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Nitrogen Application Timing, Forms, and Additives

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Wet, poorly drained soils throughout North America and Europe are often artificially drained with subsurface tile systems to remove excess (gravitational) water from the upper 1 to 1.2 m soil profile. Improved crop production that often results from drainage is in large part due to better physical conditions for field operations and a deeper unrestricted root zone for greater crop rooting, nutrient uptake, and yields. Removal of excess water by drainage lessens the potential for anaerobic conditions and consequently reduces the potential for nitrate to be lost from the soil profile by the process of denitrification. The combination of greater soil organic matter N mineralization with increased aerobic soil conditions, less N lost via denitrification, and increased transport of subsurface water results in higher nitrate concentrations in the receiving surface water bodies. Watersheds containing similar production systems and soils without subsurface drainage generate lower nitrate concentrations because anaerobic conditions exist more frequently. Under anaerobic conditions, denitrification predominates, resulting in nitrate losses as N gas to the atmosphere as well as economic losses to the farmer because of reduced available N.

Factors influencing nitrate content in subsurface waters draining from agricultural production landscapes can be divided into two categories: noncontrollable and controllable. Precipitation, including variation in annual amount, temporal distribution within a year, and extreme daily events, provides noncontrollable factors that have the greatest impact on nitrate loss. Controllable factors are those management practices that crop producers use to improve the yield and profitability of their enterprise. Time of N application, N fertilizer product, and nitrification inhibitors play a significant role in minimizing nitrate loss, especially under wetter and warmer fall, winter, and spring conditions (Dinnes et al., 2002).

Time of N Application

Agronomically and environmentally, spring applications are frequently superior to fall application because less loss of N occurs in the time between application and N uptake by the crop. However, many U.S. corn growers, especially in the northern part of the Corn Belt, desire to apply N in the fall because they usually have more available time and field conditions are more suitable for application. Early planting of corn as soon as the soils are tillable in the spring is desirable for highest yields and profit. Consequently, if a farmer wishes to separate spring N fertilizer application from preemergence herbicide application, the window of opportunity for spring N application

Table 6-1. Effect of N rate and time of application on nitrate-N losses to subsurface drainage and corn yield in Minnesota (adapted from Randall and Mulla, 2001).

N[a]		Annual Loss of Nitrate-N in Drainage (lb N ac^{-1} year^{-1})	Five-Year Yield Average	
Rate (lb ac^{-1})	Time		Yield (bu ac^{-1})	Net Return ($ ac^{-1})
0	0	7	66	--
120	Fall	27	131	100
120	Spring	19	150	135
180	Fall	34	160	143
180	Spring	26	168	154

[a] Ammonium sulfate applied to continuous corn about 1 November or 1 May.

becomes very narrow (Randall and Schmitt, 1998). Risk of soil compaction and extended periods of rainy weather can also be deterrents to spring application of N.

In an extensive review of N application timing, Bundy (1986) concluded that fall N application is an acceptable option on medium to fine-textured soils where winter temperatures retard nitrification. However, under these conditions, fall-applied N is usually 10% to 15% less effective than spring-applied N. A recent Iowa study (Kyveryga et al., 2004) reported more rapid nitrification of fall-applied anhydrous ammonia in soils with pH >7.5, which influenced the amount of nitrate lost by denitrification or leaching during spring rainfall. They suggested that economic and environmental benefits of delaying application of fertilizer N may be greater on high pH soils than in lower pH soils. In Europe, N applied in autumn, either as mineral fertilizer (Goss et al., 1993) or as animal manure (Thompson et al., 1987) is very vulnerable to leaching in the winter.

Nitrogen was applied as ammonium sulfate in the fall (early November) and spring (late April) for continuous corn to determine the effect of N application time and rate on nitrate losses to subsurface drainage and corn yields on a Canisteo clay loam, glacial till soil in Minnesota (Randall and Mulla, 2001). Over the five-year study period, corn yields from the late fall application averaged 8% lower (146 vs. 159 bu ac^{-1} year^{-1}) than with spring application (table 6-1). Moreover, annual losses of nitrate-N in the tile drainage water averaged 36% higher (30 vs. 22 lb ac^{-1} year^{-1}) with fall application compared to spring application. It is interesting to note that less nitrate was lost in the drainage water for the 180 lb spring-applied treatment than for the 120 lb fall-applied treatment; yet greater yields (37 bu ac^{-1}) and net return ($54 ac^{-1}) were obtained for the spring treatment.

