doi:10.2489/jswc.2022.02152

Farmer adoption of efficient inorganic nitrogen fertilizer management practices in South Dakota

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Abstract: Nitrogen (N) fertilizer use has led to reductions in air and water quality but is essential for increasing crop production. Following the 4Rs of nutrient management (right: source, rate, timing, and placement), specifically following university N rate guidelines, proper urea fertilizer management, use of enhanced efficiency fertilizers, and splitting up inorganic fertilizer-N applications can minimize potential negative environmental effects. Data from a 2019 probability sample survey of 465 South Dakota farmers were used to examine how local and operational characteristics (geographic location, tillage practice, and farm size) are related to the adoption of these four Rs of nutrient management practices. Factors included in inorganic N rate decisions from most to least were use of preplant soil test N (74%), yield potential (68%), previous crop credit (48%), manure credit (25%), and tillage type (16%). Of all the factors used to make fertilizer-N rate decisions, only the use of previous crop and manure credit factors were influenced by farm location and tillage method but not farm size. Of all respondents, 30% used urease inhibitors to minimize ammonia (NH_3) loss and 31% applied urea before predicted precipitation. However, farms in drier, central South Dakota and no-till farms used urease inhibitors and applied before predicted precipitation more often than farms in wetter, eastern South Dakota and conventional- and reduced-tillage farms, who were more likely to use tillage to incorporate urea. To minimize leaching and denitrification loss, farms in eastern South Dakota where normal rainfall is greater used nitrification inhibitors or slow-release fertilizers and split-N applications (48% and 53%, respectively), while fewer farms in central South Dakota where normal rainfall is less used these technologies (34% and 36%, respectively). Larger farms more frequently used urease and nitrification inhibitors, and/or slow-release fertilizer technologies to minimize N loss. These results indicate that local and operational characteristics including geographic location, tillage, and farm size influence on-farm decisions concerning the adoption of these 4R management practices and should be considered when investigating and promoting 4R practices.

Key words: adoption—conservation—nitrogen—nutrient management

The use of nitrogen (N) fertilizers has led to greater crop yields; however, it is one of the main sources of nonpoint N pollution and needs to be minimized to protect water and air quality (Vitousek et al. 1997; Ribaudo et al. 2011). The main N loss pathways from cropland come from fertilizer runoff, ammonia (NH_3) volatilization, greenhouse gas emissions from denitrification, and nitrate (NO_3^-) leaching (Ribaudo et al. 2011). Programs such as the 4Rs of nutrient management (right: source, rate, timing, and placement) were created to inform farmers of the best ways to manage fertilizers like inorganic N to maximize crop production and minimize N loss. Some of the 4R recommended practices for corn (*Zea mays* L.) to avoid losses and maximize uptake of N include applying fertilizer-N at a rate that accounts for all sources of N, incorporating or placing N in the soil or using enhanced efficiency fertilizers (e.g., urease and/or nitrification inhibitors and slow-release fertilizers), and timing N application close to when the crop needs it (Dinnes et al. 2002; Ribaudo et al. 2011; Morris et al. 2018).

The above-mentioned 4R practices for inorganic fertilizer-N can increase crop production and minimize N loss. However, surveys conducted in 2006 across the United States showed that only 35% of fields followed recommended 4R practices for inorganic fertilizer-N (Ribaudo et al. 2011, 2012). Similarly, farmers in Illinois on average used two of six recommended practices and were likely to only adopt one more in the next three years (Upadhyay et al. 2003). For South Dakota, it is currently unknown how well farmers are following 4R recommendations. It is important to understand if and how well these 4R fertilizer-N management practices are being utilized as it would indicate whether our current approach to educating farmers about the 4Rs related to fertilizer-N is working well. It is also important to understand what factors farmers use to make inorganic fertilizer-N management decisions to improve educational resources that can lead to increased adoption of 4R practices for N management. This manuscript will focus on the recommended 4R practices for corn using inorganic fertilizer-N as it is the most frequently used source of N for crops in the United States (MacDonald et al. 2009; Ribaudo et al. 2011).

To this point, much research has focused on perceptions and attitudes of farmers regarding the adoption of recommended practices that can lower potential negative environmental effects (Upadhyay et al. 2003; Knowler and Bradshaw 2007; Baumgart-Getz et al. 2012; Stuart et al. 2014; Osmond et al. 2015; Weber and McCann 2015; Ulrich-Schad et al. 2017; Denny et al. 2019). In a recent review of this

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Received September 30, 2021; Revised February 22, 2022; Accepted April 9, 2022.

literature, Prokopy et al. (2019) determined that few variables (i.e., perceptions, attitudes, education, and equipment) by themselves had a consistent impact on the use of recommended nutrient management practices. However, the variables that most consistently had a positive relationship with adopting recommended nutrient management practices were stewardship motivated farmer, positive attitude toward and awareness of the practice, previous adoption of conservation practices, seeking and using information, vulnerable land, larger farm, greater income and education, and expected yield increase.

A potential reason for the lack of consistent impact of specific variables is that many of these studies are regional and are not capturing important differences that occur on a smaller scale (i.e., soil type, tillage, drainage, climate, geography, etc.) (Weber and McCann 2015). These smaller-scale differences are likely important for the adoption of recommended 4R practices for inorganic fertilizer-N as N loss avenues are influenced by weather, soil texture, drainage, fertilizer application methodology, and chemical form of N (Hargrove 1988; Dinnes et al. 2002; Chen et al. 2008; Fan et al. 2011; Fernández et al. 2016; Drury et al. 2017; Silva et al. 2017; Thies et al. 2020; Venterea et al. 2021). For example, the use of nitrification inhibitors is most effective in sandy soils, poorly drained soils, or when NH_3-based fertilizers are applied in the fall (Clay et al. 1990; Norton 2008; Fernández et al. 2016; Vetsch et al. 2019). Additionally, slow-release fertilizers perform better under moist conditions and coarse-textured soils (Fan et al. 2011; Grant et al. 2012; Yang et al. 2017; Spackman 2018; Ransom et al. 2020a).

The local and operational variables in South Dakota that may be a factor in determining the use and effectiveness of recommended 4R practices for inorganic fertilizer-N include location of the farm within South Dakota, utilized tillage practice, and farm size. The effect of location and associated regional differences was demonstrated in Indiana where farms in regions with flatter topography were more likely to adopt variable rate application technologies (Ulrich-Schad et al. 2017). The notable geographical dividing factor in South Dakota is the change in annual precipitation in an east to west direction. Precipitation in the eastern region (559 to 711 mm) is normally greater than the central region (406 to 559 mm) (Fisichelli et al. 2016). This is important as precipitation is a primary driver of N loss, resulting in it being an important factor in the effectiveness of enhanced efficiency fertilizers (Clay et al. 1990; Norton 2008; Fan et al. 2011; Grant et al. 2012; Fernández et al. 2016; Yang et al. 2017; Spackman 2018; Vetsch et al. 2019; Ransom et al. 2020a). Additionally, the drier, central region has largely adopted no-till practices (79%) that help conserve their more limited precipitation, whereas the wetter, eastern region primarily uses conventional- or reduced-tillage (71%) (table 1). Movement from tillage to no-till removes one method to incorporate urea fertilizer (most used inorganic fertilizer-N source in the United States [USDA ERS 2019]) and will likely result in no-till farmers being more reliant on a preciptation event of at lest 25 mm or use of a urease inhibitor (delays the conversion of urea into volatile NH_3 gas) to minimize volatilization losses (Bouwmeester et al. 1985; Clay et al. 1990; Upadhyay 2012; Goos 2013; Goos and Guertal 2019; Rochette et al. 2013; Silva et al. 2017).

