AGRONOMIC, ECONOMIC AND ENVIRONMENTAL CONSEQUENCES OF NITROGEN MANAGEMENT PRACTICES

Gyles W. Randall - University of Minnesota

Profitable corn production is affected more by nitrogen (N) fertilization practices than by any other nutrient. At the same time, environmental consequences such as leaching of nitrate to ground and surface waters and denitrification of nitrogen and nitrous oxide to the atmosphere are closely related to N management practices used by corn producers.

Agronomic factors involved in N management include: cropping system, rate of N applied, time of N application, nitrification inhibitors, source of N, tillage, and cover crops. The purpose of this paper is to present information from research conducted across southern Minnesota that relates these agronomic and N management factors to the economic and environmental consequences of corn production in Minnesota. Although research information presented from the northern latitudes of the Corn Belt may not be exactly relevant to Indiana conditions, the principles involved in these studies should assist corn producers throughout the Corn Belt optimize N management, improve economic return, and reduce loss of N to ground and surface waters.

Methods

The field studies cited in this paper were conducted at three sites: (1) the Lawler Farm in Olmsted County near Rochester in the southeastern Minnesota, (2) the Southern Research and Outreach Center at Waseca in south-central Minnesota, and (3) the Southwest Research and Outreach Center at Lamberton in southwestern Minnesota. The Lawler site is a highly productive, well-drained, deep loess Port Byron silt loam soil over Karst limestone. Leaching of nitrates into groundwater aquifers is a serious concern in this area of the state where annual rainfall is 34 to 36 inches. The sites at Waseca and Lamberton are located on inherently poorly drained, glacial till soils, which have been pattern tile drained. The dominant soils at Waseca are Nicollet, Canisteo, and Webster clay loams with about 5.5 percent organic matter and 35 percent clay. At Lamberton, the dominant soils are Normania and Ves clay loams with about 4.5 percent organic matter and 30 percent clay. Nitrate losses to surface water via subsurface tile drainage is a concern at both sites. Annual rainfall is about 34 inches at Waseca and 28 inches at Lamberton. About 75 percent of the annual tile drainage occurs during April, May, and June. Soils at all three sites are usually frozen from early December through late March.

Corn and soybean production was optimized at all sites with early planting, a seeding rate of 30,000 to 34,000 corn seeds/acre, appropriate tillage depending on cropping system and soil, perfect control of weeds, and adequate control of insects. A 30-inch row spacing was used for both crops.

Results

Cropping Systems

From an environmental perspective, the cropping system grown has a huge effect on the amount of nitrate lost from the agricultural landscape to ground and surface waters. A four-year study conducted at Lamberton showed significantly more tile drainage and higher nitrate-N concentration in the drainage water from row-crop systems (corn and soybean) compared to the perennial systems (alfalfa and CRP grasses) (Table 1). Nitrate-N losses in the drainage water were 30-50 times greater for the corn and soybean cropping systems compared to the perennial crops even though BMPs such as a spring 0-4-foot nitrate soil test and sidedress applications were used. These data clearly indicate the corn-soybean system to be very leaky with respect to nitrate, suggesting a suite of BMPs for N will need to be implemented if nitrate losses from this dominant cropping system are to be reduced significantly.

Table 1. Effect of cropping system on drainage volume, average flow-weighted nitrate-N concentration, and nitrate-N losses in subsurface tile drainage during a four-year period (1990-1993) at Lamberton, Minnesota.

Cropping system	Total discharge	Nitrate-N Concentration	Nitrate-N Loss
	Inches	mg/L	lb./acre
Continuous Corn	30.4	28	194
Corn-Soybean	35.5	23	182
Soybean-Corn	35.4	22	180
Alfalfa	16.4	1.6	6
CRP grasses	25.2	0.7	4

Rate of N application

Rate of N application is generally the N management practice having the greatest effect on profitability and magnitude of N loss. This is especially true when credits for manure applied the last two years or previous legume crops are not taken. The data in Table 2 show how the economic return to N fertilizer improved as the optimum N rate was reached, (The Economic Optimum N Rate, (EONR) was 148 lb. N/acre at this site.) and then declined with N rates the above the EONR. Residual soil nitrate (RSN) in the profile after harvest, which has a high potential for being leached below the rooting depth and into the shallow groundwater aquifers before uptake by the next year's crop, increased very slowly with increasing N rate until nearly reaching the optimum N rate. At this point, RSN increased rapidly as the rate of fertilizer N applied exceeded the amount of N taken up by the corn. In summary, these four-year data clearly show the relationship between rate of N fertilizer applied and the economic return to fertilizer as well as the potential for large amounts of nitrate to be leached to the groundwater when excess N rates are applied.

