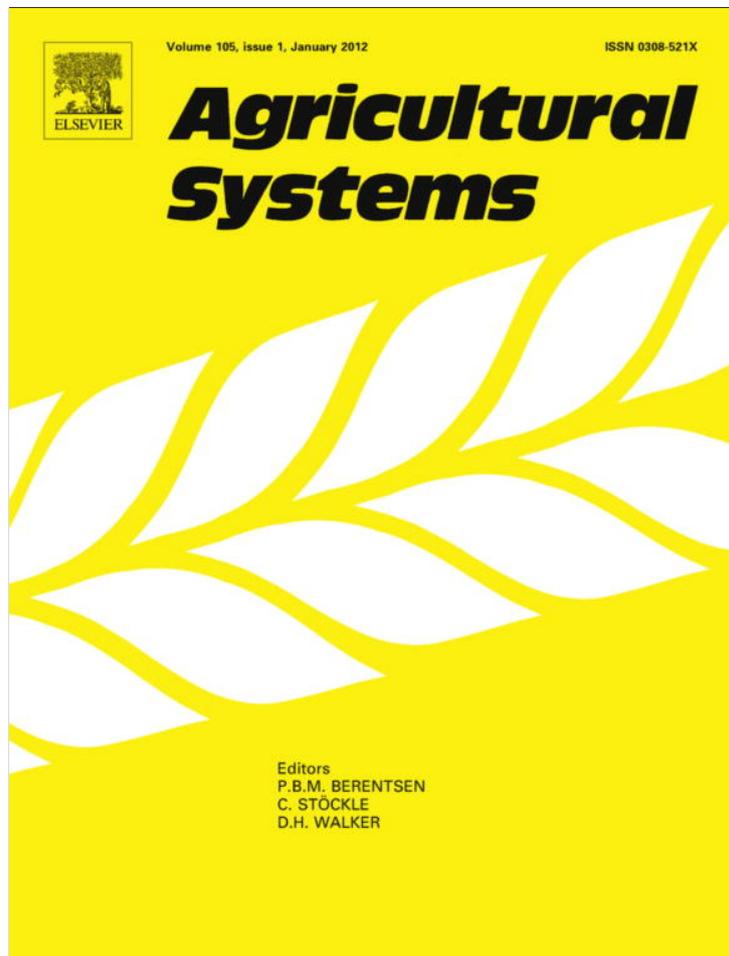


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Survey of nitrogen fertilizer use on corn in Minnesota

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ABSTRACT

A survey was conducted in the spring of 2010 to characterize the use of nitrogen (N) fertilizer on corn (*Zea mays* L.) by Minnesota farmers in the 2009 growing season. Detailed information on synthetic N fertilizer management practices was collected from interviews with 1496 farmers distributed across all of the corn growing regions in the state. The total amount of corn they grew represented 6.8% of the ha of corn harvested in Minnesota in 2009. This report summarizes data on: (1) N fertilizer rates, (2) major N sources (excluding manures), (3) application timing of the major N source, (4) use of nitrification inhibitors, additives, and specialty N fertilizer formulations, (5) fertilizer placement and incorporation practices, (6) use of starter fertilizer, split and sidedress applications, and other N sources such as ammonium phosphates, (7) N fertilization of irrigated corn, and (8) use of soil testing as a fertility management tool. Many of the survey results are reported as statewide averages, but where regional differences occurred the data are broken down and presented separately for different parts of the state. This survey provides the most comprehensive set of data on N fertilizer use on corn that has been collected in Minnesota. The information can be used to target research and education programs to improve N management for both production and environmental goals. The statewide average N fertilizer rate was 157 kg N ha⁻¹. Variable rate application was used to apply N by 23% of farmers. About 59% of surveyed farmers applied the majority of their N fertilizer in the spring before planting, 32.5% made their main N application in the fall, and 9% sidedressed the majority of their N after corn emergence. Most farmers used anhydrous ammonia (46%) or urea (45%) as their major source of N fertilizer, while 6.5% used a liquid N formulation as their primary N source. Soil testing was used as a fertility management tool on 84% of the surveyed fields in the last 5 years. Overall results indicate that N fertilizer use by Minnesota corn farmers is generally consistent with University of Minnesota Extension N management guidelines. Fertilizer N use could probably be improved by taking adequate N credit for previous soybean crops. In the South Central region of the state, fertilizer N recovery could potentially be improved by increased use of nitrification inhibitors with fall-applied anhydrous ammonia or by delaying anhydrous ammonia application until spring.

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1. Introduction

A farmer survey of nitrogen (N) fertilizer use on corn (*Zea mays* L.) in Minnesota was conducted in the spring of 2010 to characterize N fertilizer management in the 2009 growing season. The survey was part of a project with the objectives of developing effective educational tools, decision-support tools, and extension programs to improve N fertilizer management, increase N use efficiency (NUE), and reduce the potential for N losses to air and water. Knowledge of current N management practices is necessary to provide a basis for identifying opportunities to improve NUE, but detailed evaluation of N fertilizer management practices has not previously been undertaken in Minnesota or other areas of the Upper Midwest.

This survey was restricted to N management on corn, because corn is the most widely grown crop in Minnesota that requires N application and the majority of the synthetic N fertilizer applied in the state is used for corn production. The National Agricultural Statistics Service (NASS) of the United States Department of Agriculture (USDA) has reported average N fertilizer rates applied to corn in Minnesota and other states, although their last report was for the 2005 crop year (NASS, 2006). In 2005, the average rate of N fertilizer applied to corn in Minnesota was 156 kg N ha⁻¹. Average rates in nearby corn belt states were 158 kg N ha⁻¹ in Iowa, 120 kg N ha⁻¹ in Wisconsin, 164 kg N ha⁻¹ in Illinois, and 165 kg N ha⁻¹ in Indiana. For the 5-year period 1999 to 2003, the average N fertilizer rate for corn in Minnesota ranged from 120 to 137 kg N ha⁻¹ with a 5-year overall average of 130 kg N ha⁻¹ (NASS, 2000–2004). Comparable data for nearby corn belt states were: overall average of 143 kg N ha⁻¹ with a range of 137–149 kg N ha⁻¹ in Iowa, overall average of 106 kg N ha⁻¹ with a

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range of 96–120 kg N ha⁻¹ in Wisconsin, overall average of 178 kg N ha⁻¹ with a range of 174–180 kg N ha⁻¹ in Illinois, and overall average of 170 kg N ha⁻¹ with a range of 166–172 kg N ha⁻¹ in Indiana. The surveys by NASS included fields where both manure and commercial N fertilizer were applied, which probably reduced average N rates compared with a survey that excluded manured fields. This was probably an important factor in the lower N fertilizer rates reported for Wisconsin. Wisconsin has a large dairy industry and manure is a major N source for corn on these farms.

More recent data on N fertilizer rates and sources of data on other aspects of N fertilizer management on corn are not available. Therefore, this N-use survey was designed to collect current information on N management practices in Minnesota with respect to: (1) application rates (kg N ha⁻¹), (2) application timing (fall or spring, single or multiple applications), (3) application method (surface or subsurface), and (4) chemical form of the applied N. Project personnel collaborated with the Minnesota Department of Agriculture (MDA) to develop survey questions and MDA worked with the Minnesota Field Office of NASS to conduct the survey.

