Summary

Globally, ammonia (NH_3) loss to the atmosphere from agriculture (fertilizer and manure) represents a significant pollution source, accounting for 50% of global emissions. Elevated atmospheric NH3 can lead to formation of fine particulates, a major source of haze that reduces visibility. Further its deposition into natural, undisturbed ecosystems that are typically nutrient poor can to lead to changes in plant communities, soil acidification, and eutrophication of natural waters. In addition, because N is the primary nutrient limiting crop growth, NH_3 loss to the environment represents a potential economic loss to farmers as a result of N deficiency and reduced crop yield and quality. This project was conducted to quantity on-farm NH_3 losses from legume green manure and fertilizer inputs in Montana identify environmental and soil conditions conducive to large NH_3 losses, define management strategies to mitigate losses, and communicate the results to producers and agricultural professionals. The emphasis for our fertilizer studies was urea, because it represents 86% of the fertilizer N consumption in the state and is often broadcast applied to the soil surface in no-till systems that dominate Montana dryland cropping systems.

Field trials were conducted on private farms under long-term no-till management in north and central Montana. In 2011 and 2012, trials conducted with field peas (*Pisum sativum* L.) revealed that termination of this crop by mowing or with herbicides resulted in only nominal NH_3 losses equivalent to only 0.3 to 0.5% of the N in plant biomass and indicating that N fertility was not diminished appreciably following legume termination. A urea application timing trial was conducted over three seasons in central Montana and revealed that cumulative NH_3 losses averaged 16.3, 11.4, and 1.9% for applications (100 kg N ha-1) in the late-fall, mid-winter, and spring. The lower NH_3 loss for the spring applications was attributed to the greater frequency of large precipitation events that resulted in urea infiltration in the soil where it is protected against volatility. Conversely, applications in the late-fall and winter to cold frozen soils were typically followed by light precipitation events, and as a result urea remained at, or near, the surface for an extended period of time. Under these conditions, urea hydrolysis occurred slowly as a result of cold temperatures and limited water, and although NH3 fluxes were low in intensity, they were prolonged, lasting 80 to 100 d post-application.

Several strategies to mitigate NH_3 loss from urea were tested with varying results. Addition of the urease inhibitor, NBPT or Agrotain®, produced consistent results and reduced cumulative NH3 losses by 64% over untreated urea. Four field trials were conducted to determine if surface applying urea in advance of seeding would mitigate NH_3 loss. Interest in this strategy came as a result of communication with growers at meetings where they asked if the disturbance created by their air-seeders configured with hoe-style openers was sufficient to cover urea prills on the soil surface and thereby mitigate NH3 loss. The results of these tests were negative, meaning there was no significant difference in NH3 losses between applying urea pre or post seeding. Growers also asked whether urea applications onto snow would result in nominal NH3 losses. This mitigation strategy was evaluated in the winter of 2011 at a field site in central Montana. Urea was broadcast onto a field with a modest snowpack (0.9 cm water equivalent). Cumulative NH_3 loss from urea was found to be equivalent to 21% of the N application (100 kg N ha-1) over an 8- wk period, invalidating this mitigation approach. Results from this last trial and other trials indicate that NH_3 emissions in the winter were typically most intense during thaw-periods, when the snowpack disappears and/or the soil transitions from wet to dry (referred to as “wet to dry cycle”).

This study conducted an active education and outreach program to producers and agricultural professionals that produced three referred publications, seven abstracts and proceedings, four MSU

extension publications, two ag-industry articles, one press release, a web site and 33 oral presentations to a diverse audience that included growers, commodity groups, ag-industry reps, and scientists. We were successful in reaching (and exceeding) our performance target of 1000 people-hr and indirect contact with another 5,000 people through radio, news releases, ag-professional training, and farmer to farmer communication. The impact of our results with producers was evaluated through online surveys (MT), and the surveys at the conclusions of meetings (ID and MT). The results show that approximately 50% of MT and 12% of ID growers made changes to their N managements in response to information presented from this study. The economic impact of these changes to Montana either through reduced fertilizer N loss, or greater net revenue from higher wheat yield or protein was found to be approximately $5 million annually. However, because we disseminated our results nationally with a focus in the West, the actual savings would likely be greater.