A long-term corn-soybean rotation study comparing late-October application of ammonia with and without N-Serve, and a spring preplant application without N-Serve showed distinct yield, economic, and environmental advantages for spring application, but not in all years (table 6-2). Across the 15-year period, corn yields averaged about 10 bu ac^{-1} greater for the fall N + N-Serve (nitrapyrin) and spring N treatments compared with fall N without N-Serve (Randall et al., 2003b; Randall and Vetsch, 2005b). In addition, compared with fall application of N without N-Serve, nitrate-N losses in the drainage water were reduced by 14% and 15% (Randall et al., 2003a; Randall and Vetsch, 2005a), economic return to N was increased by $9 and $19 ac^{-1}, and N recovery in the grain was increased by 8% and 9% for fall N + N-Serve and spring N, respectively. However, corn yields were significantly affected by the N treatments in only seven of 15 years. In those seven years, when April, May, and/or June were wetter than normal, average corn grain yield was increased by 15 and 27 bu ac^{-1} and average economic return was increased by \$22.50 and \$51.00 ac^{-1} for the fall N + N-Serve and spring N treatments, respectively. In summary, the 15-year data suggest that applications of ammonia in the late fall + N-Serve or in the spring preplant were better management practices. However, when spring conditions were wet, especially in May and June, spring application gave substantially greater yield and profit than the fall N + N-Serve treatment. Therefore, fall N + N-Serve application is considered to be economically more risky than a spring preplant application of ammonia.

Anhydrous ammonia applied at 110 lb N ac^{-1} without N-Serve in late October after soybean harvest was compared with ammonia applied midway between the rows in late April across four different tillage systems (no-till, strip-till, spring field cultivate, and chisel plow plus field cultivate) in 1997-1999 (Vetsch and Randall, 2004). Yields were not different between fall and spring-applied N in 1997 or 1998 (table 6-3). The effect of wet spring conditions was evident in 1999 when corn yields were 36 bu ac^{-1} lower for fall-applied N. An interaction between tillage system and time/placement of N was not found, indicating that the effect of fall vs. spring application was the same for all tillage systems in each year.

A four-year (2000-2003) study conducted on Nicollet, Webster, and Canisteo soils in Iowa found NO_3-N concentrations in subsurface drainage from a corn-soybean rotation to not be different between fall and spring application of aqua ammonia, either with or without N-Serve, under slightly dry to normal precipitation conditions (Lawlor et al., 2004) (table 6-4). Although timing and method of N application may be important, the authors concluded that applying the correct amount of N was perhaps the most important factor.

Split application of N should theoretically result in increased N efficiency and reduced nitrate losses because of greater synchronization between time of application and crop uptake. However, evidence in the literature to support this concept is mixed. Baker and Melvin (1994) reported losses of nitrate-N to be higher for split application compared to a spring preplant application with continuous corn. Losses with split application for the corn-soybean rotation were lower in the year of application but tended to be higher in the subsequent year when soybean followed corn. In another Iowa study, Bjorneberg et al. (1998) concluded that combining a split N fertilizer management strategy based on the pre-sidedress nitrate soil test (PSNT) with no-tillage practices can have positive environmental benefits without reducing corn yields in a corn-soybean rotation. Jaynes et al. (2004) reported nitrate reductions of 30% in drainage water in the last two years of a four-year Iowa study when the in-season N rate of a split-application strategy was determined by the late spring nitrate test (LSNT); however, the four-year average corn yield was slightly lower (3%) but not statistically different for the LSNT-based N rate compared to the non-limiting N rate (200 lb N ac^{-1}).