Table 2. Effect of N rate on continuous corn production (yield, N recovery, and economics) and residual nitrate-N in the soil profile after harvest in Olmsted County, Minnesota.

Annual N rate	Four-year average yield	Apparent[1/] N recovery	Economic return[2/] to N fertilizer	Residual NO_3-N in 0-7-foot soil profile, Oct. '03
lb./acre	bu./acre	Percent	$/acre/year	lb./acre
0	67.3	--	--	23
60	129.8	68	110	38
90	148.4	63	140	52
120	162.5	60	160	62
150	168.1	54	164	158
180	168.4	46	157	173

[1/] Three-year (2001-2003) data, 2004 not complete.
[2/] Based on $2.00 per bushel and $0.25/lb. N.

Nitrogen rates applied as anhydrous ammonia (AA) in late October with N-Serve were compared to a spring preplant N rate for a corn-soybean rotation on a tile drainage facility at Waseca. Data for corn from 2000-2002 shown in Table 3 indicate grain yield, apparent N recovery, and net return to fertilizer N were optimized with the spring-applied 120-lb. rate without N-Serve. When N was applied with N-Serve in the fall, a 160-lb. N rate was needed to optimize yield and profitability, but N recovery was much poorer (45 percent vs. 65 percent in spring) and economic return was $27/acre less than the spring 120-lb. rate. Nitrate-N concentrations in the tile water in the corn phase of the rotation are also shown in Table 3. Averaged across the three years, nitrate-N concentrations were decreased 14 percent (2.6 mg/L) when the N application rate was decreased by 40 lbs./acre from the recommended 120-lb. N rate (33 percent reduction to 80 lbs./acre). Applying 160 lbs. N/acre (a 33 percent increase over the recommended 120-lb. N rate) increased nitrate-N concentrations by 4.3 mg/L (23 percent). These results clearly show that nitrate-N concentration in tile drainage water is influenced by N application rate, but the change in nitrate-N concentration is considerably less than the respective change in N application rate. From a risk-benefit basis, a 40-lb. N rate reduction (33 percent) resulted in a tremendous loss in profitability ($40/acre) for a small (14 percent) gain in nitrate-loss reduction. On the other hand, a 40-lb. (33 percent) "over-application" of N in the fall increased profitability somewhat ($8/acre) but also increased nitrate losses by 23 percent.

Table 3. Corn grain yield after soybeans, bushels of corn per pound of fertilizer N, apparent N recovery, net economic return to fertilizer N, and three-year average flow-weighted annual nitrate-N concentration in tile drainage water in the year corn was grown as affected by N fertilizer rates in 2000-2002 at Waseca, Minnesota.

Nitrogen application			Three-year yield avg.		Apparent N recovery[1/]	Net return[2/] to fert. N	Three-year Nitrate-N conc.
Time	Rate	N-Serve					
	lb./acre		bu./acre	bu./lb. N	Percent	$/acre/year	mg/L
--	0	--	106	--	--	--	--
Fall	80	Yes	135	0.36	37	30	15.8
“	120	“	160	0.45	45	70	18.4
“	160	“	169	0.39	45	78	22.7
Spring	120	No	175	0.58	65	105	--

[1/] (Total N uptake - total N uptake in control) ÷ Rate of N application.
[2/] Based on corn = $2.00/bu., fall N = $0.25/lb., spring N = $0.275/lb., N-Serve = $7.50/acre.

Nitrate-N concentrations and losses in the subsurface tile drainage from the plots described above were determined for the soybean phase of the corn-soybean rotation in 2004 (Table 4). Using the University of Minnesota N recommendation of 120 lbs. N/acre for a yield goal of 170 bu./acre corn for comparison purposes, nitrate-N concentrations in the drainage water were reduced 28 percent when the 80-lb. N rate was applied but were increased 64 percent when the 160-lb. rate was applied. Nitrate-N losses were affected similarly. These data indicate: (1) the rate of N applied for corn has a substantial effect on nitrate-N losses in tile drainage in the following year when soybeans are grown and (2) a 40-lb. “over-application” in excess of the recommended rate (120 lbs. N/acre) generates substantially greater nitrate losses compared to reductions in nitrate loss accomplished by a 40-lb. “under-application”.

Table 4. Flow-weighted nitrate-N concentration and loss from the soybean plots for May-September 2004 as affected by N rate applied for corn in 2003 at Waseca.