Introduction

Ammonia (NH_3) volatilization is a significant pathway of N loss from agricultural systems accounting for 50% of global emissions (Schlesinger and Hartley, 1992). Elevated atmospheric NH3 may pollute surface waters and contribute to loss of diversity in natural ecosystems. In addition, NH3 losses reduce economic sustainability when N that would otherwise be utilized by crops is lost to the environment. Farmers in Montana and neighboring states are likely experiencing significant N losses as NH3 from chemical or biological inputs without their knowledge. One example is provided by N fertilization programs currently being practiced on Montana farms. Montana family farms are characterized by large acreage, no-till or minimal disturbance management, and wheat or related grains as the primary incoming producing crop. Optimum winter wheat seeding in the NGP occurs over a short time window resulting in considerable time constraints on individual farmers who often seed 1500 to 2000+ acres. Although most modern air-drills are capable of injecting N fertilizer below the soil surface where it is less susceptible to volatilization, this practice is often not performed as it is slows seeding operations down. Therefore, most growers defer N fertilization until late-fall to early spring when urea (46-0-0) is typically surface broadcast. The rationale for this management decision is based on the desire to expedite seeding operations, and the belief that NH3 volatilization is not problematic if urea is applied to cold soils. In 2008, a micrometeorological study conducted in Montana found substantial volatilization losses (up to 40%) can occur even when urea is applied to cold soils (~0˚ C); thereby, contradicting these long-held beliefs, and impacting sustainability of no till in the NGP (Engel and Wallander, 2009).

Although NH3 volatilization from chemical fertilizer is a significant path of N loss, few on-farm studies using a micrometeorological approach (SARE database, Nat. Agric. Library, USDA-CRIS) have been conducted in Montana and semiarid climates in the West. Also, many N fertilizer studies focus on losses that occur under warm temperatures (> 50 F). In Montana, N fertilizer is rarely applied under these warmer conditions, but rather during cold weather months. Similarly, only a few studies have looked directly at NH3 losses associated with legume green manure termination or decomposition. Legume green manures, often promoted as an N fertilizer source in diversified production systems. Previous research has indicated that volatilization losses of NH3 from decomposing green manure may appreciably diminish its fertility benefit and represent an important contribution to atmospheric N (Janzen et al., 1991). As an example, a study in Sweden found volatilization losses of NH3 from alfalfa and high-N grass mulch were equivalent to 17% and 39% of the assimilated plant N (Larsson et al., 1998). In addition, grain N following legume green manures has been found to be higher after tillage than after chemical termination especially at low N rates, suggesting higher N loss from chemical termination (Burgess et al 2014).

The proposed study utilized a mass-balance micrometeorological approach referred to as the integrated horizontal flux method to quantify NH_3 emissions associated with urea fertilization (chemical) and legume green manure termination (biological). Studies were conducted at dryland farms in northern and central Montana, and provided new knowledge to alert growers about NH3 loss from their fields and to inform them of management strategies that minimize these losses. The proposed research and education project seeks to expand upon this existing work recently initiated in this region (http://landresources.montana.edu/ureavolatilization/) and to provide outreach and education to the agricultural community, including farmers and agricultural professionals.

References

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Objectives/Performance Targets

i. To quantify on-farm ammonia loss from urea fertilizer applications (chemical) and legume termination (biological) from NGP dryland cropping systems.

Our performance target was to determine the fraction of applied urea fertilizer lost as NH_3 for applications to winter wheat applied from late-fall to early spring. Our study sought to identify the environmental and soil conditions that were most conducive to high NH_3 losses. Our second performance target was to determine the fraction of N in legume manure lost as NH_3 following its termination by mowing and/or glyphosate spraying.

ii. Identify mitigation strategies or production practices that minimize ammonia-N losses where losses were found to be significant from inorganic and organic N inputs. Our performance target was to mitigate NH_3 losses to $\leq$ 5% of the N input.

iii. Develop and execute an educational outreach program to producers and agricultural professionals that will improve their understanding of on-farm N cycles and N loss mitigation, thereby leading to enhanced sustainability and environmental quality. Our performance target was to achieve direct contact with 1000 people (or people-hrs) and indirect contact with another 5,000 people through radio, news releases, ag-professional training, and farmer to farmer communication. Our education program targeted ag-professionals as they were involved in outreach to their grower clients. Therefore we anticipated a multiplier effect to our direct contact hours outreach program to producers and agricultural professionals that have, and will, improve their understanding of on-farm N cycles and N loss mitigation.