We expect urease inhibitors to be used more in the central versus eastern region since precipitation is less and use of no-till is greater. This lower precipitation and higher adaptation of no-till practices will likely lead farmers to use the urease inhibitor to lengthen the time urea fertilizer can be near the soil surface without volatilizing while precipitation is being waited for to incorporate the fertilizer. Conversely, since nitrification inhibitors and slow-release fertilizers often increase yield during high precipitation years (Clay et al. 1990; Randall and Vetsch 2005b; Chen et al. 2008; Drury et al. 2017; Spackman 2018), we expect these enhanced efficiency fertilizers to be more often used in the higher precipitation eastern region of South Dakota. Further, we hypothesize no-till farmers will be more likely to time urea application near precipitation events and use a urease inhibitor to lengthen the time urea can wait on the soil surface for a precipitation event with less N volatilization losses. Adoption of a conservation tillage practice is an indicator of an increased likelihood of adopting multiple conservation practices (Knowler and Bradshaw 2007; Weber and McCann 2015; Ulrich-Schad et al. 2017). Therefore, we expect that no- and reduced-till farmers will be more likely to use more factors in the university N rate recommendation algorithm and more frequently use nitrification inhibitors and slow-release fertilizers or split-N applications.

Farm size, or the number of hectares operated, has shown to affect the adoption of conservation practices as larger farms often have a greater ability to take on financial risk (Khanna 2001; Roberts et al. 2004; Ulrich-Schad et al. 2017). Larger farms also likely have more highly skilled personnel to obtain information regarding new practices, equipment, and finances to invest in recommended 4R practices for inorganic fertilizer-N. Thus, we predict that larger farms will more frequently use enhanced efficiency fertilizers, split N applications, and use more factors in the university N rate recommendation

Table 1

Percentage of farms and number of farms in parentheses within each location, tillage practice, and farms size category combination.

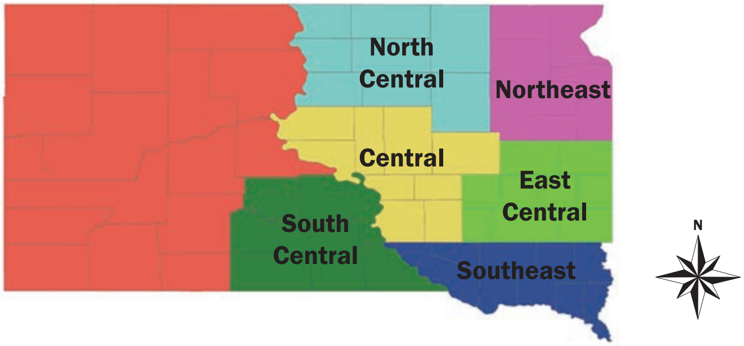
	Location		Tillage practice		
Variable category	Central (%)	East (%)	No-till (%)	Reduced (%)	Conventional (%)
Tillage practice					
No-till	79 (109)	29 (57)	NA	NA	NA
Reduced	9 (13)	18 (34)	NA	NA	NA
Conventional	12 (17)	53 (104)	NA	NA	NA
Farm size (ha)					
>809	42 (57)	17 (30)	39 (61)	18 (8)	11 (12)
405 to 809	36 (49)	31 (55)	35 (54)	35 (16)	33 (35)
202 to 404	15 (21)	34 (61)	18 (29)	36 (16)	34 (37)
1 to 201	7 (9)	18 (32)	8 (12)	11 (5)	22 (24)

Note: NA = not applicable.

algorithm. Therefore, our objective was to document the adoption of recommended 4R practices for inorganic fertilizer-N in South Dakota and evaluate the effect of farm geographic location within the State of South Dakota (i.e., to separate climatic differences), tillage practice, and farm size on the adoption rate. The recommended 4R practices for inorganic fertilizer-N evaluated were the use of university recommended factors in making fertilizer-N rate decisions, methods used to minimize N volatilization losses from urea, use of nitrification inhibitors and slow-release fertilizers, and use of split N applications.

Figure 1

County map of South Dakota highlighting the six cropping districts where farmers took part in the 2019 survey.



Materials and Methods

Data Collection. Data presented here are derived from a mail and online survey conducted by researchers in the Sociology and Rural Studies and Agronomy, Horticulture, and Plant Science departments at South Dakota State University. The survey was conducted among corn producers, including those with livestock, in central and eastern South Dakota. The survey asked farmers detailed questions regarding the information sources used to make N management decisions and the sources, rates, application timings, and placement of inorganic fertilizer-N. Questions regarding farmers' demographics and farm characteristics were also asked to determine whether these factors played a role in their N management practices.

The survey was sent to 3,000 South Dakota producers in 2019. Farmer contact information was purchased from Farm Market ID (Westmont, Illinois), a company that provides contact information for agricultural producers in the United States. Farmers were selected randomly using stratified proportionate sampling (according to the number of operations in the district) from six USDA crop reporting districts in the central and eastern part of South Dakota where most of the corn is grown (figure 1).

Producers were contacted three times using a modified tailored design approach as described in Dillman et al. (2014). Briefly, the first contact was an advance letter including a US$2 bill incentive informing them about the purpose of the survey and how the information gathered will benefit them by providing research and educational programs that will meet their needs, optimize production, and protect the environment. The advance letter also contained a link so that producers who wanted to take the survey immediately online could do so. The second contact was a mail survey that included a stamped return envelope for those who did not respond to the advance letter. The last contact was another mail survey with a stamped return envelope for those who did not respond to the first and second contact attempts to give them a final opportunity to take the survey. Emails were also sent three times with the survey link to respondents who had email addresses in the sample ($n = 1,362$), reminding them to complete the survey if they had not done so. The process of multiple contacts and incentives has proven to increase the response rate in survey research (Dillman et al. 2014), including those conducted with agricultural producers (Avemegah et al. 2020). The overall response rate for the survey was 18% with 465 producers completing the survey (online = 176 and mail = 289). Our sample represents 249,237 planted hectares and US$314,080,011 in gross farm income (GFI) in the eastern half of the state of South Dakota.

Using the supplementary data provided by Farm Market ID for our entire sample, we conducted nonresponse bias tests comparing respondents to nonrespondents on both planted hectares and GFI in 2017 using independent samples *t*-tests. Planted hectares for respondents ranged from 2 to 6,220, with an average of 556 ha. Planted hectares for nonrespondents ranged from 5 to 26,519, with an average of 553 ha. The GFI for respondents ranged from US$150,183 to US$6,956,941, with an average of US$701,071. The GFI for nonrespondents ranged from US$150,249 to US$20,496,506, with an average of US$702,600. The *t*-tests for both indicated no significant difference in hectares planted or GFI for respondents and nonrespondents. Given we used probability sample methods to randomly select operations in the State of South Dakota and subsequently determined there were no significant differences between respondents and nonrespondents on some key operational variables, we are confident that our sample is a good representation of corn producers in the eastern half of South Dakota in 2019.

Independent Variables. Local and operational variables of interest included three main categories: geographic location of farm within South Dakota, tillage practice, and farm size (table 1). The percentage of farms within each category is in table 1. The farm geographic location variable divides the survey area where most of the corn production occurs into central and eastern regions based on USDA crop reporting districts (USDA NASS 2021). The central region contains farms located in the North-Central, Central, and South-Central crop reporting districts and the eastern region contains farms located in the Northeast, East Central, and Southeast crop reporting districts (figure 1). These two categories were created based on normal annual precipitation amounts being greater or less than 559 mm (Fisichelli et al. 2016). Additionally, farms were divided into one of three tillage categories (no-till, reduced-till, and conventional-tillage) and one of four size categories (1 to 201, 202 to 404, 405 to 809, and >809 ha).