N application rate	Flow-weighted nitrate-N concentration	Nitrate-N loss
lb. N/acre	mg/L	lb. N/acre
80	9.0	36
120	12.4	52
160	20.4	81

Time of N application and N-Serve

Anhydrous ammonia with and without N-Serve was applied for corn following soybeans in the late fall (October 19-November 6) and compared to a spring preplant application (April 14-May 21) without N-Serve at Waseca from 1987-2001. Long-term soil temperature records at Waseca indicate that the daily average six-inch soil temperature does not reach 50ºF until October 29. Fall application dates in this study were very close to when the average six-inch soil temperature reached and stayed below 50ºF. Grain yields (Table 5) and nitrate-N losses in the tile drainage water (Table 6) were measured to evaluate the treatments. Corn yields in 8 of 15 years (53 percent of the time) were not affected by time of AA application or N-Serve. However, corn yields were significantly greater for fall AA plus N-Serve and/or spring-applied AA compared to fall AA without N-Serve in 7 of 15 years (47 percent of the time). In these seven years, corn yields were increased 15.0 and 27.1 bu./acre by the fall AA plus N-Serve and spring preplant AA treatments, respectively, compared to fall AA without N-Serve. These yield responses generated a net return to fertilizer N and N-Serve of \$22.50/acre/year and \$51.00/acre/year, respectively. For the 15-year period, corn yields averaged 144.5 bu./acre for fall-applied AA, 152.9 bu./acre for fall AA plus N-Serve, and 155.5 bu./acre for spring preplant AA. These 6-8 percent yield responses generating economic returns ranging from \$9.30 to \$18.80/acre/year compared to fall AA without a nitrification inhibitor (N-Serve) clearly shows improved economic return and reduced risk when AA is applied preplant in the spring or when N-Serve is added to a late fall application of AA. N-Serve was least effective in those years when rainfall was excessive in June. By that time, N-Serve applied the previous fall had degraded, and the nitrified AA was susceptible to denitrification and leaching losses.

Table 5. Corn yield response and economic return to time of anhydrous ammonia (AA) application and N-Serve during a 15-year period (1987-2001) at Waseca, Minnesota.

Year[1/]	Fall	Fall + N-Serve	Spring	Statistical[2/] significance
		- - - - - Yield (bu./acre) - - - - -		
1987	179	182	184	NS
1988	91	101	88	NS
1989	133	143	153	*
1990	146	146	142	NS
1991	122	143	151	**
1992	142	144	142	NS
1993	104	114	113	*
1994	162	170	175	**
1995	158	151	144	NS
1996	153	154	154	NS
1997	186	189	180	NS
1998	199	207	195	NS
1999	109	154	187	**
2000	135	139	160	**
2001	149	156	165	*
15-Yr Avg. Yield:	144.5	152.9	155.5	
15-Yr Avg. Economic Return[3/]				
over Fall N:	--	$9.30/A/yr	$18.80/A/yr	
7-Yr Avg. Yield[4/]	130.6	145.6	157.7	
7-Yr Avg. Economic Return[3/, 4/]				
over Fall N:	--	$22.50/A/yr	$51.00/A/yr	

[1/] Nitrogen rate was 135 lbs. N/acre from 1987-1993 and 120 lbs. N/acre from 1994-2001.
[2/] * and ** = significantly different at the 95 percent and 99 percent level of probability, respectively. NS = not significantly different at 90 percemt level.
[3/] Based on corn = $2.00/bu., fall N = $0.25/lb. N, spring N = $0.275/lb. N, and N-Serve = $7.50/acre.
[4/] Only those seven years when a statistically significant yield difference occurred among treatments.

Nitrate-N losses normalized for drainage flow for corn in the year of application and soybean the following year are found in Table 6. Appreciable drainage did not occur from 1987-1989, which were very dry years. Corn in the four cycles (one cycle equals corn plus the next year's soybean) from 1990-1994 received 135 lbs. N/acre while corn in the six cycles from 1994-2000 received 120 lbs. N/acre. Nitrate-N losses were always greatest for fall AA without N-Serve. Over the 10 cycles, adding N-Serve to fall-applied N or applying N in the spring reduced nitrate-N losses by 14 percent and 15 percent, respectively. The higher losses in 1990-1994 were probably due to the dry years that preceded drainage in 1990 and to the higher N rate used.

Similar results were obtained for apparent N recovery. Apparent N recovery by the corn was always lowest for fall AA without N-Serve and was lower in the 1987-1993 period when grain yields and N uptake were lower.

Table 6. Flow-normalized nitrate-N losses to subsurface tile drainage and apparent N recovery in a corn-soybean rotation as influenced by time of N application and N-Serve for corn at Waseca, Minnesota.

