilizer N:corn grain price ratio on net return to N (SC and CC rotations in Iowa). The closed symbols correspond to the maximum return to N (MRTN), and the open symbols indicate the range around the MRTN with similar return (within \$1.00 ac^{-1} of the maximum return).

above the MRTN increases, as evidenced by the steeper decline in net return as the rate increases above the MRTN. This economic penalty is virtually nonexistent when N is inexpensive (low price ratio), a situation likely recognized by producers and one that may have encouraged high N rates in past years. This situation does not exist today, as N prices have risen substantially. Conversely, there is increased risk of N shortage and severe economic penalty at N rates below the MRTN (fig. 5-4), as evidenced by the rapid decline in net return as N rate declines below the maximum profit range. This is likely the greatest concern for producers: increased production risk and associated severe yield and economic loss due to insufficient N. Incentives for producers to accept increased risk as rates are used at the lower end of the MRTN range could be provided by insurance programs. Another approach is documentation of N adequacy or deficiency with diagnostic tools. Examples include preplant soil testing (PPNT, preplant soil nitrate), in-season soil testing (PSNT, pre-sidedress soil nitrate), plant N stress sensing (hand-held chlorophyll meter, remote aerial color and near-infrared images, pulsed reflective light sensing), and post-season testing (end-of-season stalk nitrate, post-harvest profile nitrate). Continued research on development and refinement of diagnostic tools is needed to improve accuracy and reliability in determining fertilizer N needs.

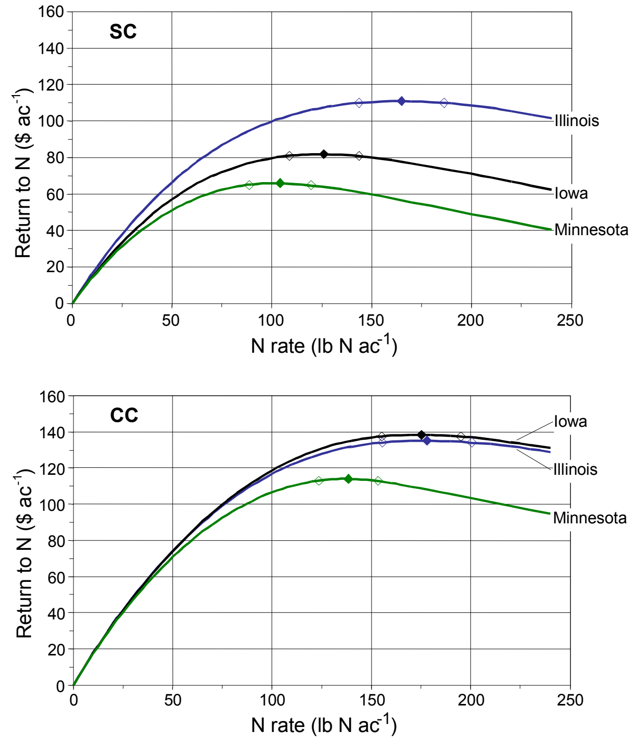

Figure 5-5. Differences between net return to N for SC and CC for various states at a 0.10 N:corn price ratio ($0.22 lb^{-1} N : $2.20 bu^{-1} corn). The closed symbols correspond to the maximum return to N (MRTN), and the open symbols indicate the range around the MRTN with similar return (response data from Illinois courtesy of Emerson Nafziger, University of Illinois).

For sound N management, crop producers should apply the rate of N that provides maximum return to the N investment. This application, however, results in increased soil nitrate, with potential for greater nitrate concentrations moving to water systems. Minimizing nitrate-N concentration or load in drainage water leaving production fields by changing N rate therefore becomes relative to the N rate that provides maximum economic return to N.