The survey was for the 2009 growing season. Survey results were compared with University of Minnesota Extension guidelines for N fertilizer rates on corn (Rehm et al., 2006) and other best management practices (BMPs) for N fertilizer use (Lamb et al., 2008; Randall et al., 2008a,b; Rehm et al., 2008a,b; Sims et al., 2008). This information was used to identify areas where N management and fertilizer N use could be improved and the environmental risks of N movement to air and water reduced.

2. Survey methods

Farmers in the survey were from a database of the Minnesota Field Office of NASS. An initial pool of 7000 farmers was randomly selected by NASS from their database of about 31,000 Minnesota farmers who have recently grown corn. The survey was carried out through phone interviews conducted at the North Dakota Field Office of NASS in Fargo. Interview staff were the same experienced interviewers that are routinely used to perform the regular surveys conducted by NASS. The survey consisted of 42 questions and it took about one-half hour to complete the interview with farmers who were able to finish the entire survey. Interviews and follow-up calls necessary to clarify some of the responses were conducted between February and June of 2010.

Interviewers were able to contact 4461 of the initial pool of 7000 farmers. Those not contacted were called more than once, but failed to answer the phone. Of the farmers contacted, 3358 grew corn in 2009. The 2769 farmers who continued the interview grew corn on 265,806 ha in 2009. Manure had been applied to 32% of these ha in the previous 5 years. The focus of the survey was use of manufactured N fertilizers, so to avoid the complicating effects of previous manure application on N fertilizer rates the farmers were asked to report on an average field with no manure applied in the last 5 years. The 866 farmers who did not have a field where no manure had been applied in the last 5 years were eliminated. Also eliminated were 407 of the remaining farmers who did not have a field where they knew the total amount of N fertilizer applied per ha. This left 1496 farmers, who grew corn on 195,539 ha in 2009. The survey results reported below are from this subsample of Minnesota corn farmers.

There were survey participants from 74 of Minnesota's 87 counties and they were distributed across all of the major corn growing regions in the state (Fig. 1). The total corn production of surveyed farmers represents about 6.8% of the 2.9 million ha of corn harvested in Minnesota in 2009 (NASS Minnesota Field Office, 2010).

The number of ha of corn grown on surveyed farms was different than the distribution of corn production reported for all Minnesota farms growing corn in 2007 (Table 1). About 44% of surveyed farms grew more than 100 ha of corn, compared with 31% of all Minnesota corn farms in the 2007 Census of Agriculture (NASS, 2009). This suggests that surveyed farms were slightly larger than the statewide average, although some of the difference could have been due to increases in farm size between 2007 and 2009.

Before interviewers began asking the series of questions on specific aspects of N fertilizer use, they instructed farmers to “think about an average corn field you planted in 2009 with no manure or compost applied in the last 5 years” and to answer questions in relation to that specific field. If fertilizer was applied at more than one rate or at a variable rate in this field, they were asked to report a field average rate. Therefore, responses of individual farmers in this survey represent their “average” or “typical” N management practices. In some cases farmers may have strayed from the “average field” restriction, especially as the interview progressed, and some of their answers may have reflected the entire range of the N management options they employed.

All data in this report are expressed as averages among the participating farmers for the individual fields on which they are reporting. They are averages among these fields and data are not adjusted to account for differences in field size. Data analysis also does not reflect differences among the farmers in the total number of ha of corn grown. Averaging on a field basis rather than adjusting for field size or total ha of corn grown was deemed appropriate due to the large sample size, the variation in average field size among different regions of the state, and the fact that farmers were asked to respond based on an average field rather than the whole farm. Data from NASS surveys are frequently reported as averages among surveyed fields (NASS, 2000–2004, 2006).

Many of the survey results are reported as statewide averages, but where regional differences occurred the data are broken down and presented separately for different parts of the state. For this purpose, the state was divided into the regions defined in the pub-

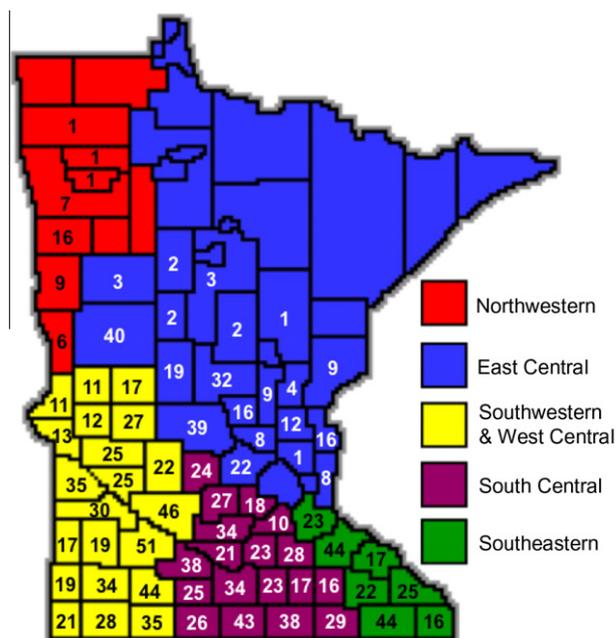


Fig. 1. Statewide distribution by county of farmers participating in the survey of nitrogen fertilizer use on corn in the 2009 growing season and division of the state into regions for nitrogen best management practices.

Table 1

Number of hectares of corn grown on surveyed farms in 2009 compared with the distribution of corn hectares on all Minnesota farms growing corn in 2007.

Hectares of corn grown	Surveyed farms (% of total)	All MN farms ^a (% of total)
1–10	5.0	12.5
11–40	20.1	30.1
41–100	30.5	27.1
101–200	24.1	17.0
201–400	14.2	9.5
401 or more	6.1	4.1

^a 2007 Census of agriculture (NASS, 2009). Percentages sum to 100.3% because of rounding.

lication *Best Management Practices for Nitrogen Use in Minnesota* (Lamb et al., 2008). There are five BMP regions: (1) Northwestern, (2) East Central, (3) Southwestern and West Central, (4) South Central, and (5) Southeastern. The regions are mapped in Fig. 1. The original publication used the term “Irrigated and Non-irrigated Sandy Soils” for one of the regions, which is changed to “East Central” in this report.

The division of the state into BMP regions is based on geographic differences in soil parent material and climate (precipitation and temperature). These factors are important because of their effects on water movement in the soil, chemical and biological transformations of N, and therefore the potential for N transport and loss. Soil parent materials affect drainage characteristics of the soils formed in them. Precipitation and temperature combine to determine the amount of water in the soil and the rate of chemical and biological reactions.

Soils in the Northwestern region primarily developed in lacustrine parent material and are poorly drained. This region has the lowest normal annual precipitation, ranging from 455 to 635 mm, and mean annual temperatures range from 1.7 to 5.0 °C. Many soils in the East Central region formed in glacial outwash, so they are often coarse-textured and excessively well-drained. Normal annual precipitation across the region is 560–800 mm and mean annual temperature is 1.7–7.2 °C, which are the widest ranges of any region. Soils in this region are not uniformly coarse-textured and the area also includes some soils formed in glacial till that are not excessively drained. In the Southwestern and West Central region, soils formed in glacial till parent material or loess deposited over glacial till and they are generally poorly drained. Normal annual precipitation ranges from 560 to 740 mm and mean annual temperatures from 5.0 to 7.2 °C. Most soils in the South Central region also formed in glacial till and are poorly drained. Normal annual precipitation across this region is 660–840 mm and mean annual temperatures are 5.6–7.2 °C. Soils in the Southeastern region formed in loess parent material over fractured limestone and have very good internal drainage. This region has the highest precipitation and temperatures. Normal annual precipitation ranges from 790 to 890 mm and mean annual temperatures from 6.1 to 7.8 °C.