Materials and Methods

Field trials were established at private farms in Hill and Fergus County, Montana over four seasons in support of Objectives i and ii. All trials were conducted in fields under no-till management. Ammonia gas loss measurements were quantified according to the integrated horizontal flux method using circular plots (20 m radius), and a center mast equipped with five or six NH_3 Leuning samplers (traps). Details on the mast and shuttle design, NH_3 loss calculations, corrections for atmospheric background NH_3, shuttle elution, and chemical analysis of NH_3 can be found at http://landresources.montana.edu/ureavolatilization. The design of many of our field trials was done with the participation and input from growers and consistent with SARE foundation respect for agricultural producers. The trials included the following experiments.

- Two field trials conducted in northern Montana (Hill County) in 2011 and 2012 focused on NH_3 loss following termination of field peas (*Pisum sativum* L.) by mowing or with herbicides (2011 only).

- Growers in Montana frequently surface-apply urea during cold weather months and growers have wondered whether NH_3 losses from urea could be mitigated if applications were made to cold soils during the winter. In addition, the use of NBPT or Agrotain® has been promoted by the fertilizer industry as a way to mitigate NH_3 loss from urea. To address these questions, we conducted a cold weather urea and urea+ N-butyl thiosphoric triamide (NBPT) application timing experiment over three seasons (2011-2012, 2012-2013, and 2013-2014) in central Montana (Fergus County). The timings included a late-fall application at freeze-up, a mid-winter application in February, and a spring application in April. The three urea timings were included in order to cover the time window (late-fall to spring) when most urea applications are made to winter wheat in Montana. At each timing urea was surface-applied at (100 kg N ha^{-1}) without and with NBPT (0.1%) or Agrotain®. NBPT is a urease inhibitor that reduces the rate of urea hydrolysis in the soil, thereby inhibiting NH_3 loss, and was included in order to quantify the potential of this product to mitigate NH_3 loss.

- A pre-plant urea application timing experiment was conducted at four field sites in northern Montana (Hill County) during the fall of 2010 and 2011. *Interest in investigating this mitigation strategy came as a result of our discussions with growers at meetings and one-on-one visits. During these meetings, growers asked if the disturbance created by their air-seeders configured with hoe-style openers was sufficient to cover urea granules on the soil surface, thereby mitigating NH3 losses.* Urea was applied as a pre-plant (< two hr prior of seeding) and post-plant (< two hr following seeding) at a rate of 100 kg N ha^{-1}. The post-plant urea treatment was included as a positive control to assess the potential for NH_3 loss from urea without incorporation.

- The final mitigation strategy tested was to apply urea onto snow. This mitigation approach was tested at a field site in central Montana (Fergus County) in the winter of 2011 as we were asked by growers if NH_3 loss from urea could be prevent if applications were made onto a snowpack.

Our education and outreach program consisted of scientific articles, proceedings at regional meetings, producer directed publications, and oral presentations to diverse audience groups. Grower surveys (pre-study and post-study) were conducted near the beginning (Dec 2011) and end of this study

(March-July 2014) in support of Objective iii (see attachments). The surveys were conducted to identify more clearly grower N management and cropping practices, and knowledge of conditions that are conducive to fertilizer N volatilization losses. Surveys were approved by MSU's Institutional Review Board prior to delivery. The pre-study survey was emailed to all Montana Grain Growers Association (MGGA) members who provided email addresses (n=~700) and a hardcopy mailed to the remainder (n=~300). It was also handed out at several workshops in Montana, Idaho, and Wyoming. Numbers completing the survey were 86, 47, and 7, for MT, ID, and WY, respectively. The area farmed by those respondents totaled 540,000 acres. The post-study online survey was emailed to all MGGA members with email addresses (vast majority), and was advertised in an MSU press release, the Montana Conservationist (June), and the Montana Grain News (July edition). A total of 75 producers responded, representing 240,000 acres. In addition, a post-study survey (4 questions) was conducted at two oral presentations in Montana and five presentations in Idaho, with 31 and 230 respondents, respectively.