Dependent Variables. Producers were asked about (1) the types of information they use to make N rate decisions, (2) fertilizer-N sources and rates, including specific urea application management practices, (3) usage of nitrification inhibitors and slow-release fertilizers, and (4) N application timing strategies. Respondents were asked to indicate (yes = 1; no = 0) if they typically use a variety of types of information to determine fertilizer-N rates, including those in the categories of university recommended factors (five items), fertilizer-N rate recommendation help (three items), and other potential variables (seven items). To determine N fertilization sources and rates, respondents were asked to indicate (yes = 1; no = 0) which N products (six types as well as the option to write in two other types if it was not provided; excluding starter fertilizer) they typically apply and at which time of the year (fall, spring, early season, or mid-season) to produce corn. Farmers who applied urea fertilizer were also asked about the management practices they typically use (yes = 1; no = 0) with each urea application timing (e.g., incorporation timing [less than 24 hours, later than 24 hours but less than a week, and later than a week], application of urease inhibitor, and application before rain). Respondents were also asked if they used (yes = 1; no = 0) any additives or enhanced efficiency N fertilizers in the past three years, including (1) urease inhibitors (e.g., NBPT products: Anvol, Agrotain, etc.), (2) nitrification inhibitors (e.g., nitrapyin and DCD products: N-Serve, Instinct, NZone etc.), (3) both urease and nitrification inhibitors (e.g, SuperU, Agrotain Plus SC, etc.), (4) use/used an inhibitor, but unsure what category it falls under, and (5) use/used a slow-release fertilizer (polymer coated urea or sulfur coated urea). Finally, to measure N application timing strategies, respondents were asked to write in the approximate N rate (excluding starter fertilizer) they applied at various timings (e.g., fall, spring preplant, early season, or mid/late season) and the application method they used (e.g., broadcast: incorporated, broadcast: not-incorporated, banding: with strip-till, banding: under the row, subsurface banding: next to row, subsurface banding: mid row; surface banding: mid row; top dress: foliar feed, and with irrigation). If respondent indicated they used multiple application timings, they were coded as split, and if they indicated they used only one timing, they were coded as single.

Data Analysis. For some variables, we simply provide a univariate descriptive analysis (e.g., frequencies and percentages) of survey data to provide basic information about fertilizer-N use among respondents. To examine bivariate relationships between variables, given that all our variables of interest were measured categorically, we used chi-square tests of independence to examine whether there were significant differences in our fertilizer-N use variables of interest (dependent variables described above) according to the farm geographic location, tillage practice, and farm size (independent variables described above). These tests were conducted in Stata to determine significant associations ($P \leq 0.05$) between variables of interest. For example, we used chi-square tests of independence to determine whether there was a significant difference between producers in central and eastern South Dakota with regards to using yield goal as a factor in making fertilizer-N rate decisions. When the effects of independent variables on dependent variables were significant ($P \leq 0.05$) and there were greater than two levels of that factor, additional chi-square tests were conducted to determine differences among them.

Results and Discussion

Information Used to Make Nitrogen Rate Decisions. To best account for all sources of N when determining a N fertilizer rate, each state in the United States has developed N fertilizer guidelines (recommendations) based on research conducted in their area (Morris et al. 2018). In South Dakota, researchers at South Dakota State University developed an algorithm that uses the factors of yield potential, preplant soil test N to a depth of 60 cm, previous crop credit, manure application credit, and tillage type (Clark et al. 2019), which was validated by Kim et al. (2013). Among all respondents, yield potential and preplant soil test N factors were used the most frequently to determine fertilizer-N rates (68% and 74%, respectively) while the other N rate factors were used <48% of the time (table 2). The use of soil test N is important as recent research in South Dakota and other parts of the United States suggests it can reduce fertilizer-N needs by an average of 63 kg N ha^{-1} without reducing yield (Williamson 2011; Kim et al. 2013; Clark et al. 2020, 2021; Ransom et al. 2021). This fertilizer rate reduction would lead to an average cost savings of US\$54 ha^{-1} (using an average fertilizer-N cost of US\$1.19 kg^{-1} N [USDA ERS 2019]). Therefore, it is important to continue working with farmers and those they consult with when making fertilizer-N rate decisions to help them understand the potentially improved accuracy and cost savings when preplant soil test N is used to adjust fertilizer-N recommendations.

Following the use of yield potential and soil test N to determine fertilizer-N rate recommendations were the use of previous crop credit (48%), manure credit (25%), and tillage type (16%) (table 2). One reason these numbers may be low is that only the farmers that grew legumes as the previous crop (or two years before in the case of a previous perennial legume), applied manure, or used no-till considered themselves as using these factors because only when using these factors results in a change in the N rate recommended by the university N rate algorithm. Whereas for farmers who did not grow legumes, apply manure, or use no-till, these N credit/debit factors were zero; because their fertilizer recommendation rate did not change, they may not have considered themselves as using these factors. In a subset analysis, we evaluated the percentage of farmers who grew legumes, applied manure, or used no-till and used the associated credit or debit in their N rate calculation. Of those who grew legumes, 55% used the previous crop credit, 47% of manure applicators used the manure credit, and 20% of no-tillers used the no-till adjustment. These results increase the overall use of manure credit substantially but only a small amount for the legume and tillage adjustments. These results indicate even with the increased use of these factors (previous crop, manure, and tillage) shown with the subset analysis, their use was still poor. Therefore, the use of the previous crop, manure, and tillage factors and their ability to improve the accuracy of fertilizer-N recommendations and reduce fertilizer costs needs to be emphasized in educational programming.

Location and tillage were related to the use of some factors used to make fertilizer-N rate decisions, but farm size was not (table 2). Only the use of previous crop and manure credit factors varied by location and only previous crop credit by tillage. Farmers in eastern relative to central South Dakota used both the previous crop and manure credits approximately 10% more often to make fertilizer-N rate decisions. The main climate and management practice differences in eastern and central South Dakota (precipitation and tillage type) did not seem likely to affect the use of previous crop or manure credit. One other potential reason for the difference may

Table 2

Percentage of survey respondents who use the following management factors and tools to make fertilizer-nitrogen (N) rate decisions, overall and by location, tillage system, and farm size.

		Location		Tillage			Farm size (ha)			
Variables	Overall (%)	Central (%)	East (%)	No-till (%)	Reduced (%)	Conventional (%)	>809 (%)	405 to 809 (%)	202 to 404 (%)	1 to 201 (%)
University recommended factors										
Yield goal	68	64	72	78	78	77	77	76	73	78
Soil test	74	70	76	85	86	80	84	81	82	81
Previous crop credit	48	43b*	53a	56ab	71a	48b	61	53	46	56
Manure credit	25	20b	30a	27	39	29	26	30	29	30
Tillage system	16	13	18	20	23	14	20	16	18	22
Other potential variables										
Use of cover crop	15	15	14	20	16	11	20	14	13	17
Presidedress soil nitrate test	8	4b	12a	8	14	10	12	8	7	7
In-season tissue test	14	12	16	14	18	18	22	16	13	10
Crop canopy sensor	1	1	1	1	2	2	0	1	0	5
Visual deficiency symptoms	17	14	19	17	27	19	24	20	16	15
Basal stalk nitrate test	3	1	4	3	4	2	1	6	2	2
Fertilizer and/or grain prices	29	24	33	35	35	34	36	37	29	37
Fertilizer-N rate recommendation help										
Commercial prediction tool	6	4	8	7	12	4	7	7	8	5
Independent consultant	27	26	29	30	33	26	22	21	32	37
Co-op recommendation	35	30	38	41	41	50	35	45	48	51
Percentage of farms in each category										
		47	53	49	14	37	27	34	23	13

*Percentages with different letters within each row of each variable category (i.e., location, tillage, and farm size) are statistically different ($P \leq 0.05$). If no letters are present, there are no significant differences.

be the greater number of farmers in eastern compared to central South Dakota that grew legumes (73% versus 59%) or applied manure (55% versus 43%) who would be more likely to consider themselves as using these credits as discussed earlier.

Previous crop credit was utilized more in N rate decisions among no- and reduced-till farmers (56% and 71%, respectively) compared to conventional-till farmers (48%). This finding supports our hypothesis that farmers who adopt no- or reduced-till practices are more likely to consider more factors when making fertilizer-N rate decisions. This finding is also supported by others who determined that the adoption of one conservation practice (e.g., no- or reduced-till) is a good indicator of adopting multiple conservation practices (Weber and McCann 2015; Ulrich-Schad et al. 2017). These results indicate that geographic location and tillage system can be related to recommended 4R practices for inorganic fertilizer-N and should be studied more to increase understanding regarding how and why these factors affect adoption.