Chi-square analysis was used to evaluate regional differences in major N sources, statewide differences in application timing for the three major N sources, and regional differences in N application timing. Chi-square tests were performed using SAS[®] statistical software (SAS 9.2, SAS Institute, Cary NC, 2002–2008).

3. Results and discussion

The average size of the corn fields reported on by farmers in this survey was 33 ha. The average yield of these fields over the previous three corn crops was 9.98 Mg ha⁻¹ (Table 2).

3.1. Average N rates

The overall average N fertilizer rate for all surveyed fields was 157 kg N ha⁻¹ (standard error = 1.0, 1496 survey responses), but average rates varied across the different BMP regions of the state (Table 2). The lowest N fertilizer rates (mean ± standard error, *n* = number of survey responses) were in the East Central (144 ± 3.3, *n* = 248) and Northwestern (147 ± 7.2, *n* = 41) regions and the highest average N rate was in the South Central region (164 ± 1.4, *n* = 474). Rates in the Southwestern and West Central (156 ± 2.6, *n* = 542) and Southeastern (157 ± 1.4, *n* = 191) regions were similar to the statewide average.

Differences in N rates for the different regions may have been caused by differences in productivity potential. Average yields for the previous three corn crops in the surveyed fields ranged from 7.97 to 10.92 Mg ha⁻¹ across the different BMP regions (Table 2) and there was a strong correlation between previous corn yield and average N rate (*r* = 0.98). The productivity potential of the soil is an important factor in the determination of University of Minnesota Extension N rate guidelines (Rehm et al., 2006). For a crop of corn following corn in a year with an N price to crop value ratio of 0.10, the maximum return to N fertilizer on a highly productive soil would occur at a rate of 157 kg N ha⁻¹. Under the same conditions, the maximum return to N fertilizer on a soil with medium productivity would occur at a rate of 134 kg N ha⁻¹.

The effect of productivity potential on N fertilizer rate is evident in the differences between irrigated and non-irrigated corn fields in the East Central region (Table 2). Average yield for the previous three corn crops was 2.83 Mg ha⁻¹ greater in irrigated fields than in non-irrigated fields and the average N rate was 27 kg N ha⁻¹ greater. About 8.1% of the surveyed corn fields in the East Central region were irrigated.

The amount of N fertilizer applied varied with the preceding crop (Table 3), although differences were not as great as might have been expected. For corn following soybeans (*Glycine max* L.), which accounted for about 75% of all fields in the survey, the statewide average N rate was 157 kg N ha⁻¹. When corn followed corn, the average N rate was 162 kg N ha⁻¹. These results suggest that many farmers did not take full advantage of the N supplying capacity of soybeans. Soybeans are a leguminous crop capable of fixing atmospheric N, and N requirements for corn are commonly about 34 kg N ha⁻¹ lower following a healthy soybean crop (Rehm et al., 2006). Another possibility is that farmers were not as aggressive in choosing N rates for corn following corn as they were for corn following soybeans, and that they may not have applied enough N to corn following a previous corn crop.

Table 2

Average N fertilizer rates applied to corn in 2009 by surveyed farmers reporting on an average field, and average yields of previous corn crops grown in that same field, in different BMP regions of Minnesota.

BMP region	N rate (kg ha ⁻¹)	Previous yield ^a (Mg ha ⁻¹)
Northwestern	147	8.60
East Central	144 ^b	7.97 ^b
Irrigated ^c	169	10.61
Non-irrigated	142	7.78
Southwestern and West Central	156	10.11
South Central	164	10.92
Southeastern	157	10.42
Overall	157	9.98

^a Average yields of the previous three corn crops in the surveyed fields.

^b Average for all fields in the region.

^c 8.1% of the fields in the East Central region were irrigated.

Table 3
Nitrogen fertilizer rates on corn following different crops in 2009 by surveyed farmers reporting on an average field.

Previous crop	N rate (kg ha ⁻¹)	Fields (% of total)
Soybeans	157	74.8
Corn	162	16.8
Corn/alfalfa ^a	144	2.0
Alfalfa	109	2.0
Other	147	4.4
Overall	157	100

^a 2009 was the 2nd year of corn following a previous alfalfa crop.

Alfalfa (*Medicago sativa* L.) is a legume with an even greater capacity to fix N than soybeans and N requirements for corn following alfalfa are frequently less than the average N rates of 109 kg N ha⁻¹ for the first year of corn, and 144 kg N ha⁻¹ for the second year of corn, found in this survey. Following alfalfa crops with good to excellent stands, University of Minnesota guidelines suggest an N credit of 112–168 kg N ha⁻¹ for 1st year corn and 56–84 kg N ha⁻¹ for 2nd year corn (Rehm et al., 2006). This survey included only 30 fields of 1st year corn following alfalfa, and 30 fields of 2nd year corn following alfalfa, so survey results may have been skewed by factors such as a higher than normal number of fields where the alfalfa stand was poor. The methods used to conduct the survey may also have caused N rates for corn following alfalfa to be overestimated. Fields that did not receive any N fertilizer were not included in the survey, so corn following an excellent stand of alfalfa that could supply all of the N needed by the crop (Rehm et al., 2006) would have been excluded. Therefore, no zero N fertilizer fields were used to calculate the average N rate for corn following alfalfa, but it is not known how many fields like this were included in the survey sample.

The average N rate for corn following a crop other than soybeans, corn, or alfalfa was 147 kg N ha⁻¹. The survey did not provide information on what was included in the category “Other”, so it is not clear why the average N rate was lower than for corn following corn or corn following soybeans. It may have resulted from the fact that 63% of the fields where corn followed “Other” crops were in the Northwestern and East Central regions, which had the lowest average N rates (Table 2).

For 23% of farmers the field they reported on was fertilized using variable rate application methods, so the N rate they reported for the survey was an average for the field. When asked whether they applied the same amount of N on all fields with similar crop rotations and no manure applied in the last 5 years, 29% of the farmers reported that they used different N rates on some fields.

The overall average N fertilizer rate of 157 kg N ha⁻¹ found in this survey was similar to the statewide average of 156 kg N ha⁻¹ reported by NASS for the 2005 crop year in their most recent survey of N fertilizer use in Minnesota (NASS, 2006). Both of these rates were greater than the average N rates of 120–137 kg N ha⁻¹ reported by NASS for Minnesota in the 5-year period from 1999 to 2003 (NASS, 2000–2004). The overall average N rate for this period was 130 kg N ha⁻¹. The surveys by NASS did not exclude fields where both manure and commercial N fertilizer were applied, which would probably result in lower average N rates than a survey like the one reported on here where manured fields were excluded. The magnitude of this effect is not clear, because the percentage of fields receiving both manure and commercial N fertilizer in the NASS surveys was not reported.