Results and Discussion/Milestones

Ammonia volatilization following termination of field peas

The results of this trial are summarized in the Canadian Journal of Soil Science (Engel et al. 2013. Ammonia volatilization losses were small after mowing field peas in dry conditions. Can. J. Soil Sci. 93:239-242). In 2011, peas were terminated (6-July) by mowing (**Figure 1**) and herbicide spraying (2,4-D amine) at the early-pod stage. In 2011, peas were terminated by mowing only at the flowering stage. Field pea biomass at termination was equivalent to 3610 and 2780 kg dry matter ha^{-1} in 2011 and 2012, respectively. These pea biomass yields were somewhat above normal for this semiarid region. The N content in the biomass at termination was 105 and 79 kg N ha^{-1} in 2011 and 2012, respectively. Ammonia losses were measured over two weeks following termination. Cumulative NH_3 loss from peas was equivalent to 0.3 and 0.5% of the N in the above-ground tissue for the 2011 and 2012 trials, respectively. These results indicated no reduction in the fertilizer N value of field pea residue as a result of NH_3 volatilization, at least for the 2-wk following termination. Peas were terminated by mowing in this study, which was very destructive to plant tissue and left the residue on the soil surface exposed to the atmosphere. The level of disturbance likely equals, or exceeded, what might be expected from tillage by a farm implement. Hence, we would expect NH_3 loss to be nominal from peas terminated by tillage under similar environmental conditions. Also, tillage will bury a portion of the green manure residue, which should further mitigate NH_3 emissions to the air as has been reported in the literature. The results of this study represent good news to growers in the semiarid Great Plains who are concerned about N losses from NH_3 volatilization following green manure termination.

Figure 1. Field peas were terminated at the early-pod stage in 2011 (top) and flowering in 2012 (bottom) at field sites near Havre, Montana. A mast with Leuning samplers was erected inside of the circular plots to trap NH_3 loss according to the integrated horizontal flux method.

Surface-urea applications timing during cold weather months

Cumulative NH_3 losses for the three growing seasons are summarized in **Table 1**. A summary of the results and conclusions is provided below.

1. Cumulative NH_3 loses from urea were greater for late-fall (16.3% of applied N) and mid-winter (11.4% of applied N) than spring applications (1.9 % of applied N). Ammonia emission activity following the late-fall and mid-winter was often of modest intensity but prolonged in duration. An example was provided by the NH_3 flux vs. time relationships for the late-fall applications (Figure 2). Maximum NH_3 fluxes were observed between 14 and 28 d post-fertilization and ranged from 18.3 to 26.6 g N ha^{-1} hr^{-1}. This equates to 3.1 to 4.5 kg N ha^{-1} per week. The modest emission intensity and prolonged NH_3 emission activity was a result of the cold temperature and dry conditions during Montana winters that slowed urea hydrolysis rates. Soil temperatures during the winter were typically near or below 0 ˚C and sometimes covered by modest snow-pack, but periods of intermittent thaw created snow-free conditions. Emissions did not permanently fall to < 1 g ha^{-1} hr^{-1} until 103 and 130 d post-fertilization in 2012-2013 and 2013-2014, respectively. Ammonia emission measurements in 2011-2013 never fell to < 1 g ha^{-1} hr^{-1} after 87 d. It is possible our NH_3 loss measurements would have been somewhat higher had the gas sampling campaign been continued.
2. Elevated NH_3 emission fluxes were strongly related to evaporation i.e. fluxes rose as evaporation increased. An example was provided by the photographs from trials conducted in 2011-2013 (late-fall application) (**Figures 3**) showing the change in field conditions over a 1 week period. Winters in Montana are typified by light snowfall events that result in modest snow accumulation, followed by periods of thaw or melting where the snowpack disappears. During this period of snowpack melting and evaporation, the soil surface transitions from wet to dry, referred to as a wet to dry cycle, and NH_3 emission activity from urea becomes elevated.
3. Cumulative losses of NH_3 were lower for the early-spring application compared to the late-fall and winter applications because of the occurrence of more frequent and intense precipitation events following fertilization. For example, in 2011-2012, a large spring precipitation event (25 mm) occurred over 2-4 d following fertilization resulting in only a 1.2% cumulative N loss. In 2012-2013, a total of 187 mm of precipitation was recorded over the 55 d following fertilization, and resulted in only a 4.2% N loss; and in 2013-2014 17 mm of precipitation was received over the first 2 wk post-fertilization resulting in less than 1% loss. Our performance target at the start of this study was to mitigate NH_3 losses to ≤ 5% of the N input. The results of this study indicate that by delaying N applications to early-spring we have a better chance of synchronizing N applications in advance of large precipitation events that are more common in the spring compared to the winter and reducing N losses to less than 5% of the N input.
4. Addition of NBPT or Agrotain® reduced NH_3 loss from urea by 64% (average of early and mid-winter trials) thereby validating its efficacy to mitigate NH_3 loss. Coating urea with Agrotain® cost approximately $55 per ton of fertilizer. Assuming urea cost $500 per ton this represents an 11% added cost which would need to be recovered through increase wheat yield or protein, or in reduced N fertilizer application in order to justify its use.