A split application of ammonia with 40% applied preplant (55 lb N ac^{-1}) and 60% applied sidedress (80 lb N ac^{-1}) at the V8 corn growth stage was compared with late October and spring preplant applications of ammonia (135 lb N ac^{-1}) (table 6-5). In

Table 6-2. Corn yield and economic return to N program as affected by time of anhydrous ammonia application and N-Serve at Waseca, 1987-2001 (adapted from Randall and Vetsch, 2005a, 2005b and Randall et al., 2003a, 2003b).[a]

	Time of Application		
Parameter	Fall	Fall + N-Serve	Spring
15-year avg. yield (bu ac^{-1})	144	153	156
15-year avg. economic return over fall N ($ ac^{-1} $year^{-1}$)[b]	--	$9.30	$18.80
7-year avg. yield (bu ac^{-1})[c]	131	146	158
7-year avg. economic return over fall N ($ ac^{-1} $year^{-1}$)[b]	--	$22.50	$51.00
15-year flow-weighted NO_3-N concentration in tile drainage from the corn-soybean rotation (mg L^{-1})	14.1	12.2	12.0
15-year N recovery in the corn grain (%)[d]	38	46	47

[a] Rate of N was 135 lb ac^{-1} $year^{-1}$ for 1987-1993 and 120 lb N ac^{-1} $year^{-1}$ for 1994-2001.

[b] Based on corn = $2.00 bu^{-1}, fall N = $0.25 lb^{-1} N, spring N = $0.275 lb^{-1} N, and N-Serve = $7.50 ac^{-1}.

[c] Only those seven years when a statistically significant yield difference occurred among treatments.

[d] N recovery = (N content in grain - N content in grain from 0 lb check) / fertilizer N rate.

Table 6-3. Corn yield as affected by time/placement of anhydrous ammonia at Waseca (adapted from Vetsch and Randall, 2004).

	Yield (bu ac^{-1})		Three-Year
Time/Placement	1997-1998	1999	Average
Fall, near row	188	145	174
Spring, between rows	188	181	186
LSD (0.10):	NS	5	3

Table 6-4. Average annual flow-weighted NO_3-N concentration in subsurface drainage from a corn-soybean rotation in Iowa as affected by time of N application, N-Serve, and N rate (2000-2003) (adapted from Lawlor et al., 2004).

Nitrogen Treatment			Four-Year Average
Time	Rate (lb N ac^{-1})	N-Serve	Flow-Weighted NO_3-N (mg L^{-1})
Fall	150	No	14.2
Fall	150	Yes	16.2
Fall	225	No	18.1
Spring	150	No	15.4
Spring	150	Yes	17.7
Spring	225	No	24.4
		LSD (0.05):	3.0

Table 6-5. Corn production and nitrate loss as affected by time of anhydrous application and N-Serve at Waseca, 1987-1993 (adapted from Randall et al., 2003a, 2003b).

Nitrogen Treatment		Seven-Year Average			Flow-Weighted
Time	N-Serve	Corn Yield (bu ac^{-1})	N Recovery[a] (%)	Economic Return to N[b] ($ ac^{-1})	NO_3-N Concentration in Tile Drainage[c] (mg L^{-1})
Fall	No	131	31	34	16.8
Fall	Yes	139	37	43	13.7
Spring	No	139	40	47	13.7
Split	No	145	44	56	14.6
LSD (0.10):		4			

[a] N recovery = (N content in grain - N content in grain from 0 lb check) / fertilizer N rate.

[b] Based on corn = $2.00 bu^{-1}, fall N = $0.25 lb^{-1}, spring N = $0.275 lb^{-1}, N-Serve = $7.50 ac^{-1}, and application cost = $4.00 ac^{-1} $time^{-1}$.

[c] Across the four-cycle corn (1990-1993) - soybean (1991-1994) rotation.

this seven-year period, grain yields were significantly greater (6 bu ac^{-1}) for the split-applied treatments, resulting in slightly greater N recovery in the grain and economic return to N compared to the fall and spring treatments (Randall et al., 2003b). However, flow-weighted nitrate-N concentration in the tile drainage across the four-cycle corn-soybean rotation (1990-1993) for the split N treatment was also slightly higher than for the spring N and fall N + N-Serve treatments (Randall et al., 2003a). Intuitively, one could rationalize suggesting lower rates of N when split-applied in a manner similar to this study. But to our knowledge, there are no other corn yield data that support the recommendation to reduce N rate below the preplant recommended rate in this production system. Perhaps the difference between an optimal single-application preplant N rate of ammonia and a split application rate is so small that field experiments cannot distinguish yield or water quality differences.