The data reported above, both from this survey and the NASS surveys, are expressed as averages among the participating farmers for the individual fields they reported on. For comparative purposes, we also calculated average N rates for this survey that were

adjusted to account for differences in field size and differences among farmers in the total number of ha of corn grown. Averaging by field, the average statewide N rate was 157 kg N ha⁻¹ (which is the way we reported it); adjusting by field size, it would be 160 kg N ha⁻¹; and weighting by total ha of corn grown, it would be 165 kg N ha⁻¹. Based on the data collected, larger corn growers tended to apply more N.

3.2. Major N sources

Anhydrous ammonia and urea were the most commonly used chemical forms of N (Fig. 2). About 91% of survey participants used one of these fertilizers to apply the majority of the N used on their average field. Anhydrous ammonia was used by 46.3% of the farmers, while 44.9% used urea. Liquid N products, defined by the survey as UAN (urea–ammonium nitrate) solutions, were the major N source for about 6.5% of the farmers. The remaining 2.4% of the farmers either used another fertilizer as their major N source or did not know the major source of N applied to their typical field. The survey did not ask for additional information on what may have been included in the category “Other” for the major N source.

Relative use of the major N sources varied across the different BMP regions (Fig. 3) and chi-square analysis found significant differences among most of the regions. The Northwestern and East Central regions had similar distributions in use of the major N sources ($p = 0.14$), but both of these regions were significantly different from the other three regions (p -values for the six individual comparisons ranged from <0.01 to 0.03). The Southwestern and West Central, South Central, and Southeastern regions were also all significantly different from each other for their distributions in use of the major N sources (p -values for the three comparisons were all <0.01).

Urea was the dominant N source in the Northwestern (79%) and East Central (67%) regions, where only about 20% of farmers used anhydrous ammonia as their major N source. The greatest use of anhydrous ammonia was in the South Central region (64%), where urea was used as the major N source by about 29% of the farmers. The second highest rate of anhydrous ammonia use was in the Southwestern and West Central region (48%), where nearly as many farmers (43%) used urea as their major N source. In the Southeastern region, 55% of surveyed farmers used urea as their major N source and 35% used anhydrous ammonia. The Southeastern region had the greatest use of liquid N fertilizers with 9% of the farmers using them as their major N source. None of the surveyed farmers in the Northwestern region used liquid N as the major N source on the average field on which they reported.

The three major N sources tended to be applied at different rates, with differences in both the amount of N applied from the major N source and the total N rate after including all N applications

Form of the majority of N fertilizer applied (Statewide)

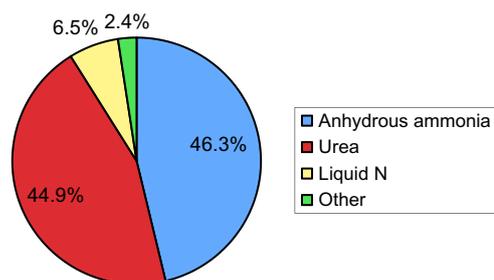


Fig. 2. Chemical form of the majority of the N applied to corn in 2009 by surveyed farmers reporting on an average field.

Form of the majority of N fertilizer applied in different BMP regions

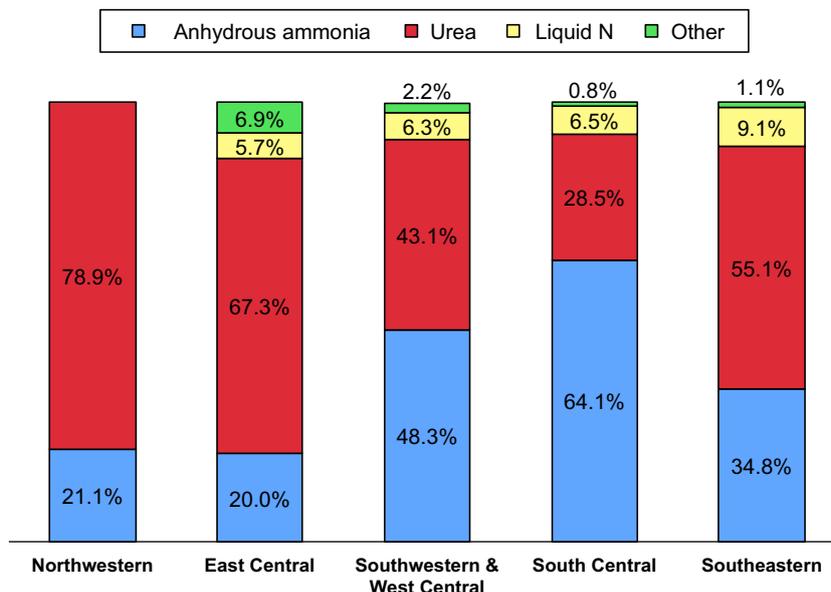


Fig. 3. Chemical form of the majority of the N applied to corn in different BMP regions of the state in 2009 by surveyed farmers reporting on an average field.

Table 4

Differences in N rate among the three major N sources applied to corn in 2009 by surveyed farmers reporting on an average field.

Major N source	N rate from major source (kg ha ⁻¹)	Total N rate (kg ha ⁻¹)
Anhydrous ammonia	148	164
Urea	138	152
Liquid N	127	147

(Table 4). Average N rates (statewide) from the three major sources were 148 kg N ha⁻¹ from anhydrous ammonia, 138 kg N ha⁻¹ from urea, and 127 kg N ha⁻¹ from liquid N. Total N rates were 164 kg N ha⁻¹ when anhydrous ammonia was the major N source, 152 kg N ha⁻¹ when urea was the major N source, and 147 kg N ha⁻¹ when liquid N was the major N source. Differences in N rate were probably affected by differences in the price of N among the three major N sources. The cost per unit of N is highest for liquid N, lowest for anhydrous ammonia, and intermediate for urea. As the price of N goes up, the N rate providing the maximum economic return goes down (Rehm et al., 2006).

Another factor in the greater N rates for anhydrous ammonia compared with urea may have been differences in productivity potential of the fields involved. Average yields for the previous three corn crops were 10.55 Mg ha⁻¹ for the fields fertilized in 2009 with anhydrous ammonia and 9.54 Mg ha⁻¹ for the fields fertilized with urea. Differences in productivity potential were not a factor in the fields fertilized with liquid N having the lowest N rates, since their average yield for the previous three corn crops was 10.17 Mg ha⁻¹.

3.3. Application timing of the major N source

About 59% of the surveyed farmers applied the majority of their N fertilizer in the spring, 32.5% did their main N application in the fall, and about 9% used sidedress (beside the row after plant emergence) applications for the majority of their N (Fig. 4). For sidedress applications, the survey did not ask whether the major N source

Application timing of the major N source (Statewide)

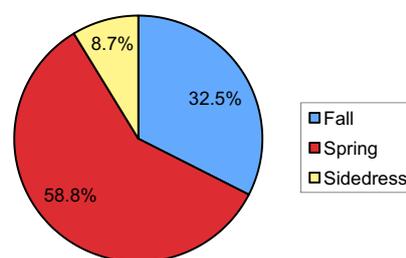


Fig. 4. Application timing for the major source of N applied to corn in 2009 by surveyed farmers reporting on an average field.

was applied in a single application or in a series of split sidedress applications.