	Time of application		
Period, rotation cycles	Fall	Fall + N-Serve	Spring
	- - - - - Nitrate-N loss (lb./acre/inch of drainage)- - - - -		
1990-1994, 4 cycle avg.	3.76	3.11	3.13
1994-2000, 6 cycle avg.	2.84	2.54	2.45
1990-2000, 10 cycle avg.	3.20	2.77	2.72
Reduction compared to Fall N (%):	--	14	15
	- - - - - - - - - - Apparent N recovery (%) - - - - - - - - - -		
1987-1993	31	37	40
1994-1999	47	56	56

Continuous corn yields and economic return to fertilizer N on a well-drained silt loam soil in Olmsted County were optimized at the 150-lb. N rate as AA applied preplant in the spring (Table 7). Four-year average yields for fall-applied N were about 3 bu./acre less, largely due to a 10 bu./acre reduction in 1990. Adding N-Serve to fall N did not improve yield or economic return to fertilizer N. Nitrate-N concentrations in the soil water at a five-foot depth in September, a good indicator for potential leaching of nitrate to the groundwater, was increased as N rate increased and was greatest when N was applied in the fall with N-Serve. These data do not support fall application of N on these loess soils, which are more vulnerable to nitrate leaching than glacial till soils.

Table 7. Continuous corn grain yield and economic return to fertilizer N for the 1987-1990 period and nitrate-N concentration in soil water at five feet in 1990 in Olmsted County, Minnesota.

Nitrogen treatment[1/]				Four-year average		Nitrate-N[3/] conc. in
Tillage	Time	N rate	N-Serve	Grain yield	Economic return [2/] to fertilizer	soil water @ 5'
		lb N/acre		bu./acre	$/A	mg/L
Chisel	--	0	--	83.6	--	1
"	Spring, preplant	75	No	155.5	123	11
"	" "	150	No	172.5	137	29
"	" "	225	No	167.1	105	43
"	Fall	150	No	169.4	134	43
"	"	150	Yes	169.1	126	50
No Till	Spring, preplant	150	No	168.0	128	20

[1/] Applied as anhydrous ammonia (AA).
[2/] Based on corn = $2.00/bu., fall N = $0.25/lb. N, spring N = $0.275/lb. N, and N-Serve = $7.50/acre.
[3/] September 5, 1990.

A three-year (2001-2003) study was conducted at Waseca to determine the efficacy of alternative N application systems compared to fall-applied AA on two conservation tillage systems. Data shown in Table 8 indicate highest three-year average yields and N recoveries with applications of UAN split 20-40 percent at planting and 60-80 percent sidedressed at the V3 to V4 stages. Although no water quality data were obtained in these studies, the yield and N recovery data indicate some attractive and profitable alternative application methods to conventional fall AA.

Table 8. Corn yield and apparent N recovery following soybeans as affected by tillage system and time/method of N application at Waseca for 2001-2003.

Nitrogen Treatment				Tillage System: Spring field cult.		Tillage System: Strip till	
Time	Source	Rate	N-Serve	Yield	N recov.	Yield	N recov.
		lb. N/acre		bu./acre	Percent	bu./acre	Percent
--	--	0	--	122.3	--	111.2	--
Fall	AA	100	Yes	167.0	54	161.3	59
Spring	AA	100	No	164.6	54	167.6	66
Spring	Urea	100	No	167.4	60	166.1	61
Planting[1/] + SD	UAN	20 + 80	No	--	--	170.5	70
"[1/] + SD	"	40 + 60	No	173.7	59	162.8	63
"[2/] + SD	"	40 + 60	No	171.8	68	173.7	74

[1/] Dribbled near the row.
[2/] Broadcast with herbicide (weed and feed).

Nitrogen source

Nitrogen losses to drainage water are often perceived to be greater from livestock manure compared to fertilizer N. A four-year study was established at Waseca to determine the effect of dairy manure and urea applied at equivalent rates of total "available" N on (1) yield and N uptake by corn, and (2) loss of nitrate to subsurface tile drainage water. The liquid dairy manure was applied and incorporated immediately on three plots in early November. Samples were taken and analyzed for ammonium N and total N. "Available" N from the manure was calculated. In the spring, urea was broadcast and incorporated on the other three plots at an N rate equivalent to the calculated total "available" manure N applied the previous fall. Yield data shown in Table 9 indicate a significant yield advantage for the urea treatment across the four-year period. This indicates we may have slightly overestimated "available" N from the manure or that denitrification may have been greater in the manured plots. However, nitrate-N concentrations and losses in the tile drainage were not different between the two N sources. These data suggest that the N leaching potential from fall-applied dairy manure is not different from spring-applied urea when applied at equivalent rates of "available" N.