Split application is an N management strategy that will likely gain momentum in the next five to ten years. Growers are looking for combinations of preplant techniques (rates, sources, and placement methods) and sidedress techniques (in-season diagnostic tools to determine optimum N rate, time of application, and placement) that optimize N use efficiency (NUE), improve profitability, and minimize N losses. Localized placement of some N near the seed at planting has stimulated greater early corn growth and has resulted in positive yield responses, particularly in research conducted in very reduced tillage systems. Others are looking for the ideal proportion of preplant N vs. sidedress N to both optimize return on investment and/or to facilitate in-season diagnostic methods to determine optimum sidedress N rates. Remote sensing techniques, perhaps in conjunction with other diagnostic tools and/or climate models, may provide the necessary information to fine-tune in-season application techniques. These techniques would guide the application of spatially variable rates of N throughout the field and could help determine the optimum application window for sidedress application. At this time, these technologies appear to be much more feasible and dependable under irrigated conditions because the N can be applied with the irrigation water and moved down into the active root zone for quick uptake. Given the complex interactions between soils, weather, cropping systems, N sources, application equipment, etc., that affect the outcomes, research will continue to address these questions in an effort to determine those strategies with the greatest potential for providing economic and environmental success.

As the literature clearly indicates, however, sidedressing N does not necessarily reduce nitrate losses to drainage water. Nitrate losses in the drainage water are generally lower in the year of sidedress application unless fall rainfall is excessive, but due to greater potential carryover in the soil, nitrate tends to leach from the profile the following spring when precipitation exceeds evapotranspiration (ET) and soils are saturated. However, if the preplant or planting time N rate can be optimized in combination with applying a more precise sidedress rate, determined by in-season diagnostic methods, the total rate applied using this split N strategy should optimize NUE and profitability and may reduce nitrate losses below those found with current split-application strategies.

To estimate the extent of fall-applied N in the Corn Belt, state extension soil fertility specialists and state fertilizer associations were contacted to solicit estimates of the percent of each state's annual fertilizer N amount that is applied in the fall. The estimates are: Illinois = 25% to 30%, Indiana = 5% to 10%, Iowa = 25% to 30%, Michigan = <5%, Minnesota = 60% to 65%, Missouri = 15% to 20%, Ohio <5%, and Wisconsin = 10%. Total corn acreage in 2005 for these states was 12.1, 5.9, 12.8, 2.2, 7.3, 3.1, 3.4, and 3.8 million acres, respectively (NASS, 2005). Based on these data, an estimated 25% (12.9 million acres) of the 50.6 million acres of corn in this eight-state area receives N in the fall. States with the largest amount of fall-applied N are Minnesota (4.56 million acres), Iowa (3.52 million acres), and Illinois (3.28 million acres). Not only are these states major corn producers, they are also major contributors of nitrate to the Mississippi River. Thus, changing N application from the fall to spring or split applications could have a significant impact on nitrate loss in these three states, but may have limited impact in terms of the larger Mississippi River/Gulf of Mexico hypoxia issue.

Nitrification Inhibitors

Nitrification inhibitors are sometimes added to ammonium fertilizers (anhydrous ammonia and urea) to retard or slow the conversion of ammonium to nitrate after fertilizer application. N-Serve has been the most commonly used nitrification inhibitor in the U.S. and has been a component in many N research studies. The length of time that N-Serve remains active in the soil before it degrades largely determines its efficacy. The period of inhibition depends primarily on when N-Serve is applied, soil temperature, and soil pH. In Minnesota, when N-Serve is applied with anhydrous ammonia in late October (soil temperatures at the 6-inch depth average about 50°F and soils are frozen from early December through late March), inhibition activity continues into May. When N-Serve is applied in mid- to late April, inhibition can continue into June. Warm soil temperatures and high-pH soils speed the degradation process, thus shortening the inhibition activity period.