Application timing varied considerably, depending on the N source (Fig. 5), and chi-square analysis found significantly different distributions in application timing among the three major N sources (*p*-values for the three individual comparisons were all <0.01). Anhydrous ammonia was applied 63% of the time in the fall and 28% of the time in the spring, whereas urea was applied 90% of the time in the spring and only 4% of the time in the fall. For farmers using liquid N as their major N source, about 71% made spring applications, 23% made sidedress applications, and 7% made fall applications. Part of the N in liquid N fertilizers is in the nitrate form, which is very soluble and susceptible to leaching. For this reason applying liquid N in the fall is not a recommended practice in any part of the state, including the drier western regions where leaching rainfall may be limited (Rehm et al., 2008a; Sims et al., 2008). Eliminating fall application of liquid N fertilizer would increase fertilizer N recovery in most years, although the overall effect would be relatively small since less than 1% of surveyed farmers used this practice for their major N application.

Application timing of the major N source also varied across the different BMP regions of the state (Fig. 6) and chi-square analysis

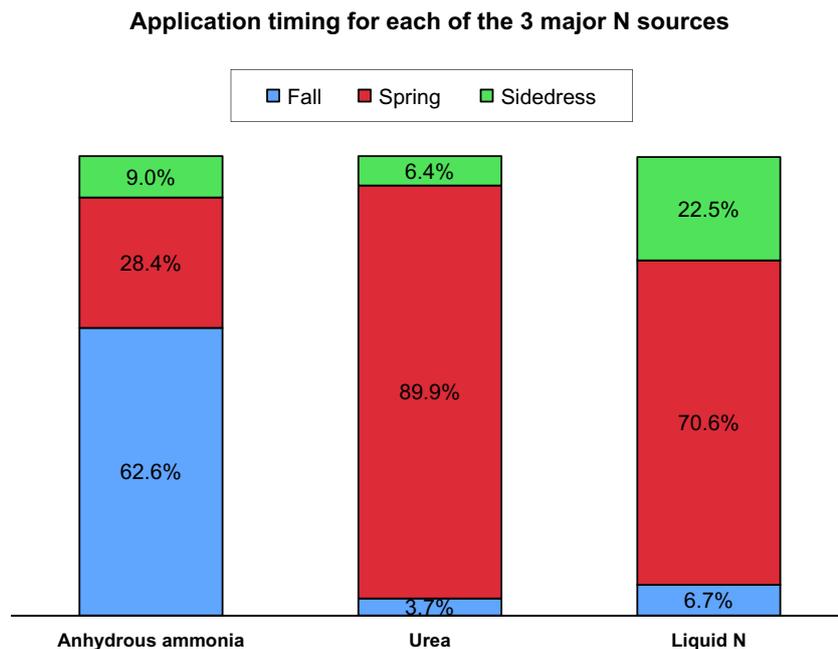


Fig. 5. Application timing for anhydrous ammonia, urea, and liquid N when used as the major source of N applied to corn in 2009 by surveyed farmers reporting on an average field.

found significant differences among most of the regions. Similar distributions in application timing of the major N source were found in the Northwestern and Southeastern regions ($p = 0.12$), and in the South Central and Southwestern and West Central regions ($p = 0.11$), but the other eight individual comparisons between BMP regions found significantly different distributions in application timing of the major N source (p -values were all < 0.01).

Spring N applications dominated in the Northwestern (89%) and Southeastern (88%) regions. Spring was also the most common time to apply N in the East Central region (70%), but sidedressing the major N source was also much more frequent in the East Central region (25%) than in any other region. Sidedressing was not used at all in the Northwestern region and was used by only 4–7% of surveyed farmers in the other three regions. Fall and spring applications were equally common in the Southwestern and West Central region (about 47%). This distribution in application timing was not significantly different from the South Central region, where 43% of surveyed farmers made their major N application in the fall and 53% in the spring.

Application timing is an important criteria differentiating BMPs for N use in various parts of Minnesota. In the East Central and Southeastern regions, which have the highest leaching potential, fall application is not a recommended practice for any of the N sources (Rehm et al., 2008b; Randall et al., 2008b). About 5% of surveyed farmers in both of these regions made their major N application in the fall (Fig. 6), primarily as anhydrous ammonia, so there is some potential for improving N fertilizer recovery and efficiency in these regions by eliminating this practice. This potential may be limited in the East Central region, where some of the fall N was probably applied to finer-textured soils present in the region.

In the South Central region, less than 5% of urea and liquid N applications were in the fall, but 63% of anhydrous ammonia was fall-applied. Fall N application is not a recommended BMP in this region (Randall et al., 2008a), so reducing fall-applied anhydrous ammonia presents a substantial opportunity for improving N management. Fall application of anhydrous ammonia is considered “acceptable, but with greater risk” in the South Central region if it includes a nitrification inhibitor and this practice is discussed in the next section.

3.4. Use of N-Serve® with anhydrous ammonia

N-Serve® (Dow AgroSciences, Indianapolis, Indiana, United States) is a nitrification inhibitor that can be applied with anhydrous ammonia to delay the conversion of ammonium-N to nitrate-N. This can reduce N losses from nitrate leaching (Owens, 1987). Overall, about 20.8% of the farmers applying anhydrous ammonia used N-Serve® (Table 5). The additional cost of applying N-Serve® may be a barrier to more widespread use, but there were important regional differences and differences related to the timing of anhydrous ammonia application.

Use of N-Serve® was most common in the South Central BMP region, where it was included with 35.1% of all anhydrous ammonia applications. It was used with about 15.6% of the anhydrous ammonia applications in the Southeastern region, 15.6% in the East Central region, 6.7% in the Southwestern and West Central region, and 0% in the Northwestern region.

The risk of N loss is greatest with fall application, because of the long time period between N application and crop uptake, and use of N-Serve® was most common in the fall. N-Serve® was included with 28.6% of anhydrous ammonia applications made in the fall, 7.4% of spring applications, and 8.3% of sidedress applications (Table 5). Over 95% of the fall anhydrous ammonia applications were in the South Central or the Southwestern and West Central regions, but there were large differences in the use of N-Serve® between these two regions. N-Serve® was included with 51.1% of fall anhydrous ammonia applications in the South Central region and only 6.6% of fall applications in the Southwestern and West Central region.

The difference in N-Serve® use between the South Central and the Southwestern and West Central regions is consistent with greater rainfall and greater potential for leaching and gaseous N losses in the South Central region. The general pattern is also consistent with University of Minnesota Extension best management practices for N use in those regions (Randall et al., 2008a; Rehm et al., 2008a). However, the fact that 48.9% of fall anhydrous ammonia applications in the South Central region did not include N-Serve® provides an opportunity for improved N management and NUE. In the Southwestern and West Central region, as well

Application timing of the major N source in different BMP regions

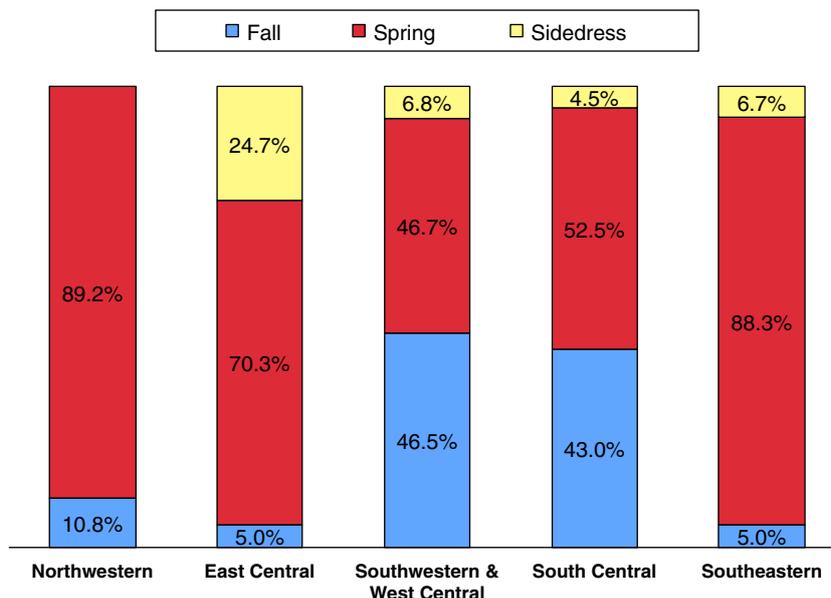


Fig. 6. Application timing for the major source of N applied to corn in different BMP regions of the state in 2009 by surveyed farmers reporting on an average field.