Table 1. Cumulative ammonia loss (% of applied N) from urea as affected by NBPT from surface-applied urea following late-fall, winter, and early-spring applications to winter wheat fields.

Season	Fertilizer application		Trial duration	Cumulative NH_3 loss		NBPT
	timing	date		Urea	Urea + NBPT	mitigation
			d	---- % applied N † ----		%
2011-2012	late-fall	29-Nov	87	13.4	5.9	56.0
	mid-winter	28-Feb	49	13.0	4.1	68.5
	spring	24-Apr	21	1.2	0.0	-
2012-2013	late-fall	12-Dec	106	19.3	5.3	72.5
	mid-winter	8-Feb	48	10.6	3.6	66.0
	spring	12-Apr	55	4.2	1.4	66.7
2013-2014	late-fall	1-Dec	103	16.3	6.2	62.0
	mid-winter	21-Feb	62	10.6	4.9	53.8
	spring	18-Apr	26	0.2	0.0	-
$\bar{x}$	late-fall			16.3	5.8	
	mid-winter			11.4	4.2	
	spring			1.9	0.5	

† N application rate = 100 kg N ha^{-1}; NBPT added as Agrotain® at 0.1%

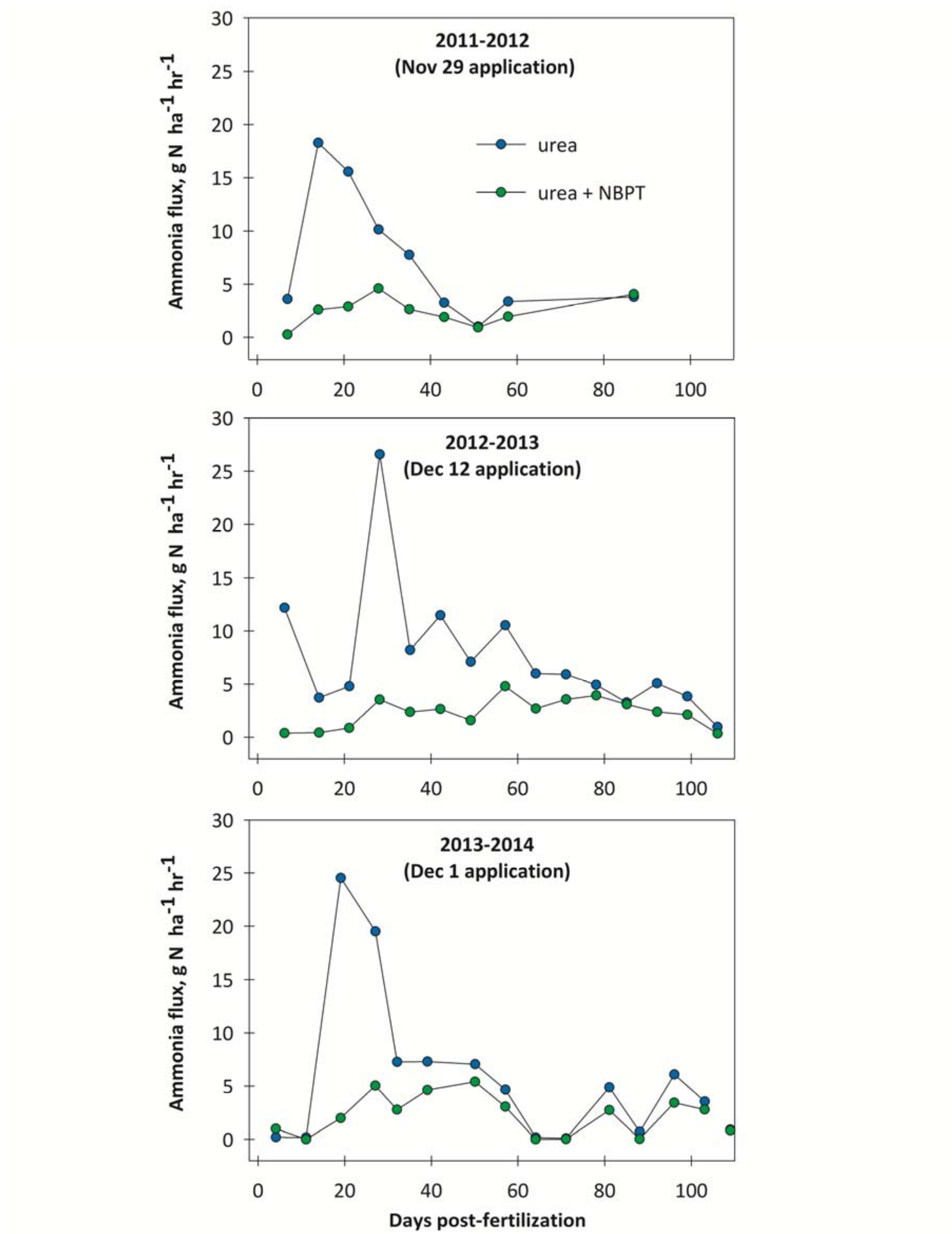

Figure 2. Ammonia flux vs. day post-fertilization following the late-fall applications of urea and urea + NBPT in 2011-2012, 2012-2013, and 2013-2014.

Figure 3. These photographs illustrate the change in field conditions over a 1-wk period in January 2013, and following the late-fall application during season 2012-2013 for the Fergus County site. Highest ammonia losses from fertilizer were typically associated with wet to dry cycles. During this period, 4.5 kg N ha^{-1} (4.5% of applied N) was lost to the atmosphere as ammonia (see emission peak at 28 d in Figure 2 - middle).

Pre-plant urea application timing experiments to mitigate ammonia loss