Potential ways to further improve the use of all university recommended factors when determining fertilizer-N recommendations can be through the creation of educational programming, demonstrating "why" and "how" to use these factors. Government agencies could also require the use of all the factors in the university N rate recommendations algorithm for farmers to participate in their various programs that help farmers adopt sustainable management practices. Further demonstration of how these factors influence fertilizer-N recommendations, including present-day case studies, may improve producer implementation of the factors when making N rate decisions.

Other plant and soil tests asked about, but not currently used in university recommendations for South Dakota, included visual nutrient deficiency symptoms, in-season tissue tests, crop canopy sensors, in-season soil NO_3^--N tests, and the use of cover crops (table 2). However, only some farmers used these testing options (<17% overall). Similar results were also found in a Michigan study where in-season N testing and canopy sensors were used to determine fertilizer-N rates <12% of the time (Stuart et al. 2014). This low adoption rate may be due to labor, time, money, and equipment required to use in-season soil and plant tests. For example, crop canopy sensors require additional equipment and the use of algorithms to make fertilizer recommendations. Further, the algorithms used are routinely modified by industry and academic researchers to improve their accuracy. Most farmers would likely be more willing to adopt such technologies as research improves their consistency in providing an accurate fertilizer rate estimate (Bean et al. 2018; Ransom et al. 2020b). In addition, these in-season testing methods can only be used to refine N recommendations when farmers move most of their N application from near planting to in the growing season after in-season tests occur. Currently, only 45% of South Dakota farmers split up their N application that would allow them to use these in-season tests to refine their fertilizer-N rate (table 3). This percentage of farmers applying N in-season is likely lower than in other states in the eastern Corn Belt where greater amounts of precipitation are observed during the early part of the growing season.

Fertilizer and grain prices were a factor used by only 29% of farmers when deciding on a fertilizer-N rate (table 2). One way to improve the use of grain and fertilizer prices would be to incorporate these costs into N rate recommendations. An example of this is the Maximum Return to N recommendation system developed by Iowa State University (Sawyer et al. 2006) and adopted by many states in the US Midwest.

Another emerging field in N recommendation systems are the development and use of models including HybridMaize (Yang et al. 2004), Encirca (DuPont Pioneer Johnston, Iowa), Climate FieldView (The Climate Corp., St. Louis, Missouri), and Adapt-N (Yara International ASA Oslo, Norway). However, the use of these commercially available systems is limited in South Dakota with only 6% of growers using a commercially available fertilizer-N rate recommendation tool (table 2). Most growers who turn to people outside their farm for help in making fertilizer rate decisions turn to their co-op (35%) or an independent crop consultant (27%). Thus, working with individual farmers along with fertilizer dealers and crop consultants, who normally work with many farmers, regarding fertilizer recommendations would likely enable educational programming to reach more farmers faster. This type of process could result in individual farmers adopting emerging technologies more quickly to help in their fertilizer-N rate decisions.

Urea Application Management Practices. The most used inorganic fertilizer-N source in South Dakota is urea at 65% with all other sources being used ≤24% of the time (e.g., urea ammonium nitrate [UAN] that contains 28% N [24%], UAN that contains 32% N [6%], and anhydrous NH_3 [5%]). Urea fertilizer is most frequently applied in the spring before planting (57%). At this spring application, timing, farm location, tillage, and farm size were related to urea fertilizer management practices ($P \leq 0.05$).

Appropriate management of urea fertilizer is important to avoid N losses from volatilization that occur when urea is converted by enzymes to NH_3 gas (Francis et al. 2008; Kissel et al. 2008; Fernández et al. 2016; Vetsch et al. 2019; Thies et al. 2020). Ammonia volatilization can be reduced by incorporating urea into the soil through tillage or injection, applying it prior to a precipitation event of at least 25 mm, or use of a urease inhibitor (Bouwmeester et al. 1985; Clay et al. 1990; Upadhyay 2012; Rochette et al. 2013; Silva et al. 2017). To minimize NH_3 volatilization loss from urea, farmers in central South Dakota were most likely to apply urea with a urease inhibitor (39%) or time the application before precipitation (39%) and least likely to use tillage (≤12%) (table 2). This result is likely because no-till practices are most used in central South Dakota (79%) that removes their ability to incorporate urea with tillage (table 1). Conversely, farmers in eastern South Dakota relied primarily on tillage within 24 hours (47%) compared to using a urease inhibitor (24%) or timing the urea application prior to a precipitation event (24%). In eastern South Dakota, conventional- and reduced-tillage practices are most used (71%). Eastern South Dakota also normally has greater annual precipitation. This greater annual precipitation may influence farmers to use tillage more often to help dry their fields and prepare them for planting. Tillage also gives them an added tool to minimize NH_3 volatilization losses by incorporating the urea fertilizer at the same time they prepare their fields for planting. Evidence

Table 3

Percentage of survey respondents who use various urea fertilizer application practices in spring, enhanced efficiency fertilizers (nitrification inhibitors and slow-release fertilizers), and single- or split-nitrogen (N) application timing, overall and by location, tillage system, and farm size.

	Urea management							N application timing strategy	
	Incorporation timing				Other practice				
Variables	<24 h (%)	>24 h but < a week (%)	> a week (%)	None (%)	Apply before rain (%)	Use of urease inhibitor (%)	Use of nitrification inhibitor and slow-release fertilizer (%)	Single (%)	Split (%)
Overall	34	11	3	28	31	30	43	55	45
Location									
Central	12b*	5b	0b	50b	42a	39a	34a	53aa	37b
East	47a	16a	6a	15a	24b	24b	48b	47b	63a
Tillage									
No-till	10b	7b	2	49a	45a	43a	53	65	35
Reduced	48a	28a	12	24b	24ab	28ab	43	50	50
Conventional	67a	12ab	2	0c	16b	16b	39	48	52
Farm size (ha)									
>809	23	4	2	44a	38	33	49	49	51
405 to 809	31	17	2	31ab	33	45	40	67	33
202 to 404	38	22	8	16b	38	24	42	44	56
1 to 201	52	10	5	14b	19	19	46	73	27

Notes: N = nitrogen; h = hours.

*Percentages with different letters within each column are statistically different ($P \leq 0.05$). If no letters are present, there are no significant differences.

of this theory is provided as no-till farms (more abundant in central South Dakota) were the most likely to use a urease inhibitor (43%) and work to time application before a precipitation event (45%) and not incorporate urea with tillage (49%). In contrast, fewer farms that used conventional- or reduced-tillage (more abundant in eastern South Dakota) used a urease inhibitor (16% and 28%, respectively) or applied before a precipitation event (16% and 24%, respectively).

Farm size was also a factor in whether urea fertilizer was incorporated to minimize N volatilization losses. Larger farms primarily relied upon using a urease inhibitor (33% to 45%) or trying to time the application prior to a precipitation event (33% to 38%), and lastly using tillage to incorporate the urea fertilizer (23%) (table 3). These results likely occurred because larger farms (>405 ha) mostly used no-till practices (74%) that did not allow them to use tillage to incorporate urea fertilizer and avoid N volatilization losses (table 1). Conversely, smaller farms (<405 ha) primarily relied on tillage to incorporate urea fertilizer (38% to 52%) to minimize N volatilization losses and infrequently used a urease inhibitor (19% to 24%) or tried to time urea application before a precipitation event (19% to 38%) (table 3). These results likely occurred because smaller farms were more likely to till their fields (47% to 56%; table 1). Use of tillage and incorporating fertilizer enabled them to minimize N volatilization losses without needing to invest in a more expensive fertilizer containing a urease inhibitor or time fertilizer application before a precipitation event. These results also provide further evidence that larger farms are more likely to adopt conservation tillage practices (Prokopy et al. 2019), including no-till where tillage is no longer an option to incorporate urea to avoid volatilization losses.