Nitrogen Rate and Nitrate-N Losses in Subsurface Drainage

When no N is applied, there is a baseline nitrate-N in subsurface drainage from land cropped to corn or corn in rotation with soybean. This concentration or load varies depending on the climate, soil properties and tile system characteristics, but it often spans the range of 3 to 10 mg L^{-1} or 8 to 20 lb ac^{-1}. As N is applied at increasing rate, the concentration and load of nitrate-N in tile flow increases; examples are shown in tables 5-1 and 5-2 and in figures 5-6 and 5-7, with further examples in Baker et al. (1975), Baker and Johnson (1981), Davis et al. (2000), Jaynes et al. (2001), Kladivko et al. (2004), Jaynes et al. (2004), Clover (2005), and Lawlor et al. (2005). While withholding N application may reduce tile-flow nitrate-N concentrations to less than the USEPA drinking water maximum contaminant level (MCL) standard of 10 mg N L^{-1}, it will not result in concentrations at or less than currently proposed USEPA nutrient ecoregion VI nutrient criteria of 2.18 mg total N L^{-1} for rivers and streams or 0.78 mg total N L^{-1} for lakes and reservoirs (USEPA, 2002).

The change in nitrate in subsurface drainage as N application rate increases is not consistent across locations, but generally increases steadily as N application rate increases (examples in figs. 5-6 and 5-7). Data from some locations show a more rapid increase (curvilinear) as N rate increases, especially well above the EONR. Other locations do not have this trend. While many studies have monitored nitrate in subsurface drainage with a limited number of N rates (due to research cost constraints and interest in multiple practices affecting N loss), there is a scarcity of site data with an adequate number of rates to fully characterize nitrate loss and concurrently determine corn yield response over a long-term period.

It is common to find nitrate-N concentrations in subsurface drainage or discharge from watersheds above the 10 mg N L^{-1} MCL drinking water standard when the EONR or lower rate is applied for corn production (Baker et al., 1975; Baker and Johnson, 1981; Owens et al., 2000; Jaynes et al., 2001; Jaynes et al., 2004; Clover, 2005; Lawlor et al., 2005). In the work of Baker et al. (1975), N applied only to corn at a rate of 100 lb N ac^{-1} in an oat-corn-oat-corn-soybean sequence resulted in an average annual 21 mg nitrate-N L^{-1} in tile flow (site located at Boone, Iowa). Continuing

Table 5-1. Corn production and nitrate loss to tile drainage as affected by rate and time of N application at Waseca, Minnesota, 2000-2003.

N Treatment			Four-Year Average		
Time	N Rate (lb N ac^{-1})	N-Serve	Grain Yield (bu ac^{-1})	Net Return to N[a] ($ ac^{-1})	Flow-Weighted NO_3-N Conc.[b] (mg L^{-1})
--	0	--	111	--	--
Fall	80	Yes	144	38	11.5
Fall	120	Yes	166	72	13.2
Fall	160	Yes	172	74	18.1
Spring	120	No	180	105	13.7

[a] Corn = $2.00 bu^{-1}, fall N = $0.25 lb^{-1}, spring N = $0.275 lb^{-1}, and N-Serve = $7.50 ac^{-1}.
[b] Across four SC rotation cycles.

Table 5-2. Corn production and nitrate loss to tile drainage as affected by spring-applied anhydrous ammonia N rate at Filson, Illinois, 2002-2004 (Clover, 2005).

			Change Per 70-lb N Rate Increment			
N Rate (lb N ac^{-1})	Grain Yield (bu ac^{-1})	Tile-Flow NO_3-N[a] (lb ac^{-1})	Yield (bu ac^{-1})	NO_3-N (lb ac^{-1})	Net Loss[b] ($ ac^{-1})	Net Loss per Unit NO_3-N ($ lb^{-1})
210	180	61	---	---	---	---
140	169	41	11	20	10	0.52
70	130	30	39	10	68	6.64
0	69	26	61	4	119	29.70

[a] Rotation total from the average across three years of each crop in a SC rotation, i.e., the total amount for the two-year rotation.
[b] Nitrogen at $0.22 lb^{-1} N and corn grain at $2.20 bu^{-1}.