Results from the four trials comparing pre-plant vs. post-plant urea applications are summarized in **Table 2**. Cumulative NH_3 loss averaged 14.0 and 12.8% of applied N for the pre- and post-plant applications, respectively. A paired t-test indicated there was no significant difference between the treatments (P=0.64), indicating the soil disturbance created by air-drills seeders was not sufficient to mitigate NH_3 loss. In two trials (Trial 3 and 4), seeding was done into soil which was extremely dry (< 5% moisture by weight) near the surface such that dust clouds were created behind the seeder (**Figure 4a**). The disturbance level created by the air-drills at these sites was nominal and urea granules were still visible at the surface (**Figure 4 b,c**). In contrast, the surface soil layer at Trials 1 and 2 contained 15.0 and 12.6% moisture and the air-drill created somewhat more disturbance at these sites. Although many of urea granules were not visible, no reduction in NH_3 loss was observed. Overall, NH_3 losses were lower at Trials 3 and 4 relative to Trials 1 and 2 because of dry soil conditions at seeding and minimal rainfall amounts following seeding. These conditions likely limited urea hydrolysis. Precipitation totaled only 7.7 and 19.2 mm over the first 7 weeks post-fertilization at Trials 3 and 4, respectively. A large percentage of the applied urea likely never hydrolyzed during Trial 3 because of drought conditions.