Another potential reason larger farms more frequently use a urease inhibitor or rely on precipitation to incorporate urea may be due to the time, energy, and labor savings. Fertilizer can be broadcast on the soil surface faster and requires less equipment power (and use of energy) compared to banding urea (or UAN solution) or broadcasting it on the surface and then using tillage to incorporate the fertilizer. These savings for larger (>405 ha) compared to smaller farms (<405 ha) are more likely to be sufficient to pay for the added price of purchasing fertilizers with a urease inhibitor. Whereas it may be more cost-effective for smaller farms to incorporate urea fertilizers with tillage compared to relying on precipitation or urease inhibitors to minimize NH_3 volatilization losses. Further, smaller farms may not have their own application equipment to time fertilizer application or what fertilizer sources (e.g., urease inhibitor) are applied and must rely on the co-ops' equipment, timing, and urease inhibitor availability.

These results ultimately support our hypothesis that larger farms due to their often-greater finances and ability to spread the financial risk over larger geographical areas (lessening the chance that all areas would produce low yields) would be more likely to adopt newer technologies such as urease inhibitors. These results also support our hypothesis that local and operational factors including geographic location and its associated weather patterns, tillage, and farm size influence farmers' decisions on what 4R practices to adopt and should be considered when investigating and promoting 4R practices for N management.

Use of Nitrification Inhibitors and Slow-Release Fertilizers. Nitrification inhibitors and slow-release fertilizers can be used to minimize N loss by reducing the chance of N being lost to leaching or denitrification processes and increasing the chance the crop will take up the N (Fan et al. 2011; Halvorson et al. 2014; Fernández et al. 2015; Yang et al. 2017). Nitrification inhibitors are used to inhibit the conversion of ammonium (NH_4^+) to NO_3^- that is highly susceptible to loss via leaching and denitrification (e.g., nitrous oxide gas) (Laboski 2006; Trenkel 2010; Drury et al. 2017; Goos and Guertal 2019). Slow-release fertilizers are coated or encapsulated fertilizers that release nutrients slowly over time based on temperature and moisture (Trenkel 2010; Adams et al. 2013; Ransom et al. 2020a). The use of nitrification inhibitors and slow-release fertilizers were related to location ($P \leq 0.05$) but not tillage or farm size ($P > 0.05$). However, there were important trends to consider with the effect of tillage and farm size. The nitrification inhibitors and slow-release fertilizers were 14% more likely to be used by farms in eastern compared to central South Dakota (48% versus 34%) (table 3). This is the opposite trend compared to looking at the use of urease inhibitors and is likely due to the annual precipitation differences in eastern versus central South Dakota.

In the higher precipitation areas in eastern South Dakota, there is a greater chance of receiving needed precipitation to incorporate urea fertilizer after application before extensive NH_3 volatilization loss occurs, lowering the need for urease inhibitors. However, the greater precipitation also increases the chance of N loss through leaching and denitrification, which can be lessened using nitrification inhibitors and slow-release fertilizers that keep N in the more stable NH_4^+ form (Laboski 2006; Trenkel 2010; Drury et al. 2017; Goos and Guertal 2019). These results are supported by research where nitrification inhibitors and slow-release fertilizers were more effective at minimizing N loss and increasing crop yield in wetter conditions (Fan et al. 2011; Grant et al. 2012; Yang et al. 2017; Spackman 2018; Ransom et al. 2020a). Conversely, farmers in the lower precipitation areas in central South Dakota are less concerned about leaching and denitrification losses and more concerned with N loss from volatilization.

Although statistically not significant ($P > 0.05$), farmers who used no-till compared to conventional-till were approximately 14% more likely to use nitrification inhibitors and slow-release fertilizers (53% versus 39%) (table 3). Farmers who used conservation versus conventional-till were also more likely to use nitrification inhibitors and slow-release fertilizers in a national US study (Weber and McCann 2015). Farmers who switch from conventional- to no-till or reduced-till are required to think about changing their entire cropping management system and not only skipping tillage passes. Therefore, it takes a willingness to change and adjust the entire operation to effectively manage a new cropping system (Upadhyay et al. 2003; Denny et al. 2019). This willingness to change and try new technologies is also likely the attitude needed for these no-till compared to conventional-till farmers to more frequently adopt nitrification inhibitors and slow-release fertilizers that can help minimize N loss. It appears farms >810 ha tend to use nitrification inhibitors and slow-release fertilizers more frequently than smaller farms (table 3); however, these differences were not statistically significant. As discussed earlier this is likely due to larger farms more frequently having the capital available to invest in higher cost fertilizer technologies, nitrification inhibitors, and slow-release fertilizers, to ensure they can apply fertilizers efficiently on their entire operation. Therefore, this may be the reason that on average larger farms were more likely to use nitrification inhibitors and slow-release fertilizers to help minimize N loss. Overall, these results indicate that when conducting research and creating educational programs related to the adoption of nitrification inhibitors and slow-release fertilizers that local climate, tillage practices, and adoption costs need to be considered and addressed.

Splitting Up Nitrogen Applications. Delaying and aligning N application to crop needs is another possible tool to lower N loss. In the US Midwest, early season (April through June) precipitation events when crop N uptake is low often leads to the greatest N losses through leaching and denitrification (Randall and Vetsch 2005a; Abendroth et al. 2011; Fernández et al. 2016; Struffert et al. 2016). However, after the V6 development stage (Abendroth et al. 2011), corn grows rapidly and takes up large amounts of nutrients and water, reducing the potential for N loss (Randall et al. 2003; Ma et al. 2003; Fernández et al. 2016; Struffert et al. 2016). Thus, applying approximately 20% of the total N fertilizer needed near planting and the rest closer to when rapid nutrient uptake begins can potentially reduce N losses.

The use of split applications by South Dakota farmers was close to even overall with 55% and 45% using single- and split-N applications, respectively (table 3). Farm location was related ($P \leq 0.05$) to the use of single- and split-N applications, whereas tillage and farm size were not ($P > 0.05$). Single-N applications were used more on farms in central (53%) compared to eastern South Dakota (47%). Whereas split-N applications were used more in eastern (63%) compared to central South Dakota (37%). The more frequent use of single- compared to split-N applications in central South Dakota and the opposite occurring in eastern South Dakota was likely due to the differences in annual precipitation. As previously stated, central South Dakota receives less annual precipitation than eastern South Dakota. This is important as recent research throughout the US Midwest has shown that reliable precipitation around the timing of a split application is strongly related to the split-N management strategy increasing crop yields over single-N applications (Kovács et al. 2015; Spackman et al. 2019; Clark et al. 2020). The lower likelihood in central South Dakota of receiving precipitation to incorporate fertilizer-N and make them available to the crop during the growing season is likely the reason single- compared to split-N applications were used more frequently. Whereas the greater annual precipitation in eastern South Dakota increases the chance of receiving needed precipitation at the time of split applications to make fertilizer available to plants and is likely the reason split- compared to single-N applications were more frequently used in eastern South Dakota.

More research is needed evaluating single- and split-N applications in the various precipitation zones in South Dakota and using different placement methods (e.g., surface broadcast versus injected side-dress) before educational training and demonstrations can be created. This additional research would then be used to help farmers in both central and eastern South Dakota to determine whether single or split applying fertilizer-N would improve crop yield and minimize potential negative environmental effects. Farmers also need to have access or ownership of appropriate equipment that can apply fertilizer in a standing crop (e.g., fertilizer applicator with narrow tires that will not damage the crops). This kind of equipment is not always available everywhere and farmers may be concerned about the compaction caused by the equipment. Another concern with in-season N applications may be the short amount of time to execute in-season fertilizer application, which many times aligns with early season weed control. Overall, these results indicate that geographic location (i.e., precipitation patterns) and not tillage or farm size should be accounted for when conducting research or promoting the use of split-N applications to minimize N loss.