Table 5

Anhydrous ammonia application to corn and use of the nitrification inhibitor N-Serve in 2009 by surveyed farmers reporting on an average field.

AA application time	N-Serve used (%)
Fall	28.6
Spring	7.4
Sidedress	8.3
Overall	20.8

as the Northwestern region (Sims et al., 2008), fall applied anhydrous ammonia without N-Serve[®] is a recommended BMP if application is delayed until soil temperature at the 15-cm depth stabilizes below 10 °C. In the South Central region spring preplant or split applications of N are highly recommended, fall application of anhydrous ammonia + N-Serve[®] (after soil temperature at 15 cm is below 10 °C) is considered “acceptable, but with greater risk”, and fall application of anhydrous ammonia without N-Serve[®] is not recommended. Fall application of anhydrous ammonia is not recommended in the Southeastern region (Randall et al., 2008b) or on the coarse-textured soils in the East Central region (Rehm et al., 2008b), even with N-Serve[®], and few farmers in these regions used this practice.

3.5. Use of additives and specialty formulations of urea or liquid N fertilizers

There are a number of additives and specialty formulations of urea and urea-containing liquid N fertilizers that are designed to reduce N loss. Volatilization losses of ammonia-N can occur after breakdown of urea by the enzyme urease. As with anhydrous ammonia, N losses from nitrate leaching or denitrification can occur after nitrification of ammonia/ammonium-N to nitrate-N. Gaseous N losses can also occur during nitrification itself. Products to delay these reactions and reduce the potential for N losses were used by only 8.3% of the farmers who applied urea or liquid N fer-

tilizers as their major N source (Fig. 7). Agrotain[®] (AGROTAIN International, St. Louis, Missouri, United States), a urease inhibitor that can be combined with dry urea or liquid N fertilizers, was the most commonly used additive; but it was used by only 4.2% of the farmers who applied these fertilizers. Nutrisphere-N[®] (SFP, Leawood, Kansas, United States) contains a water soluble polymer that is intended to protect against N losses from both volatilization and leaching. It can also be combined with both dry urea and liquid N fertilizers, but it was used by only 1.1% of the farmers who applied urea or liquid N fertilizers as their major N source. ESN[®] (Agrium Inc., Calgary, Alberta, Canada) is a slow release form of N where the release of urea is physically delayed by a polymer coating on urea granules that slowly degrades. ESN[®] was used by 1.0% of these farmers. SuperU[®] (AGROTAIN International, St. Louis, Missouri, United States) is a form of urea that contains inhibitors of both urease and nitrification. It was used by 0.3% of the farmers applying this group of N fertilizers as their major N source. “Other” unspecified additives were used by 1.7% of these farmers. Herbicides were probably included in this category. Use of additives and specialty formulations of urea and urea-containing liquid N fertilizers may be limited by the added costs, as well the uncertain effectiveness, of some of these products.

Although their overall use across the state was low, 46% of the farmers who used additives and specialty formulations of urea and urea-containing liquid N fertilizers were in the East Central BMP region of the state. This is logical, since the potential for nitrate leaching is greatest on the coarse-textured soils that dominate this region (Rehm et al., 2008b). In this region, 15% of the farmers who applied urea or liquid N fertilizers as their major N source used an additive or specialty formulation. They used Agrotain 74% of the time, presumably for non-incorporated sidedressed urea to prevent ammonia volatilization as described in the next section.

3.6. Incorporation of urea and liquid N fertilizers

Soil incorporation of urea and urea-containing liquid N fertilizers is an effective method of reducing loss of N through volatilization, although the amount of time urea remains on the surface of

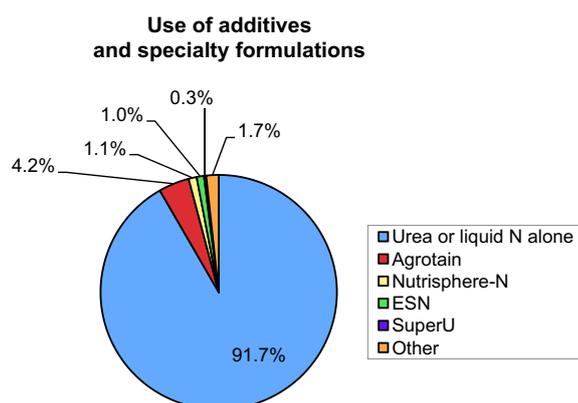


Fig. 7. Use of additives and specialty formulations of urea and liquid N fertilizers applied to corn in 2009 by surveyed farmers reporting on an average field.

the soil is an important factor. The University of Minnesota Extension BMP is to incorporate urea-containing fertilizers within three days or less following application (Randall et al., 2008a,b). About 74% of fall urea applications, 94% of spring applications, and 58% of sidedress applications were incorporated in less than 24 h (Table 6). About 17% of fall applications and 40% of sidedress applications were never incorporated. Some of these may have been on irrigated fields and were watered in.

Because spring was the most common time to apply urea (Fig. 5), about 89% of all urea applications were incorporated within 24 h (Table 6). This varied slightly throughout the state. The 24-h incorporation rate was 100% in the Northwestern BMP region, 94% in the South Central and Southeastern regions, 88% in the Southwestern and West Central region, and 82% in the East Central region. The lower rate in the East Central region may have been affected by the inclusion of irrigated fields where urea was watered in after application.

All fall-applied liquid N and about 95% of spring and sidedress liquid N applications were incorporated in less than 24 h (Table 6). The remaining spring and sidedress applications were incorporated, but incorporation occurred more than 24 h after application.

3.7. Starter fertilizer

Nitrogen was applied in starter fertilizer by 58% of the surveyed farmers. The average starter N rate was 17 kg N ha⁻¹, although this varied with the physical form of the fertilizer applied. Liquid fertilizer was used by 53% of the farmers applying starter at an average N rate of 12 kg N ha⁻¹. The other 47% of the farmers applying starter used a granular fertilizer at an average rate of 22 kg N ha⁻¹.

Table 6
Incorporation practices following application of urea or liquid N as the major N source for corn in 2009 by surveyed farmers reporting on an average field.