Many studies have shown that nitrification inhibitors, such as N-Serve, are effective in delaying conversion of ammonium to nitrate when N is fall-applied (Hoeft, 1984), but use of nitrification inhibitors with fall-applied N has not given consistent crop yield responses. Bundy (1986) concluded that nitrification inhibitors can improve the effectiveness of fall-applied N, but spring N is more effective than fall N applied with an inhibitor when conditions favoring N loss from fall application develop.

Anhydrous ammonia was applied at a rate of 135 lb N ac^{-1} in four treatments [late fall, late fall + N-Serve, spring preplant, and split (40% preplant + 60% sidedress)] to drainage plots in Minnesota from 1987 through 1993. Subsurface tile drainage did not occur in 1987 through 1989 due to very dry conditions. Flow-weighted nitrate-N concentrations across the four-year corn-soybean rotation flow period (1990-1993) averaged 16.8, 13.7, 13.7, and 14.6 mg L^{-1} for the four treatments, respectively (table 6-5). Yields were increased significantly in the very wet years by the addition of N-Serve to the fall application.

Table 6-6. Corn grain yield as affected by fall and spring application of N-Serve with anhydrous ammonia at Waseca, 1994-1999 (adapted from Randall and Vetsch, 2005b).

	Six-Year Average Yield (bu ac^{-1})	
Time of Application	With N-Serve	Without N-Serve
Fall	161	171
Spring	172	176

A six-year study comparing fall vs. spring application of N-Serve with ammonia (120 lb N ac^{-1}) showed a statistically and economically significant 10 bu ac^{-1} yield response to N-Serve applied in the fall (table 6-6). The 4 bu ac^{-1} yield increase to spring-applied N-Serve was not statistically significant and was considered economically neutral (Randall and Vetsch, 2005b). However, a yield response to spring-applied N-Serve occurred in years when June rainfall was excessive. Because the above data do not suggest a consistently significant and economical response to N-Serve applied in the spring, and because excessive June rainfall cannot be predicted at the time of spring ammonia application, adding N-Serve to spring-applied ammonia is not considered to be an effective practice in Minnesota.

The interaction between time of N application and N-Serve in the above study was significant for nitrate-N concentration in the drainage water in three of six years during the corn phase and in two of six years during the soybean phase. Annual nitrate-N concentrations were reduced 2 to 4 mg L^{-1} when N-Serve was added to fall-applied N but were increased 1 to 3 mg L^{-1} when N-Serve was added to spring-applied N. These increased concentrations of nitrate-N in the drainage water with spring-applied N-Serve are similar to the results with split-applied N (spring + sidedress) shown in table 6-5.

N-Serve added to spring-applied urea for continuous corn in Ohio reduced nitrate losses in drainage water from lysimeters (Owens, 1987). A three-year drainage study in Illinois showed significant differences among fall, spring, and sidedress application of N to corn on tile flow, nitrate-N concentration, and loss in corn and in soybean the following year (R. G. Hoeft, personal communication, 2005). However, the addition of N-Serve to fall-applied N did not affect either nitrate-N concentration or loss in the drainage water or corn yield.

Response to N-Serve appears to be particularly dependent on time of N application. Quesada et al. (2000) reported the agronomic and economic effects of N-Serve applied with ammonia in the spring during a ten-year period in Iowa. Grain yield responses occurred with N-Serve in one year for continuous corn but did not occur for corn in rotation with soybean. The Minnesota data for N-Serve shown in tables 6-2 and 6-4 suggest that applying N-Serve with anhydrous ammonia in late October when soil temperatures are at or below 50°F is economically beneficial on the Canisteo and associated glacial till soils. Corn yields were increased by 9 bu ac^{-1} and net economic return was increased by \$9.30 ac^{-1}. Moreover, NO_3-N losses in tile drainage water were reduced by 14%. These data further suggest that N-Serve applied with ammonia in the spring would not likely be beneficial in reducing nitrate losses to tile drainage or in increasing yields and profitability.