Summary and Conclusions

Geographical location (east-west) and local operational characteristics mattered when farmers were making decisions related to the recommended 4R practices for inorganic fertilizer-N. Geographic location within South Dakota, tillage, and farm size were associated with the use of different fertilizer-N management decisions. Farmers using no- and reduced-tillage practices compared to conservation tillage practices more frequently used previous crop credit and farms in eastern compared to central South Dakota used previous crop and manure credits more frequently. The use of all other variables in the N rate recommendation algorithm were not influenced by farm location, tillage, or farm size. Overall, yield potential and preplant soil test N factors were the most used to determine fertilizer-N rates (>68%) while the other university N rate factors were used <48% of the time. The use of all factors in the university N rate recommendation algorithm is important for determining the most accurate fertilizer-N rate. Future educational and research projects can work to improve the use of these various factors through the creation of educational programming that shows why and how each factor influences N rate recommendations and their accuracy.

Farm geographic location was related to urea fertilizer management practices, use of nitrification inhibitors, slow-release fertilizers, and use of split-N applications. To minimize NH_3 loss from urea fertilizer, farmers in central South Dakota (lower annual precipitation) were more likely to use a urease inhibitor and apply it before a predicted precipitation event, whereas farmers in eastern South Dakota (higher annual precipitation) were more likely to use tillage to incorporate urea fertilizer. To minimize N loss from leaching and denitrification, farms in eastern South Dakota used nitrification inhibitors and slow-release fertilizers and split up their fertilizer-N applications, while fewer farms in central South Dakota used these technologies. The use of different management practices to minimize N loss between central and eastern South Dakota was likely due to the precipitation differences as the effectiveness of urease and nitrification inhibitors and splitting up N applications is influenced by precipitation amounts (Norton 2008; Fan et al. 2011; Grant et al. 2012; Kovács et al. 2015; Yang et al. 2017; Spackman 2018; Ransom et al. 2020a). These results give evidence that geographic location and precipitation amounts need to be considered when promoting the use of different 4R management practices for inorganic fertilizer-N. Future research into N management practices needs to include field areas in various precipitation areas to provide better information to farmers regarding their effectiveness for their farm location.

Tillage type was related to the use of all 4R inorganic N management practices except the use of split-N applications. This was especially true for urea management as one of the most used methods to lessen NH_3 volatilization loss from urea is to incorporate it with tillage. However, with the increased use of no-till, incorporating urea with tillage to minimize NH_3 loss is no longer an option. This likely explains why farmers who use no-till were most likely to use a urease inhibitor and time urea application before a predicted precipitation event to minimize NH_3 loss, whereas farmers that used tillage were most likely to incorporate urea with tillage. Further, farmers who used no- or reduced-tillage practices were also more likely to use nitrification inhibitors and slow-release fertilizers to minimize N loss from denitrification and leaching. This result supports the theory that farmers who use one conservation practice are more likely to use others (Weber and McCann 2015; Ulrich-Schad et al. 2017). Overall, these results show that the tillage system directly affects N management decisions and should be accounted for when promoting 4R N management practices and completing future research related to ways to increase fertilizer-N use by crops and minimize N loss.

Farm size was related to the use of urea management practices and nitrification inhibitors and slow-release fertilizers. Larger farms most frequently used urease and nitrification inhibitors, and/or slow-release fertilizer technologies to minimize N loss. This greater use was likely due to their greater ability to absorb financial risk and economies of scale (Khanna 2001; Roberts et al. 2004; Ulrich-Schad et al. 2017). Thus, larger farms are more likely to have the financial ability to pay for higher cost fertilizers. These results also show that adoption costs of 4R inorganic N management practices is an important factor to consider when evaluating and promoting the adoption of 4R inorganic N management practices.

These results support the hypothesis that the adoption of 4R fertilizer-N management practices is affected by factors that occur on a smaller scale such as farm location and its precipitation amounts, tillage practice, and farm size (Weber and McCann 2015). Future studies should incorporate smaller-scale local and operational characteristics when determining the variables that affect the adoption of 4R inorganic N management practices. The inclusion of these variables will likely increase the consistency of variables found related to the adoption of 4R fertilizer-N management practices. As these local and operational factors are better understood, nutrient management professionals can incorporate them into their educational and research programs that can provide the needed help to increase the use of 4R fertilizer-N management practices that can ultimately increase the use of fertilizer-N by crops and minimize N loss to the environment.

Acknowledgements

We thank the farmers who participated in the survey and the graduate and undergraduate students who assisted with data collection. Funding for the survey was provided by the South Dakota Nutrient Research and Education Council and National Institute of Food and Agriculture (NIFA) Hatch project SD000H676-18.

References

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR 1009. Ames, IA: Iowa State University Extension.

Adams, C., J. Frantz, and B. Bugbee. 2013. Macro- and micronutrient-release characteristics of three polymer-coated fertilizers: Theory and measurements. Journal of Plant Nutrition and Soil Science 176:76–88. https://doi.org/10.1002/jpln.201200156.

Avemegah, E., W. Gu, A. Abulbasher, K. Koci, A. Ogunyiola, J. Eduful, S. Li, K. Barington, T. Wang, D. Kolady, L. Perkins, A.J. Leffler, P. Kovács, J.D. Clark, D.E. Clay, and J.D. Ulrich-Schad. 2020. An examination of best practices for survey research with agricultural producers. Society and Natural Resources 34:538–549. https://doi.org/10.1080/08941920.2020.1804651.

Baumgart-Getz, A., L.S. Prokopy, and K. Floress. 2012. Why farmers adopt best management practice in the United States: A meta-analysis of the adoption literature. Journal of Environmental Management 96:17–25. https://doi.org/10.1016/j.jenvman.2011.10.006.

Bean, G.M., N.R. Kitchen, J.J. Camberato, R.B. Ferguson, F.G. Fernandez, D.W. Franzen, C.A.M. Laboski, E.D. Nafziger, J.E. Sawyer, P.C. Scharf, J. Schepers, and J.S. Shanahan. 2018. Active-optical reflectance sensing corn algorithms evaluated over the United States midwest corn belt. Agronomy Journal 110:2552–2565. https://doi.org/10.2134/agronj2018.03.0217.

Bouwmeester, R.J.B., P.L.G. Vlek, and J.M. Stumpe. 1985. Effect of environmental factors on ammonia volatilization from a urea-fertilized soil. Soil Science Society of America Journal 49:376–381. https://doi.org/10.2136/sssaj1985.03615995004900020021x.

Chen, D., H. Suter, A. Islam, R. Edis, J.R. Freney, and C.N. Walker. 2008. Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: A review of enhanced efficiency fertilisers. Australian Journal of Soil Research 46:289–301. https://doi.org/10.1071/SR07197.

Clark, J.D., F.G. Fernandez, J.J. Camberato, P.R. Carter, R.B. Ferguson, D.W. Franzen, N.R. Kitchen, C.A.M. Laboski, E.D. Nafziger, J.E. Sawyer, and J.F. Shanahan. 2020. Weather and soil in the US Midwest influence the effectiveness of single- and split-nitrogen applications in corn production. Agronomy Journal 112:5288–5299. https://doi.org/10.1002/agj2.20446.

Clark, J., J. Gerwing, and R. Gelderman. 2019. Fertilizer Recommendations Guide, 2nd edition. Brookings, SD: South Dakota State University Extension.

Clark, J.D., M.A. Yost, T.C. Griggs, G.E. Cardon, C.V. Ransom, and J.E. Creech. 2021. Nitrogen fertilization and glyphosate-resistant alfalfa termination method effects on first-year silage corn. Agronomy Journal 113:1712–1723. https://doi.org/10.1002/agj2.20583.

Clay, D., G. Carlson, S. Clay, and E. Byamukama. 2020. Best Management Practices for Corn Production, 2020 Revision, ed. D. Clay, G. Carlson, S. Clay, and E. Byamukama. Brookings, SD: South Dakota State Extension.

Clay, D.E., G.L. Malzer, and J.L. Anderson. 1990. Ammonia volatilization from urea as influenced by soil temperature, soil water content, and nitrification and hydrolysis inhibitors. Soil Science Society of America Journal 54:263-266. https://doi.org/10.2136/sssaj1990.03615995005400010042x.