Fertilizer application time	Incorporation timing (%)		
	<24 h	>24 h	Not incorporated
<i>Urea</i>			
Fall	74.3	8.6	17.1
Spring	93.8	1.7	4.5
Sidedress	57.5	2.5	40.0
Overall	89.3	2.6	8.2
<i>Liquid N</i>			
Fall	100.0	0.0	0.0
Spring	95.7	4.3	0.0
Sidedress	94.7	5.3	0.0
Overall	95.9	4.1	0.0

Different regions of the state tended to use different forms of starter (Table 7). Liquid starter dominated in the South Central, Southwestern and West Central, and Northwestern regions. Granular starter was more common in the Southeastern and East Central regions. These results are consistent with use of granular starter fertilizers in areas where potassium application is more likely to be needed.

Rates of N applied with liquid starter were lowest in the Northwestern region, but were similar across the rest of the state. Rates of N applied with granular starter tended to be greater in the East Central and the Southwestern and West Central regions than in the South Central and the Southeastern regions.

3.8. Ammonium phosphate

Nitrogen was applied as part of the phosphorus fertilizers monoammonium phosphate (MAP) and diammonium phosphate (DAP) by 57% of the surveyed farmers. The average rate of N applied through MAP or DAP was 25 kg N ha⁻¹. About 65% of these farmers used DAP and 35% used MAP, 55% of the applications were made in the spring and 45% in the fall, and 91% of the applications were incorporated. Spring-applied ammonium phosphate was very likely in starter fertilizer, so there was overlap (double-counting) in the reporting on use of starter fertilizers in Section 3.7 and use of ammonium phosphates applied in the spring in this section.

3.9. Split and sidedress N applications, other N sources

Farmers were also asked if they made other N applications not included in previous questions, such as “split applications, sidedress, or other forms of fertilizer containing N”. About 4% of the farmers made such applications, at an average N rate of 34 kg N ha⁻¹. Seventeen percent of these applications were ammonium nitrate, 33% were ammonium sulfate, 23% were urea or liquid N fertilizers, 17% were unknown N sources, and the remaining 10% were from a variety of other products. These data exclude the 9% of farmers who reported using sidedress applications for their major N source (Fig. 4), some of which may have included a series of split sidedress applications.

3.10. Irrigated corn

The survey included 37 farmers who reported on an average corn field that was irrigated. This was 2.5% of the total number of farmers surveyed. The 2007 Census of Agriculture reported that 4.1% of the Minnesota farms growing corn used irrigation (NASS, 2009). About 54% of the farmers in this survey who grew irrigated corn were in the East Central region, which is dominated by coarse-textured soils. The irrigated corn in other parts of the state was presumably also grown on coarse-textured soils in those re-

Table 7
Differences in the physical form and N rate of starter fertilizer used on corn in different BMP regions of the state in 2009 by surveyed farmers reporting on an average field.

BMP region	Form	Farmers (%)	N rate (kg ha ⁻¹)
Northwestern	Liquid	84.2	8
	Granular	15.8	–
East Central	Liquid	20.5	15
	Granular	79.5	28
Southwestern and West Central	Liquid	79.5	12
	Granular	20.5	22
South Central	Liquid	73.1	12
	Granular	26.9	17
Southeastern	Liquid	35.4	15
	Granular	64.6	18

gions, although this information was not collected in the survey. The number of farmers reporting on irrigated corn in this survey may not have been a large enough sample to draw reliable conclusions about average N management practices on irrigated corn in Minnesota.

The average N rate for irrigated corn was 169 kg N ha⁻¹, which was greater than the overall average rate applied by all surveyed farmers of 157 kg N ha⁻¹. This may have been caused by greater than average productivity potential of the irrigated corn fields included in the survey. Their average yield for the last three corn crops was 10.61 Mg ha⁻¹, compared with the overall survey average of 9.98 Mg ha⁻¹. As previously discussed in Section 3.1, the differences in yield (2.83 Mg ha⁻¹) and N rate (27 kg N ha⁻¹) between irrigated and non-irrigated corn in the East Central region were even larger than these overall averages (Table 2).

Anhydrous ammonia and urea were the most commonly used chemical forms of N on irrigated corn (Fig. 8). Anhydrous ammonia was used as the major N source by 46% of the farmers reporting on irrigated corn and urea was the major N source for 43% of them. These percentages are very similar to the statewide averages for use of these N sources (Fig. 2). Liquid N fertilizers supplied the majority of the N used on about 11% of the irrigated corn fields, which was much greater than their 6.5% rate of use statewide.

Application timing of the major N source was different for irrigated corn (Fig. 9) than the statewide distribution of N timing reported by all surveyed farmers (Fig. 4). The largest difference was for sidedress applications, which supplied the majority of the N fertilizer used by 54% of the farmers reporting on irrigated corn compared with only 9% of all surveyed farmers. There was also a large difference in fall N applications. Less than 3% of the farmers reporting on irrigated corn applied the majority of their N in the fall, compared with 32.5% of all surveyed farmers. Spring applications of the major N source were used by 43% of the farmers reporting on irrigated corn and 59% of all surveyed farmers. On a statewide basis, the timing of N fertilizer application varied considerably depending on the major N source (Fig. 5), but similar variability among N sources in application timing did not occur on irrigated corn. In addition to the 54% of irrigated corn fields where the major N source was sidedressed, about 5% of the irrigated fields received sidedressed N to supplement the application of their major N source in the spring or fall.

Fertigation was used by 19% of the farmers growing irrigated corn, meaning that some of the N was applied through the irrigation water. Irrigated corn that was fertigated received greater overall N rates (183 kg N ha⁻¹) than irrigated corn that was not fertigated (166 kg N ha⁻¹), although it is not clear how much of the extra N was applied through fertigation since none of these farmers reported their fertigation rates. Information was also not obtained on the number of times each of these farmers used fertigation.

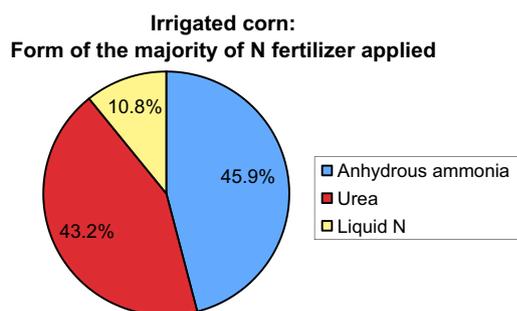


Fig. 8. Chemical form of the majority of the N applied to irrigated corn in 2009 by surveyed farmers reporting on an average field.

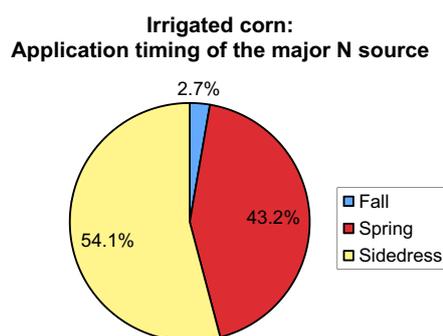


Fig. 9. Application timing for the major source of N applied to irrigated corn in 2009 by surveyed farmers reporting on an average field.

The timing of N fertilizer application on irrigated corn was consistent with University of Minnesota Extension best management practices for N use on coarse-textured soils (Rehm et al., 2008b). Coarse-textured soils have a high potential for N leaching losses, so minimizing the amount of time between N application and crop uptake is a key factor in N management guidelines. Irrigated corn growers reduced the risk of N losses by avoiding fall N applications and applying N when the crop was actively growing through sidedressing and fertigation.