N Source and Time of Application

The N source used must also be considered when selecting the proper time of application. Studies on a Webster clay loam in Minnesota in 1981 and 1982 compared fall application of anhydrous ammonia and urea at 75 and 150 lb N ac^{-1}, with and without N-Serve, to spring application of the same products and N rates. Two-year average second-year corn yields shown in table 6-7 indicate: (1) broadcast and incorporated urea was inferior to anhydrous ammonia when fall-applied, and (2) spring application of urea was superior to fall application. Although no nitrate loss data were collected in this study, it is quite likely that nitrate losses into drainage water from fall-applied urea would be similar to those from fall-applied ammonium sulfate shown in table 6-1.

A subsequent study on Nicollet and Webster glacial till soils in southern Minnesota compared late-October application 100 lb N ac^{-1} of urea (4 in. deep band) and anhydrous ammonia with and without N-Serve to spring preplant urea and anhydrous ammonia. Three-year average yields show advantages for spring application of 33 bu ac^{-1} for urea and 14 bu ac^{-1} for ammonia (table 6-8). Nitrogen recovery in the corn plant ranked: spring ammonia = spring urea > fall ammonia > fall urea. The effect of N-Serve in this study was minimal. Yield responses to the spring treatments were greatest in 1998, when April and May were warm and late May was wet, and in 1999 when the fall of 1998 was warm and April and May of 1999 were very wet. Significant yield differences were not found in 1997 when the fall of 1996 was cold and the spring of 1997 was cool and dry.

Similar findings for fall-applied urea have been observed in a long-term Iowa study (A. P. Mallarino, personal communication, 2005). Corn yields averaged across 17 years

Table 6-7. Corn yield as influenced by N source, time of application, and N-Serve at Waseca, 1981-1982 (unpublished data).

Nitrogen Treatment		Yield (bu ac^{-1})	
Source	N-Serve	Fall Application	Spring Application
None	--	104	
Urea	No	157	164
Urea	Yes	155	167
Anhydrous ammonia	No	162	168
Anhydrous ammonia	Yes	170	173

Table 6-8. Corn yield and N recovery in the whole plant as influenced by time of application and N source at Waseca, 1997-1999 (unpublished data).

Nitrogen Management			Three-Year Average	
			Yield	N Recovery[a]
Time	Source	N-Serve	(bu ac^{-1})	(%)
--	None	--	112	
Fall	Urea	No	152	43
Fall	Urea	Yes	158	47
Fall	Anhydrous ammonia	No	168	60
Fall	Anhydrous ammonia	Yes	170	63
Spring preplant	Urea	No	185	76
Spring preplant	Anhydrous ammonia	No	182	84
		LSD (0.10):	8	

[a] N recovery = (N content in grain - N content in grain from 0 lb check) / fertilizer N rate.

for the 240 lb N rate were 13 bu ac^{-1} greater with urea when applied in the spring compared with the fall. In the last four years, the yield advantage for spring-applied urea was 16 bu ac^{-1}. Moreover, the 160 lb spring rate yielded 10 bu ac^{-1} more than the 240 lb fall rate.

Controlled-release N fertilizers such as ESN produced by Agrium, where a polymer coating on each urea granule controls the release of urea to the surrounding soil matrix, and slow-release N fertilizers have potential for generating greater corn yields and reduced losses of nitrate compared with urea, especially in situations where N loss potential is high (sandy soils, plentiful spring rainfall, fall application, etc.). The authors are not aware of any published research on these new, developing N sources illustrating their effect on corn yields and nitrate losses to drainage water in the Midwest. Because of their potential to increase NUE, research is needed in this area.

Although we have not discussed manure applications in this chapter (see chapter 8), approaches to making application timing decisions should be similar to those with N fertilizers. In general, animal manures with high levels of first-year N availability (i.e., a high ratio of ammonium N to organic N) should be spring-applied for best NUE and lowest potential for nitrate loss. Manures with a greater organic N content and lower first-year N availability can be fall-applied with less potential for crop yield or nitrate loss. Results from a four-year study in Minnesota showed no difference in nitrate losses to subsurface drainage from late fall-applied dairy manure slurry compared with spring-applied urea when applied at the same rate of estimated crop-available N for continuous corn (Randall et al., 2000). Adding N-Serve to manure slurry can be quite expensive (a label rate of 2 qt N-Serve ac^{-1}), and yield results generally have not supported the practice. Manure applied after corn for soybean is not thought to cause increased nitrate losses if the application rate is appropriate (50 bu ac^{-1} soybeans take up about 200 lb N ac^{-1}) and the manure is applied late in the fall or in the spring.