Table 2. Cumulative NH_3 loss from surface-applied urea (100 kg N ha-1) following application post-plant and pre-plant to a no-till winter wheat field at four trials in Hill County, Montana. Surface soil moisture on the date of seeding.

Trial	Fertilization date	Trial duration	Surface soil moisture content (0-2 cm depth)	Cumulative NH_3 loss	
				post-plant N	pre-plant N
		d	g/g	---- % applied N † ----	
1	15-Sep-2010	64	15.0	13.8	18.7
2	27-Sep-2010	71	12.6	24.7	20.6
3	7-Oct-2010	62	3.3	5.6	4.7
4	16-Sep-2011	83	4.5	7.2	11.9
x̄				12.8	14.0

Figure 4. Seeding into dry soil conditions at a field site in Hill County, Montana. September 16, 2011. Trial 4 (a). Soil disturbance at this site was insufficient to cover urea granules and protect against volatility losses. A narrow style opener was used at this field site. Urea granules on surface before (b) and after (c)) seeding from the same microsite in the field. Arrows indicate visible granules.

Urea onto snow

Cumulative NH_3 losses from urea were equivalent to 20.7% of the application rate (100 kg N ha-1) over an 8-wk period (**Figure 5**). Losses were particularly large during the second week (6-13 d post-fertilization) when the snow-pack disappeared (**Figure 6**) and the surface soil conditions followed a wet to dry cycle. Coating urea with Agrotain provided approximately two weeks of volatility protection and reduced NH_3 losses by approximately 50% over untreated urea.

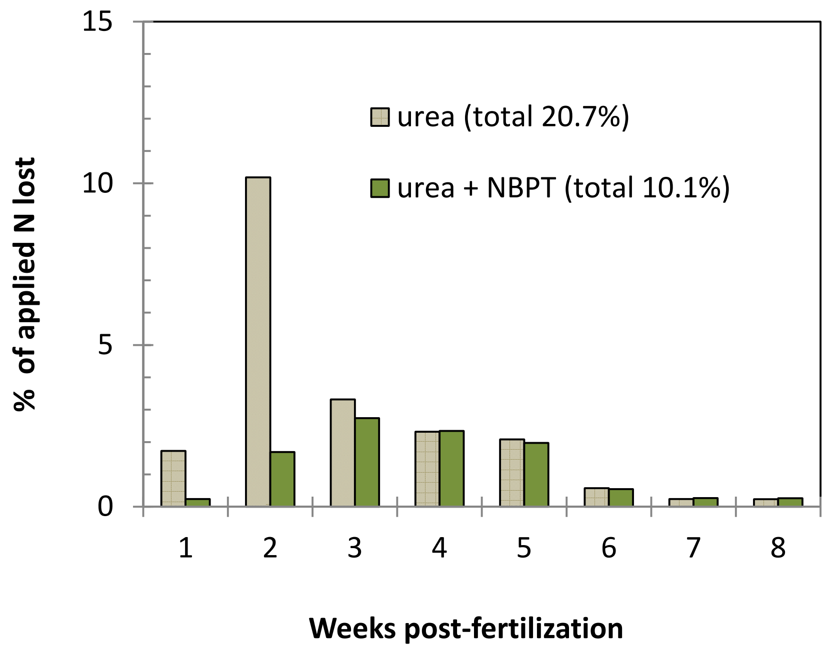

Figure 5. Weekly NH_3 losses (expressed a percentage of applied N) from surface-applied urea and Agrotain-coated urea at field site in Fergus County, Montana. Fertilizer was applied on 02-March 2011.

a.
March 2, 2011
(fertilization date)

b.
March 8, 2011
(1 wk post-fertilization)

c.
March 15, 2011
(2 w post-fertilization date)

Figure 6. Urea was surface-applied to a snow-covered (0.89 cm water) winter wheat field site in Fergus County, Montana on March 2, 2011 (a). Field site 1-wk (a) and 2-wk (b) post-fertilization.