3.11. Soil testing

Soil testing was used as a fertility management tool by most of the farmers in the survey. About 84% of the surveyed fields had been tested in the last 5 years (Table 8). Farmers employed a variety of methods to collect soil samples for testing and many of them had used more than one method on their surveyed field in the last 5 years. More than one-half of the farmers had used traditional, random sampling methods. Almost 31% had used grid or zone sampling methods, which provide a basis for applying variable fertilizer rates within a field.

Use of the nitrate-N soil test was most common in the western part of the state (Table 9). About 60% of the farmers in the Northwestern and the Southwestern and West Central regions used the nitrate test, compared with about 40% of the farmers testing for nitrate-N in the Southeastern, East Central, and South Central regions. These differences are not surprising. The test measures residual nitrate-N in the field after the previous crop and is used to adjust N fertilizer recommendations for the next crop. In the drier western part of the state, leaching of nitrate is less likely to occur and the nitrate test has long been recommended to account for residual N (Rehm et al., 2006). It is also routinely used for sugar beets grown in that part of the state (Lamb et al., 2001). A spring nitrate test was developed more recently for other parts of the state, but it is recommended for a more limited range of conditions (Rehm et al., 2006) and its use by 40% of surveyed farmers outside of western Minnesota was probably greater than expected.

Table 8
Soil sampling methods used in the last 5 years by surveyed farmers reporting on an average field.

Sampling method	Farmers ^a (%)
Traditional	56.8
Grid	20.1
Zone	10.5
None	15.9

^a Total is greater than 100%, because some farmers used more than one method.

Table 9

Use of the soil nitrate test in the last 5 years in different BMP regions of the state by surveyed farmers reporting on an average field.

BMP region	Farmers (%)
Northwestern	65.9
East Central	38.2
Southwestern and West Central	57.7
South Central	41.9
Southeastern	36.6

3.12. Improving future surveys

The category “other” was used to describe some of the responses to survey questions about previous crops and the major N source. Clarifying what was included in that category would be one way to improve the survey. This would probably require interviewers to record the details of responses that did not fit into the major categories for the questions involved. It may be difficult to summarize these responses, but they would be available for evaluation.

Another problem was the possibility of double counting N applications from starter fertilizer and from spring-applied MAP or DAP. This was because there were separate questions about the amount of N applied in starter fertilizer and the amount of N applied in the P fertilizers MAP and DAP. Double counting could be eliminated by asking farmers who applied MAP or DAP whether they had already reported this N when they answered the question about starter fertilizer.

BMPs for N use are different for coarse-textured soils, but because the survey did not ask farmers the texture of the field they reported on it was not possible to completely evaluate N management practices used on coarse-textured soils. Coarse-textured soils are widespread in the East Central BMP region, but other soil types are also included in this region and areas of coarse-textured soil exist in other regions. If farmers were asked whether their reported field was coarse-textured, these fields could be grouped for evaluation.

Fields that did not receive any N fertilizer were not included in the survey, so there were no fields where corn followed an excellent stand of alfalfa that could supply all of the N needed by the crop. This probably resulted in an overestimation of N rates for corn following alfalfa, but the size of this effect is unknown. Including these fields in the survey would permit more accurate characterization of N management practices following alfalfa.

Manure is an important source of N on many farms, so a complete survey of the amount of N applied to corn in Minnesota would include manure applications. It would have to account for both the N from current manure applications and the release of N from previous applications. Including manure would greatly expand the number of survey questions and the amount of information to be evaluated, but it would improve our knowledge of N management practices in Minnesota.

4. Conclusions

This survey provides the most comprehensive set of data on N fertilizer use on corn that has been collected in Minnesota or other areas of the Upper Midwest. It includes detailed information on application rates, timing, placement, and the chemical form of

the fertilizer used. The number of farmers successfully interviewed and their distribution across the state indicates that the results can be used to accurately characterize current N fertilizer management practices in Minnesota. This information can be used to target research and education programs to improve N management for both production and environmental goals. Survey data indicate that N fertilizer use by Minnesota corn farmers is generally consistent with University of Minnesota Extension N management guidelines, but there are opportunities for increasing fertilizer N recovery and decreasing the potential for N losses. N management on corn could probably be improved by taking adequate N credit for previous soybean crops. In the South Central region of the state, N management could potentially be improved by increased use of nitrification inhibitors with fall-applied anhydrous ammonia or by changing the timing of anhydrous ammonia application to spring preplant or sidedress.

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References

- Lamb, J., Randall, G., Rehm, G., Rosen, C., 2008. Best Management Practices for Nitrogen Use in Minnesota. Publication #08560, University of Minnesota Extension, St. Paul, Minnesota, United States.
- Lamb, J.A., Sims, A.L., Smith, L.J., Rehm, G.W., 2001. Fertilizing Sugar Beet in Minnesota and North Dakota. Publication #WW-07715, University of Minnesota Extension, St. Paul, Minnesota, United States.
- National Agricultural Statistics Service (NASS), 2000–2004, 2006. Agricultural Chemical Usage: 1999–2003, 2005 Field Crops Summaries. United States Department of Agriculture, Washington, DC. <<http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1560>> (accessed 13.06.11).
- National Agricultural Statistics Service (NASS), 2009. 2007 Census of Agriculture. United States Department of Agriculture, Washington, DC. <http://www.agcensus.usda.gov/Publications/2007/Full_Report/Census_by_State/Minnesota/index.asp> (accessed 13.06.11).
- National Agricultural Statistics Service (NASS), Minnesota Field Office, 2010. 2010 Minnesota Agricultural Statistics. United States Department of Agriculture and Minnesota Department of Agriculture, Washington, DC. <http://www.nass.usda.gov/Statistics_by_State/Minnesota/Publications/Annual_Statistical_Bulletin/index.asp> (accessed 13.06.11).
- Owens, L.B., 1987. Nitrate leaching losses from monolith lysimeters as influenced by nitrapyrin. *J. Environ. Qual.* 1, 34–38.
- Randall, G., Rehm, G., Lamb, J., Rosen, C., 2008a. Best Management Practices for Nitrogen Use in South-Central Minnesota. Publication #08554, University of Minnesota Extension, St. Paul, Minnesota, United States.
- Randall, G., Rehm, G., Lamb, J., 2008b. Best Management Practices for Nitrogen Use in Southeastern Minnesota. Publication #08557, University of Minnesota Extension, St. Paul, Minnesota, United States.
- Rehm, G., Lamb, J., Hughes, J.D., Randall, G., 2008a. Best Management Practices for Nitrogen Use in Southwestern and West-Central Minnesota. Publication #08558, University of Minnesota Extension, St. Paul, Minnesota, United States.
- Rehm, G., Lamb, J., Rosen, C., Randall, G., 2008b. Best Management Practices for Nitrogen on Coarse Textured Soils. Publication #08556, University of Minnesota Extension, St. Paul, Minnesota, United States.
- Rehm, G., Randall, G., Lamb, J., Eliason, R., 2006. Fertilizing Corn in Minnesota. Publication #FO-03790, University of Minnesota Extension, St. Paul, Minnesota, United States.
- Sims, A., Rehm, G., Lamb, J., 2008. Best Management Practices for Nitrogen Use in Northwestern Minnesota. Publication #08555, University of Minnesota Extension, St. Paul, Minnesota, United States.