As the U.S. depends on more off-shore produced fertilizer N because of higher U.S. natural gas prices and older, less efficient production facilities, we can expect to see: (1) a shift away from anhydrous ammonia to urea and urea-ammonium nitrate (UAN) solution, and (2) higher prices for N. Because urea and UAN are considered to be agronomically less dependable than ammonia under moderate to high-loss-potential conditions, improved management strategies must be employed to gain greater NUE and profitability with these N sources. This provides opportunities for comprehensive research programs supporting improved N management, particularly on split application of N, controlled/slow release N fertilizers, nitrification inhibitors, remote sensing to assess in-season plant N status for prediction of supplemental N needs, and N-efficient hybrid genetic traits.

Overall Conclusion

This chapter, summarizing much of the published research, clearly shows that best management practices (BMPs) for application timing, N forms, and additives such as N-Serve can reduce nitrate losses to subsurface drainage water. But two questions need to be asked: (1) Will BMPs be quickly and universally implemented, especially in those areas where N losses associated with these practices are most prevalent? And

(2) Is the nitrate reduction with BMPs of significant magnitude to accomplish society's goals? History has indicated that BMP implementation can be slow unless incentive and/or disincentives are offered. The current U.S. Farm Bill does little to encourage adoption of these BMPs. Furthermore, the data suggest that BMPs will not reduce nitrate losses to the level needed/expected on a regional basis, and perhaps not even on a local basis. Thus, in addition to these BMPs, farm policy changes leading to longer crop rotations and diversification involving legumes and perennials (resulting in N source reduction) coupled with landscape modification, i.e., strategically placed wetlands and cover crop establishment, will be needed in the Upper Mississippi River basin to meet society's goals for reducing nitrate losses to water resources.

Interpretation/Extrapolation Summary

Time of N Application

Site conditions: Warm and wet conditions in the spring (April-June) in the northern regions or late fall and spring (March-May) in the central to southern regions are conducive to substantial loss of fall-applied N. Losses by denitrification and/or leaching range from nil under dry conditions to more than 50% under very wet conditions.

Research findings: Spring application of N is superior to fall application in most cases. Under "very limited or no" N loss conditions, differences between fall and spring application are not significant on medium to fine-textured soils. No clear or consistent evidence shows split or sidedress applications to be superior to spring preplant anhydrous ammonia from a water quality or corn yield perspective on medium and fine-textured Corn Belt soils. For UAN, split application (preplant and sidedress) is desirable as it reduces the risk of loss when conditions are wet prior to the V10 corn growth stage. Data showing this are limited, however.

Water quality improvement: Minnesota data suggest an average 15% reduction of leaching loss in drainage water with spring application of ammonia compared to a late-October application when soil temperatures are at or below 50°F. Nitrate losses in drainage water from fall-applied N throughout the Corn Belt could range between nil to 25% depending on time of fall application (early vs. late), fall and winter soil temperatures, and spring rainfall. Benefits of spring and split applications of N would be greatest in Minnesota, Iowa, and Illinois where the extent of fall-applied N is largest.

Cost: On a pound-for-pound product basis, spring-applied N may cost up to \$5 to \$10 ac^{-1} $year^{-1}$ more than fall N. However, spring-applied N rates may be able to be reduced without a yield penalty compared to N rates applied in the fall. With spring application, the N rate should not be adjusted downward to achieve a cost savings if the N rate recommendations are based on calibration data from spring and split applications of N.

Extent of area: We estimate that 25% (12.9 million acres) of the 50.6 million acres of corn in the Corn Belt presently receives fall N. All of those acres could benefit from spring or split applications of N.

Limitations for adoption of spring N: The current mindset or tradition of fall anhydrous ammonia application among growers and suppliers will be slow to change in the absence of incentive or disincentive programs. Supplier infrastructure, although this is currently changing, will cause spring supply and storage issues and will require equipment changes and substantial capital.