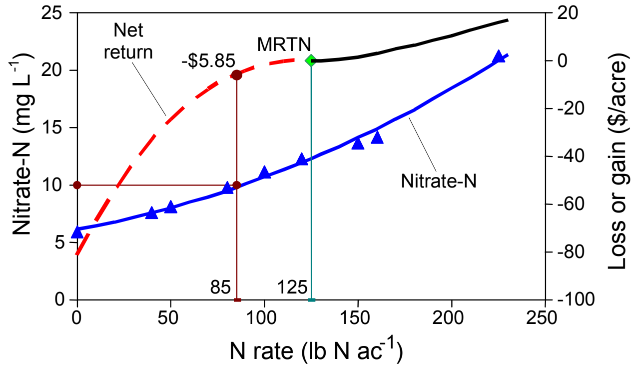

Figure 5-6. Tile-flow nitrate-N annual concentration average in a SC rotation from N rates applied in various years from 1990-2004 at the Gilmore City, Iowa, site (Lawlor et al., 2005) and the net economic gain or loss ($0.22 lb^{-1} N : $2.20 bu^{-1} corn) across N rates for SC in Iowa (Nafziger et al., 2004). The solid section of the net return line represents the gain if N rates are reduced to the maximum return to N (MRTN), and the dashed section represents the loss if N rates are reduced below the MRTN. The indicated economic loss of $5.85 ac^{-1} is for reduction of tile-flow nitrate-N from the MRTN rate to the N rate that results in approximately the 10 mg L^{-1} MCL drinking water standard.

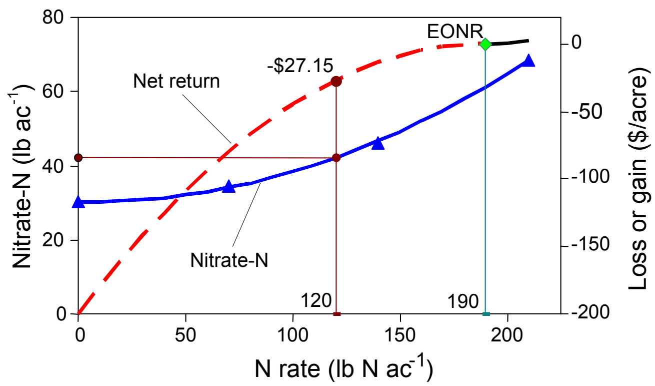

Figure 5-7. Rotation total tile-flow nitrate-N mass load and net economic gain or loss ($0.22 lb^{-1} N : $2.20 bu^{-1} corn) across spring-applied N rates in a SC rotation, average of 2002-2004 at the Filson, Illinois, site (Clover, 2005). The solid section of the net return line represents the gain if N rates are reduced to the site economic optimum N rate (EONR), and the dashed section represents the loss if N rates are reduced below the EONR. The indicated economic loss of $27.15 ac^{-1} is for reduction of tile-flow nitrate-N load from the EONR rate to the N rate that results in an approximate 30% lower load.

research at the site (Baker and Johnson, 1981) with two N rates of approximately 90 and 240 lb N ac^{-1} applied only to corn in a corn-soybean-corn-oat-soybean sequence resulted in an average annual 20 mg nitrate-N L^{-1} (24 lb nitrate-N ac^{-1} year^{-1}) with the low N rate and 40 mg nitrate-N L^{-1} (43 lb nitrate-N ac^{-1} year^{-1}) with the high N rate. Work by Andraski et al. (2000) at a site in Arlington, Wisconsin, with various crop rotations and manure history showed that the soil water nitrate-N concentration (measured in porous-cup samples at 48 in.) was 18 mg L^{-1} at the EONR, was <10 mg L^{-1} when N rates were more than 45 lb N ac^{-1} below the EONR, and was >20 mg L^{-1}

when N rates were more than 45 lb N ac^{-1} above the EONR. Work reported by Randall and Mulla (2001) with depleted ^{15}N ammonium sulfate applied to CC at Waseca, Minnesota, indicated a 17% increase in yield but a 30% higher nitrate-N loss in drainage water with 180 lb N ac^{-1} compared to 120 lb N ac^{-1}. Davis et al. (2000) reported that increasing N rates from 90 to 200 lb N ac^{-1} in CC (Waseca, Minnesota) resulted in a linear increase in nitrate-N loss (0.8 to 22.8 lb nitrate-N ac^{-1} year^{-1}). Jaynes et al. (2004) achieved a 30% reduction in nitrate-N concentration in water leaving a central Iowa sub-basin by changing the timing of N application from fall to split spring/sidedress and reducing the N input through use of soil N testing, but the weekly and annual average flow-weighted nitrate-N concentrations were not maintained below the 10 mg L^{-1} drinking water MCL.