Denny, R.C.H., S.T. Marquart-Pyatt, and M. Houser. 2019. Understanding the past and present and predicting the future: Farmers' use of multiple nutrient best management practices in the Upper Midwest. Society and Natural Resources 32:807–826. https://doi.org/10.1080/08941920.2019.1574045.

Dillman, D.A., J.D. Smyth, and L.M. Christian. 2014. Internet, phone, mail, and mixed-mode surveys: The tailored design method. Hoboken, NJ: John Wiley & Sons.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agronomy Journal 94:153–171. https://doi.org/10.2134/agronj2002.0153.

Drury, C.F., X. Yang, W.D. Reynolds, W. Calder, T.O. Oloya, and A.L. Woodley. 2017. Combining urease and nitrification inhibitors with incorporation reduces ammonia and nitrous oxide emissions and increases corn yields. Journal of Environmental Quality 46:939–949. https://doi.org/10.2134/jeq2017.03.0106.

Fan, X.H., Y.C. Li, and A.K. Alva. 2011. Effects of temperature and soil type on ammonia volatilization from slow-release nitrogen fertilizers. Communications in Soil Science and Plant Analysis 42:1111–1122. https://doi.org/10.1080/00103624.2011.566957.

Fernández, F.G., R.E. Terry, and E.G. Coronel. 2015. Nitrous oxide emissions from anhydrous ammonia, urea, and polymer-coated urea in Illinois cornfields. Journal of Environmental Quality 44:415–422. https://doi.org/10.2134/jeq2013.12.0496.

Fernández, F.G., R.T. Venterea, and K.P. Fabrizzi. 2016. Corn nitrogen management influences nitrous oxide emissions in drained and undrained soils. Journal of Environmental Quality 45:1847–1855. https://doi.org/10.2134/jeq2016.06.0237.

Fisichelli, N.A., G.W. Schuurman, A. Symstad, A. Ray, B. Miller, M. Cross, and E. Rowland. 2016. Resource management and operations in southwest South Dakota: Climate change scenario planning workshop summary January 20-21, 2016, Rapid City, SD: US Geological Survey.

Francis, D.D., M.F. Vigil, and A.R. Mosier. 2008. Gaseous losses other than through denitrification. *In* Nitrogen in Agricultural Systems, Agronomy Monograph 492, ed. J.S. Schepers, W.R. Raun, R.F. Follett, R.H. Fox, and G.W. Randall, 255-280. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Goos, R.J. 2013. Effects of fertilizer additives on ammonia loss after surface application of urea-ammonium nitrate fertilizer. Communications in Soil Science and Plant Analysis 44:1909–1917. https://doi.org/10.1080/00103624.2013.783061.

Goos, R.J., and E. Guertal. 2019. Evaluation of commercial additives used with granular urea for nitrogen conservation. Agronomy Journal 111:1441–1447. https://doi.org/10.2134/agronj2018.08.0493.

Grant, C.A., R. Wu, F. Selles, K.N. Harker, G.W. Clayton, S. Bittman, B.J. Zebarth, and N.Z. Lupwayi. 2012. Crop yield and nitrogen concentration with controlled release urea and split applications of nitrogen as compared to non-coated urea applied at seeding. Field Crops Research 127:170–180. https://doi.org/10.1016/j.fcr.2011.11.002.

Halvorson, A.D., C.S. Snyder, A.D. Blaylock, and S.J. Del Grosso. 2014. Enhanced-efficiency nitrogen fertilizers: Potential role in nitrous oxide emission mitigation. Agronomy Journal 106:715–722. https://doi.org/10.2134/agronj2013.0081.

Hargrove, W.L. 1988. Evaluation of ammonia volatilization in the field. Journal of Production Agriculture 1:104–111. https://doi.org/10.2134/jpa1988.0104.

Khanna, M. 2001. Sequential adoption of site-specific technologies and its implications for nitrogen productivity: A double selectivity model. American Journal of Agricultural Economics 83:35–51. https://doi.org/10.1111/0002-9092.00135.

Kim, K.I., D. Clay, S. Clay, G.C. Carlson, and T. Trooien. 2013. Testing corn (*Zea mays* L.) preseason regional nitrogen recommendation models in South Dakota. Agronomy Journal 105:1619–1625. https://doi.org/10.2134/agronj2013.0166.

Kissel, D.E., M.L. Cabrera, and S. Paramasivam. 2008. Ammonium, ammonia, and urea reactions in soils. *In* Nitrogen in Agricultural Systems, Agronomy Monograph 492, ed. J.S. Schepers, W.R. Raun, R.F. Follett, R.H. Fox, and G.W. Randall, 101-156. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Knowler, D., and B. Bradshaw. 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. Food Policy 32:25–48. https://doi.org/10.1016/j.foodpol.2006.01.003.

Kovács, P., G.E. Van Scoyoc, T.A. Doerge, J.J. Camberato, and T.J. Vyn. 2015. Anhydrous ammonia timing and rate effects on maize nitrogen use efficiencies. Agronomy Journal 107(4):1205–1214. doi:10.2134/agronj14.0350.

Laboski, C. 2006. Does it pay to use nitrification and urease inhibitors? Proceedings of the 2006 Wisconsin Fertilizer, Aglime & Pest Management Conference 45:44–50, Madison, Wisconsin. https://extension.soils.wisc.edu/wp-content/uploads/sites/68/2016/07/Laboski_inhibitors-2006-1.pdf.

Ma, B.L., J. Ying, L.M. Dwyer, E.G. Gregorich, and M.J. Morrison. 2003. Crop rotation and soil N amendment effects on maize production in eastern Canada. Canadian Journal of Soil Science 83:483–495. https://doi.org/10.4141/S02-071.

MacDonald, J.M., M.O. Ribaudo, M.J. Livingston, J. Beckman, and W. Huang. 2009. Manure use for fertilizer and energy: Report to congress. Washington, DC: USDA Economic Research Service. https://www.ers.usda.gov/webdocs/publications/42731/16739_ap037fm_1_.pdf?v=.

Morris, T.F., T.S. Murrell, D.B. Beegle, J.J. Camberato, R.B. Ferguson, J. Grove, Q. Ketterings, P.M. Kyveryga, C.A.M. Laboski, J.M. McGrath, J.J. Meisinger, J. Melkonian, B.N. Moebius-Clune, E.D. Nafziger, D. Osmond, J.E. Sawyer, P.C. Scharf, W. Smith, J.T. Spargo, H.M. van Es, and H. Yang. 2018. Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. Agronomy Journal 110:1–37. https://doi.org/10.2134/agronj2017.02.0112.

Norton, J.M. 2008. Nitrification in agricultural soils. *In* Nitrogen in Agricultural Systems, Agronomy Monograph 49, ed. J.S. Schepers, W.R. Raun, R.F. Follett, R.H. Fox, and G.W. Randall, 201-255. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Osmond, D.L., D.L.K. Hoag, A.E. Luloff, D.W. Meals, and K. Neas. 2015. Farmers' use of nutrient management: Lessons from watershed case studies. Journal of Environmental Quality 44:382–390. https://doi.org/10.2134/jeq2014.02.0091.

Prokopy, L.S., K. Floress, J.G. Arbuckle, S.P. Church, F.R. Eanes, Y. Gao, B.M. Gramig, P. Ranjan, and A.S. Singh. 2019. Adoption of agricultural conservation practices in the United States: Evidence from 35 years of quantitative literature. Journal of Soil and Water Conservation 74(5):520–534. https://doi.org/10.2489/jswc.74.5.520.

Randall, G.W., and J.A. Vetsch. 2005a. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by fall and spring application of nitrogen and nitrapyrin. Journal of Environment Quality 34:590–597. https://doi.org/10.2134/jeq2005.0590.

Randall, G.W., and J.A. Vetsch. 2005b. Corn production on a subsurface-drained Mollisol as affected by fall versus spring application of nitrogen and nitrapyrin. Agronomy Journal 97:472–478. https://dl.sciencesocieties.org/publications/aj/abstracts/97/2/0472.