Impact on other resources: Incorporation of broadcast urea and UAN to limit volatilization or surface runoff losses could enhance soil erosion (negative impact). Crop yields will likely become less variable, thus reducing the potential for lower yields and profitability (positive impact).

Research needs: Determine the optimum combination of preplant and sidedress N applications for greatest yield, practicability, and economic return, and lowest nitrate losses. Determine whether lower N rates can be used with split-application technologies to maintain yield and reduce nitrate losses below those for preplant N application. Evaluate the role of in-season diagnostic tools on improving the efficacy of sidedress applications and improving N use efficiency. Develop models and decision aids by monitoring in-season climatic factors (daily temperature and precipitation) and characterizing soil properties thoroughly within each of the above research efforts.

Nitrification Inhibitors

Site conditions: Conditions affecting the effectiveness of nitrification inhibitors for reducing nitrate losses are essentially the same as those for "time of application."

Water quality improvement: Minnesota data obtained on calcareous, poorly drained, glacial till soils suggest an average nitrate leaching loss reduction of 14% when N-Serve is used with anhydrous ammonia in late October compared to not using N-Serve in the fall. Leaching losses were not influenced by spring application of N-Serve. Nitrate leaching losses were not affected by fall-applied N-Serve on well drained soils in Minnesota or in the Illinois and Iowa studies.

Cost: Annual cost of \$7.50 ac^{-1} for a reduction of 3.5 lb nitrate-N ac^{-1} (range is 0 to 9 lb nitrate-N ac^{-1}).

Extent of area: Percent of corn acres in the Corn Belt that could benefit from fall N-Serve is maybe 15% at the most, depending on when fall application occurs. This percentage will decline as anhydrous ammonia loses market share. Use of N-Serve with urea and UAN is unlikely.

Limitation for adoption: Barriers include old chemistry and inconsistent, weather-related results, as well as the extra cost. New inhibitors and controlled-release forms of urea are needed that reduce nitrate loss, reliably supply crop-available N, and are inexpensive.

Impact on other resources: Nitrification inhibitors do not affect other resources. Crop yields may be improved if the inhibitor reduces nitrate losses, but yields are not reduced by use of an inhibitor.

Research needs: Evaluate efficacy of new inhibitors and slow-release products for both corn production and environmental purposes.

Source of N

Current situation: Urea and urea-ammonium nitrate solution (UAN) are gaining a greater portion of market share at the expense of anhydrous ammonia. These forms of

N are most suitable for spring and in-season application, thereby facilitating the conversion from fall application to spring application.

Research findings: Urea and UAN are acceptable sources of N for optimum crop production when spring preplant-applied and split-applied. Fall-applied urea has performed poorly.

Water quality improvement: Water quality is generally not affected by fertilizer N source as long as the N is applied using best management practices. However, specific situations involving large rainfall/leaching events shortly after N application could result in greater nitrate losses from UAN than from ammonia or urea due to the nitrate component of UAN.

Cost: Costs among the fertilizer N sources will vary depending on season, dealership, demand, supply, etc. The price difference among sources generally ranges from $0.05 to $0.10 per pound, with UAN being most expensive and anhydrous ammonia the cheapest. However, combining spring UAN application with pre-emergence herbicide application reduces fuel consumption by eliminating one field pass per growing season and can aid in "burndown" herbicide efficacy.

Extent of area: No limitation other than supplier's source inventory.

Limitations for adoptions: Two primary limitations exist. From the supplier's perspective, the distribution system and storage will present significant challenges. Substituting urea and UAN for ammonia will result in a huge volume change. From the grower's and supplier's perspectives, application equipment is a limitation. Distribution infrastructure, storage facilities, and application equipment will need to be purchased, requiring significant additional expense to overcome these limitations.

Impact on other resources: Increased erosion potential associated with the incorporation of urea containing fertilizers. Agrotain, a urease inhibitor, could be added to urea to greatly reduce volatilization of the surface-applied and non-incorporated N, but this would add an extra cost.

Research needs: Evaluate controlled-release and slow-release fertilizers and their impact on the economic and environmental aspects of corn production. Determine the effect of various livestock manures and their rate and time of application on nitrate losses.

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