If achieving the drinking water standard is a goal for nitrate concentrations in subsurface drainage, it will be difficult to achieve solely with application rate. However, if N is being applied well above rates that produce maximum economic return, then reduction in nitrate loss can be accomplished by reducing rates to those levels (examples in table 5-1 and figs. 5-6 and 5-7). The gain will depend on the specific location, rate change, and production situation.

Nitrate-N concentrations in subsurface drainage are generally greater for CC than for SC due to the frequency of annual N applications. This is especially true when N is over-applied. An over-application of 50 lb N ac^{-1} year^{-1} in a CC system provides greater potential for much higher nitrate losses than an over-application of 50 lb N ac^{-1} every other year in a SC rotation. In addition, soybean can scavenge some of the excess residual N if spring drainage is limited. When N is being applied closer to optimal rates, differences in nitrate-N concentrations in the drainage water between CC and SC will be less and may be minimal. Because nitrate moves in drainage water after soybean harvest, this moderates differences in nitrate loss between the rotations. Data from the Nashua, Iowa, water quality site for 1990-1992 provide an excellent example. The average annual loss (across all tillage systems) was 30 mg nitrate-N L^{-1} (52 lb nitrate-N ac^{-1} year^{-1}) with CC and 18 mg nitrate-N L^{-1} (25 lb nitrate-N ac^{-1} year^{-1}) with SC, at N rates of 180 lb N ac^{-1} applied each year to corn in CC and 150 lb N ac^{-1} applied every other year to corn in SC (Weed and Kanwar, 1996; Kanwar et al., 1997). Continuing the study site from 1993-1998 with reduced N rates of 120 lb N ac^{-1} in CC and 100 lb N ac^{-1} in SC, the average annual loss was 11 mg nitrate-N L^{-1} (15 lb nitrate-N ac^{-1} year^{-1}) with CC and 11 mg nitrate-N L^{-1} (12 lb nitrate-N ac^{-1} year^{-1}) with SC (Bakhsh et al., 2005). Another example is the tile-flow data collected by Randall et al. (1997), in which N (based on spring soil sampling) applied in CC compared to SC increased average annual nitrate-N concentrations by approximately 8 mg L^{-1} (from 24 to 32 mg L^{-1}) and increased flux 7%.

While not directly comparing N rates, at a site in southeastern Indiana, Kladivko et al. (2004) found that, over time, decreasing the frequency of N application (moving away from CC to SC after nine years), decreasing the N rate (changing to the SC rotation and changing the N rate over time from an initial 250 to 160 lb N ac^{-1}), and growing a winter cover crop after corn in the SC rotation significantly reduced tile-flow nitrate. Over a 14-year period, the flow-weighted nitrate-N concentration was reduced from approximately 28 to 8 mg L^{-1}. Important characteristics that influenced nitrate-N concentrations and changes over time at the site included relatively shallow tile, low organic matter soil, drainage all winter, and spring-applied anhydrous ammonia fertilizer. Similar results were found in lysimeter studies in Ohio (Owens et al., 1995). When the cropping sequence was changed from CC with an N rate of 300 lb N ac^{-1} to SC with an N rate of 200 lb N ac^{-1} and a winter cover crop, annual flow-weighted nitrate-N concentrations were reduced from about 22 to 12 mg L^{-1}.

In summary, rate of N application and frequency of corn in the cropping sequence are important factors influencing nitrate losses in subsurface drainage. Since losses are greater in a CC system than in a SC system, largely due to annual versus every-other-year frequency of application, it is of greater importance to use the correct amount of N in the CC system than with a SC system if nitrate losses are to be minimized and maximum return to N achieved.