Randall, G.W., J.A. Vetsch, and J.R. Huffman. 2003. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by time of nitrogen application and use of nitrapyrin. Journal of Environmental Quality 32:1764–1772. https://doi.org/10.2134/jeq2003.1764.

Ransom, C.J., V.D. Jolley, T.A. Blair, L.E. Sutton, and B.G. Hopkins. 2020a. Nitrogen release rates from slow- and controlled-release fertilizers influenced by placement and temperature. PLoS ONE 15:1–21. https://doi.org/10.1371/journal.pone.0234544.

Ransom, C.J., N.R. Kitchen, J.J. Camberato, P.R. Carter, R.B. Ferguson, F.G. Fernández, D.W. Franzen, C.A.M. Laboski, E.D. Nafziger, J.E. Sawyer, P.C. Scharf, and J.F. Shanahan. 2020b. Corn nitrogen rate recommendation tools' performance across eight US midwest corn belt states. Agronomy Journal 112:470–492. https://doi.org/10.1002/agj2.20035.

Ransom, C.J., N.R. Kitchen, J.J. Camberato, P.R. Carter, R.B. Ferguson, F.G. Fernández, D.W. Franzen, C.A.M. Laboski, D.B. Myers, E.D. Nafziger, and J.F. Shanahan. 2021. Improving publicly available corn nitrogen rate recommendation tools with soil and weather measurements. Agronomy Journal 113:2068–2090. https://doi.org/10.1002/agj2.20627.

Ribaudo, M., J. Delgado, L. Hansen, M. Livingston, R. Mosheim, and J. Williamson. 2011. Nitrogen in agricultural systems: Implications for conservation policy. Washington, DC: USDA ERS.

Ribaudo, M., M. James, and W. Livingston. 2012. Nitrogen management on U.S. corn acres, 2001-10, EB-20. Washington, DC: USDA ERS.

Roberts, R.K., B.C. English, J.A. Larson, R.L. Cochran, W.R. Goodman, S.L. Larkin, M.C. Marra, S.W. Martin, W.D. Shurley, and J.M. Reeves. 2004. Adoption of site-specific information and variable-rate technologies in cotton precision farming. Journal of Agricultural and Applied Economics 36:143–158. https://doi.org/10.1017/s107407080002191x.

Rochette, P., D.A. Angers, M.H. Chantigny, M.-O. Gasser, J.D. MacDonald, D.E. Pelster, and N. Bertrand. 2013. Ammonia volatilization and nitrogen retention: How deep to incorporate urea? Journal of Environmental Quality 42:1635–1642. https://doi.org/10.2134/jeq2013.05.0192.

Sawyer, J.E., E. Nafziger, G.W. Randall, L. Bundy, G. Rehm, and B. Joern. 2006. Concepts and rationale for regional nitrogen rate guidelines for corn. PM 2015. Ames, IA: Iowa State University Extension. http://lib.dr.iastate.edu/extension_pubs/105.

Silva, A.G.B., C.H. Sequeira, R.A. Sermarini, and R. Otto. 2017. Urease inhibitor NBPT on ammonia volatilization and crop productivity: A meta-analysis. Agronomy Journal 109:1–13. https://doi.org/10.2134/agronj2016.04.0200.

Spackman, J.A. 2018. Nitrogen fertilizer rate, source, and application timing effects on soil nitrogen and corn yield. Master's thesis, University of Minnesota. https://conservancy.umn.edu/bitstream/handle/11299/198963/Spackman_umn_0130M_19309.pdf?sequence=1&isAllowed=y.

Spackman, J.A., F.G. Fernandez, J.A. Coulter, D.E. Kaiser, and G. Paiao. 2019. Soil texture and precipitation influence optimal time of nitrogen fertilization for corn. Agronomy Journal 111:2018–2030. https://doi.org/10.2134/agronj2018.09.0605.

Struffert, A.M., J.C. Rubin, F.G. Fernandez, and J.A. Lamb. 2016. Nitrogen management for corn and groundwater quality in Upper Midwest irrigated sands. Journal of Environment Quality 45:1557–1564. https://doi.org/10.2134/jeq2016.03.0105.

Stuart, D., R.L. Schewe, and M. McDermott. 2014. Reducing nitrogen fertilizer application as a climate change mitigation strategy: Understanding farmer decision-making and potential barriers to change in the US. Land Use Policy 36:210–218. https://doi.org/10.1016/j.landusepol.2013.08.011.

Thies, S., D.R. Joshi, S.A. Bruggeman, S.A. Clay, U. Mishra, J. Morile-Miller, and D.E. Clay. 2020. Fertilizer timing affects nitrous oxide, carbon dioxide, and ammonia emissions from soil. Soil Science Society of America Journal 84:115–130. https://doi.org/10.1002/saj2.20010.

Trenkel, M.E. 2010. Slow- and controlled-release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture, 2nd edition. Paris, France: International Fertilizer Industry Association (IFA).

Ulrich-Schad, J.D., S. Garciá De Jalón, N. Babin, A. Pape, and L.S. Prokopy. 2017. Measuring and understanding agricultural producers' adoption of nutrient best management practices. Journal of Soil and Water Conservation 72:506–518. https://doi.org/10.2489/jswc.72.5.506.

Upadhyay, L.S.B. 2012. Urease inhibitors: A review. Indian Journal of Biotechnology 11(October):381–388.

Upadhyay, D.L., D.L. Young, H.H. Wang, and P. Wandschneider. 2003. How do farmers who adopt multiple conservation practices differ from their neighbors? American Journal of Alternative Agriculture 18:27–36. https://doi.org/10.1079/AJAA2003027.

USDA ERS (USDA Economic Research Service). 2019. Fertilizer use and price. USDA ERS Data Products. Washington, DC: USDA ERS. https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx.

USDA NASS (USDA National Agricultural Statistics Service). 2021. South Dakota district and county boundary maps. Charts and Maps. Washington, DC: USDA NASS. https://www.nass.usda.gov/Charts_and_Maps/Crops_County/boundary_maps/indexgif.php.

Venterea, R.T., T.J. Clough, J.A. Coulter, E.F.C. Souza, F. Breuillin-Sessoms, K.A. Spokas, M.J. Sadowsky, S.K. Gupta, and K.F. Bronson. 2021. Temperature alters dicyandiamide (DCD) efficacy for multiple reactive nitrogen species in urea-amended soils: Experiments and modeling. Soil Biology and Biochemistry 160:108341. https://doi.org/10.1016/j.soilbio.2021.108341.

Vetsch, J.A., G.W. Randall, and F.G. Fernández. 2019. Nitrate loss in subsurface drainage from a corn–soybean rotation as affected by nitrogen rate and nitrapyrin. Journal of Environmental Quality 48:988–994. https://doi.org/10.2134/jeq2018.11.0415.

Vitousek, P.M., J.D. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and D.G. Tilman. 1997. Human alteration of the global nitrogen cycle: Sources and consequences. Ecological Applications 7:737–750. https://doi.org/10.1890/1051-0761(1997)007[0737:HAOTGN]2.0.CO;2.

Weber, C., and L. McCann. 2015. Adoption of nitrogen-efficient technologies by U.S. corn farmers. Journal of Environmental Quality 44:391–401. https://doi.org/10.2134/jeq2014.02.0089.

Williamson, J.M. 2011. The role of information and prices in the nitrogen fertilizer management decision: New evidence from the agricultural resource management survey. Journal of Agricultural and Resource Economics 36:552–572.

Yang, H.S., A. Dobermann, J.L. Lindquist, D.T. Walters, T.J. Arkebauer, and K.G. Cassman. 2004. Hybrid-maize—A maize simulation model that combines two crop modeling approaches. Field Crops Research 87:131–154. https://doi.org/10.1016/j.fcr.2003.10.003.

Yang, Y., X. Ni, Z. Zhou, L. Yu, B. Liu, Y. Yang, and Y. Wu. 2017. Performance of matrix-based slow-release urea in reducing nitrogen loss and improving maize yields and profits. Field Crops Research 212:73–81. https://doi.org/10.1016/j.fcr.2017.07.005.