Table 9. Continuous corn grain yield, flow-weighted annual nitrate-N concentration, and nitrate-N loss in tile drainage water as affected by dairy manure and urea at Waseca, Minnesota.

Year	N source	Total[1/] "available" N	Grain yield	F.W. NO_3-N conc.	NO_3-N loss
		lb. N/acre	bu./acre	mg/L	lb./acre
1994	Urea	140	197	9.5	17
"	Dairy Manure	140	184	9.7	18
1995	Urea	186	156	8.1	12
"	Dairy Manure	186	143	9.0	14
1996	Urea	138	135	10.4	10
"	Dairy Manure	138	116	10.5	11
1997	Urea	200	165	8.3	13
"	Dairy Manure	200	167	5.8	9
4-Yr	Urea	166	164	--	13
Avg.	Dairy Manure	166	153	--	13

[1/] Four-year average = 60 percent of total N applied.

Tillage

The effect of tillage on nitrate loss depends largely on the cropping system, time of year when tile drainage occurs, and whether the soils are frozen during the winter. Corn and soybean systems in the Corn Belt and southern Ontario generally show greater amounts of drain flow for no tillage and other very reduced tillage systems; whereas, nitrate-N concentrations tend to be greater with the more conventional tillage systems. This is illustrated in Table 10 where tile drainage was greater for no tillage, but nitrate-N concentration was greater for moldboard plowing. The amount of nitrate lost was not different between the two tillage systems in this Minnesota study where soils are generally frozen from December through March and 75 percent of the annual drainage occurs in April, May, and June. In the central and southern parts of the Corn Belt, where most drainage occurs in February through May and soils are only frozen for brief periods, fall tillage may stimulate over-winter and spring losses of nitrate, especially following soybeans.

Table 10. Effect of tillage for continuous corn on nitrate-N losses in subsurface drainage at Waseca, Minnesota.[1/]

Parameter	Tillage system	
	Moldboard plow	No till
Drainage volume (inches)	11.0	12.4
Nitrate-N conc. (mg/L)	15	13
Nitrate-N lost (lb./acre)	38	37
N lost as a % of applied N	21	20

[1/] 11-year (1982-1992) average.

Cover crops

Cover crops planted in the fall and killed prior to spring planting have been shown to effectively reduce downward movement of nitrate. This is particularly true in locations with a warmer fall and early spring and where soils are not frozen over a four-month winter period. The success of cover crops to reduce nitrate losses has been much less consistent and successful in the northern regions of the Corn Belt. Data from a three-year study conducted at Lamberton, Minnesota show a slight reduction in drainage (11 percent) and nitrate-N loss (13 percent) compared with cropping systems with no cover crop (Table 11). Based on these data and long-term weather records, the authors suggest that winter rye will be a successful cover crop for reducing nitrate losses in one of four years at this location. Some of this relatively low success rate is due to years with low leaching potential, while the remainder is due to climatic conditions contributing to inadequate rye establishment and growth.

Table 11. Annual tile drainage discharge and nitrate-N losses as affected by a rye cover crop planted following corn harvest during 1999-2001 at Lamberton, Minnesota. (Adapted from Strock et al., J. Environ. Qual. 33:1010-1016. 2004.)

Annual crop phase	Drainage	Nitrate-N loss
	inches/year	lb./acre/year
Corn	8.6ab[1/]	21b.[1/]
Soybean	9.1a	27a
Corn and rye	7.8b	20b
Rye and soybean	8.0b	21b.

[1/] Values within a column followed by the same letter are not statistically different at the 10 percent probability level.

Summary

The corn-soybean rotation that dominates the Corn Belt is a leaky system with respect to N. Thus, N management practices will need to be implemented across the Corn Belt to optimize crop production, N efficiency, and N recovery and minimize N losses to water resources. Best management practices (BMPs) such as a combination of proper N rate (including N credits from previous crops and manure), spring and split application, nitrification inhibitors, reduced fall tillage, and cover crops where applicable will increase profit and N efficiency and reduce nitrate losses to ground and surface waters, but will require a higher level of management by the grower. Landscape treatment methods such as constructed wetlands, improved drainage management (depth, spacing, controlled drainage), etc., will be helpful in strategic locations to reduce nitrate loss to surface water. In addition, N source reduction through lower application rates or alternative cropping systems may be necessary to meet future goals of society.