Nitrogen Rate Potential to Reduce Nitrate-N Losses

Since nitrate in subsurface drainage increases with increasing N application rate, there is potential to affect nitrate losses through change in N rate. However, the level of change will be related to the rate comparison and starting rate. In addition, and as mentioned above, the success relative to water quality goals is not likely to be achieved solely through rate adjustment. For instance, at economic optimum application rates for corn production, nitrate-N in tile flow typically exceeds the MCL drinking water standard (examples in table 5-1 and fig. 5-6). Moreover, even if no N is applied, nitrate-N will exceed the proposed EPA nutrient criteria for total N in surface waters (examples in Clover, 2005; Lawlor et al., 2005).

There are also questions regarding costs associated with reducing nitrate losses, and how those costs are to be paid. If N application rates being used are above MRTN rates, then producers can gain economically by reducing rates to those levels (figs. 5-6 and 5-7). They will achieve a net economic positive due to reduced N input and no associated loss in yield. However, if producers are already applying N at MRTN rates, then reduction below those rates will impose an economic penalty through yield loss (tables 5-1 and 5-2 and figs. 5-6 and 5-7). As an example (fig. 5-6), let's say the goal is to reduce tile-flow nitrate-N to 10 mg L^{-1} and the starting N rate is at the MRTN. At the MRTN rate for Iowa SC (125 lb N ac^{-1}), the associated tile-flow nitrate-N is approximately 12 mg L^{-1} (Lawlor et al., 2005). The N rate associated with 10 mg nitrate-N L^{-1} is 85 lb N ac^{-1}. The net economic loss due to an N rate reduction from 125 to 85 lb N ac^{-1} is \$5.85 ac^{-1}. In another example, where corn yield and tile-flow nitrate is more responsive to N application (fig. 5-7), moving from the site EONR of 190 lb N ac^{-1} to a 120 lb N ac^{-1} rate (an associated 30% reduction in tile-flow nitrate load from 61 to 42 lb nitrate-N ac^{-1}), the net economic loss is \$27.15 ac^{-1}.

Since yield response decreases with increasing N rate, the cost in yield penalty for reduced N input is less near the MRTN rate than near zero N. Therefore, cost per unit of nitrate-N reduction in drainage water becomes much larger as N rate declines below the MRTN and approaches zero (table 5-2 and fig. 5-7). For the Filson, Illinois, site, the first 70 lb N rate increment (from 210 to 140 lb N ac^{-1}) costs \$0.52 per unit of nitrate-N load reduction, but the last 70 lb N rate increment (from 70 lb N ac^{-1} to zero N) costs $29.70 per unit of nitrate-N load reduction (table 5-2).

These examples illustrate the significant risk and economic constraints that face producers if they are asked to reduce N application to rates below maximum net return. If N rates in both examples given above were reduced to zero, then the economic losses would be $81.75 ac^{-1} and $200.10 ac^{-1}, both of which are unacceptable. These examples also clearly show that potential reduction in nitrate in subsurface drainage, and costs for potential reductions, varies significantly across the Corn Belt.

Summary

Nitrate in subsurface drainage is responsive to N application rate. Increasing the rate of N applied for corn results in greater nitrate concentrations in subsurface drainage water. While rates that produce maximum net economic gain through yield return to N will moderate nitrate-N, the resulting concentrations can approach but usually will be greater than acceptable in relation to the USEPA drinking water MCL standard, and definitely above proposed water quality criteria. Growing corn in rotation, for example every other year with soybean, reduces nitrate in subsurface drainage due to lower corn N fertilization requirement and less frequent application.

Economic and water quality gains can be achieved by reducing N rates if producers are applying N at rates above those needed for maximum net economic return. However, water quality gains achieved by reducing rates below those for maximum economic return will result in economic loss due to reduction in corn grain yield greater than that offset by N input reduction. If such restrictions are placed on N application rates as part of reaching a goal in regard to gulf hypoxia or local nitrate in surface waters, then it will be important to consider mechanisms to reimburse producers for lost income. It is also important to recognize that corn N fertilization requirements, potential for reducing nitrate concentrations in subsurface drainage, and costs for potential nitrate reductions vary significantly across the Corn Belt and must be accounted for in predictions of nitrate loss improvement and associated cost estimates when considering water quality driven changes in N inputs.

Interpretive Summary

Practice Recommended

- Apply N to corn at rates that produce maximum profit.

Important Factors

- Profitability for producers.
- In corn production systems, nitrate is lost in tile-flow drainage even if no fertilizer N is applied, often in the 3 to 10 mg nitrate-N L^{-1} range.
- Nitrate-N concentration in subsurface drainage generally increases in a continuous relationship with increasing N rate.
- Application of N above optimal rates reduces economic return and further increases nitrate losses.
- Optimal rates of N must account for previous crop and for N inputs from ma-

nure, ammoniated phosphate fertilizers, starter fertilizers, and N fertilizers applied in weed and feed herbicide applications.
- Preplant and in-season soil and plant diagnostic tests are decision aids that can improve N rates.
- The potential for reducing nitrate-N concentration or load in drainage water by changing N application rate should be evaluated relative to that at rates providing maximum economic return to N and for associated producer risks.
- Reducing N rates below optimum results in economic losses to the producer because the value of lost yield is not offset by reduced N costs.
- Nitrate losses are usually higher for continuous corn than for corn rotated with soybean, small grains, and alfalfa.

Limitations
- Even with application of no fertilizer N to corn, nitrate-N concentrations in subsurface drainage are above the currently proposed EPA nutrient ecoregion VI surface water quality criteria for total N.
- Application of N near rates that provide maximum economic return usually results in tile flow having nitrate-N concentrations above the EPA drinking water MCL, often in the range of 10 to 20 mg nitrate-N L^{-1} for SC and 15 to 30 mg nitrate-N L^{-1} for CC.
- In Iowa studies, to lower the nitrate concentration to 10 mg nitrate-N L^{-1} in tile drainage with a SC rotation, the N rate applied to corn had to be reduced by 40 lb N ac^{-1} below the rate providing maximum economic return; this reduction would have an associated net loss of \$5.85 ac^{-1}.
- In an Illinois study with a SC rotation, to reduce the total nitrate-N load by 30% (relative to that at optimal N application) in tile drainage, the N rate had to be reduced by 70 lb N ac^{-1} below the economic optimum rate, with an associated net loss of \$27.15 ac^{-1}.
- The “cost” (in yield loss) per unit of nitrate-N reduction in tile flow becomes much larger as N rates decrease below the optimum rate.
- As N rates are reduced below the maximum economic return rate, production variability and risk increase due to uncertainties in the N needs of corn for any given year and location.

Potential
- Nitrogen rate reduction will directly benefit producers when current application rates are above optimum. Reduction to optimal rates will also reduce nitrate losses. While there is uncertainty in the actual N application rate for corn in specific geographic areas, and hence the possible incidence of over-application, it can be projected that adjusting N rates from a 40 lb over-application down to economic optimal rates will decrease nitrate concentration in subsurface drainage water by about 20% to 25% from fields with such over-application.
- Optimal N rates for corn, associated nitrate levels in subsurface drainage, and the potential to gain improvement in nitrate losses through optimizing N rates varies across the Upper Mississippi River sub-basin and needs to be accounted

for in water quality programs addressing N application rates.
- Crop rotations that include fewer years with corn consequently reduce the frequency of application and the total N rate, resulting in lower nitrate concentrations in subsurface drainage.
- To achieve desired water quality goals, other in-field or out-of-field practices will need to be implemented, as change in N application rates or application at optimal rates to all corn production fields will not alone “solve” nitrate loss issues.

Future Research Needs
- More research using adequate N rate increments and concurrently measuring nitrate loss in subsurface drainage is needed to better quantify that relationship.
- Research is needed to provide a better understanding of reasons for variation in optimal N rates across the Upper Mississippi River sub-basin.
- Research on development and refinement of tools such as soil N tests, plant tests, and plant sensors is needed to determine more accurately fertilizer N needs and thus reduce risk of under- or over-fertilization.

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