Our education and outreach program produced three refereed publications, seven abstracts and proceedings at professional meetings, three industry publications, one Montana State University press release, four University extension publications, and the web site devoted to the results of our work with urea (thttp://landresources.montana.edu/ureavolatilization). A detailed list of activities and outputs is provided in the Education and Outreach section. Our outreach activities were highlighted by 33 oral presentations times over the project cycle to a range of audiences that included growers, crop advisor, Extension Agents, and scientists; 7500 visits over two years to our urea volatilization web since we began tracking numbers in May 2012; and a 2013 American Society of Agronomy Excellence Award in Extension Materials for our MSU Extension publication "Management to Minimize Nitrogen Fertilizer Volatilization". Our performance target for this study was to achieve direct contact with 1000 people (or people-hr) and indirect contact with another 5,000 people through radio, news releases, ag-professional training, and farmer to farmer communication. We were successful in achieving these performance targets, Specifically, our accumulated direct contact hours exceeded 1400 people (140% of target) through our speaking engagements, and our indirect contact hour was far greater than 5000 people as evidenced by the circulation and readership numbers of the Ag-Industry and MSU Extension publications and webpage visits.

Impact of Results/Outcomes

The results of this study and previous research indicate that NH_3 losses from surface-applied urea can be mitigated by:

1. Timing urea applications that are applied to dry soil surfaces and in advance of large precipitation events. In Montana, large precipitation events are more common in the spring compared to winter. Hence, spring applications are likely to see lower NH_3 losses compared to winter applications. At least 13 mm of precipitation (0.5”) in a single event is needed to move urea into the soil deep enough to prevent volatilization. Light scattered rain is often not sufficient moisture; it may increase rather than prevent volatilization losses.
2. Avoiding urea applications to when the soil surface is wet or damp, and/or snow-covered. Large losses of NH_3 can occur under these conditions (up to 22% of applied N can be lost in 1 week) particularly if the applications to wet surfaces are followed by period of drying with little or no precipitation.
3. Utilizing urease inhibitors such as Agrotain®. Our field tests with Agrotain® indicate that NH_3 volatilization losses are mitigated by approximately 64%.
4. Applying urea in a subsurface band. Although we did not specifically test this strategy during this study, we have promoted this approach during our Education and Outreach programs because NH_3 losses from urea are known to be eliminated by placement of urea granules below the soil surface.

These recommendations were communicated to the Montana ag-community at grower meetings and oral presentations over the course of this study. Their impact on grower production practices was evaluated in a post-study survey. Growers were asked if they adjusted management practices based on the results of our study. In Montana, results from the online survey found that 30% of the growers now adjust for weather, 18% now use an enhanced efficiency fertilizer such as Agrotain˚, and 25% now subsurface band (**Figure 7**). About 12% had not made any changes yet, and 16% were already using these practices prior to the study. Only 13% of the respondents were not aware of our study. Clicker respondents (of those who changed practices) at oral presentations in Sidney and Malta found that 48% began using enhanced efficiency fertilizer products, 35% now consider weather by applying urea on dry soil or before rainfall, and 12% now apply urea in a subsurface band. Combined survey and clicker responses from Montana indicated that because of this WSARE funded research, 22% started considering weather more, 16% began using an enhanced product and 16% began subsurface banding. The increase in the number of people who subsurface band N at seeding is particular significant, because injecting N below the soil surface will eliminate NH_3 volatility losses. Our survey found 42% of our respondents now apply the majority of their N fertilizer in a subsurface band (**Figure 8**). It this survey is indicative of the entire state it now represents the primary approach for N management, followed by spring broadcast applications timings (39%) which we have found to be the least susceptible to NH_3 volatility of different broadcast timings.

Post-survey responses from Idaho were very different, where fully 77% were not aware of the research, and only 13% were both aware of the research and had made changes (31% subsurface banded or incorporated was most frequent management change). The differences between states is likely a result of a much more targeted outreach campaign (detailed elsewhere) in Montana than in Idaho (or Wyoming). There is also a much higher percentage of dryland cropping and hence unincorporated urea broadcast applications in MT than in ID, so interest in MT is higher.

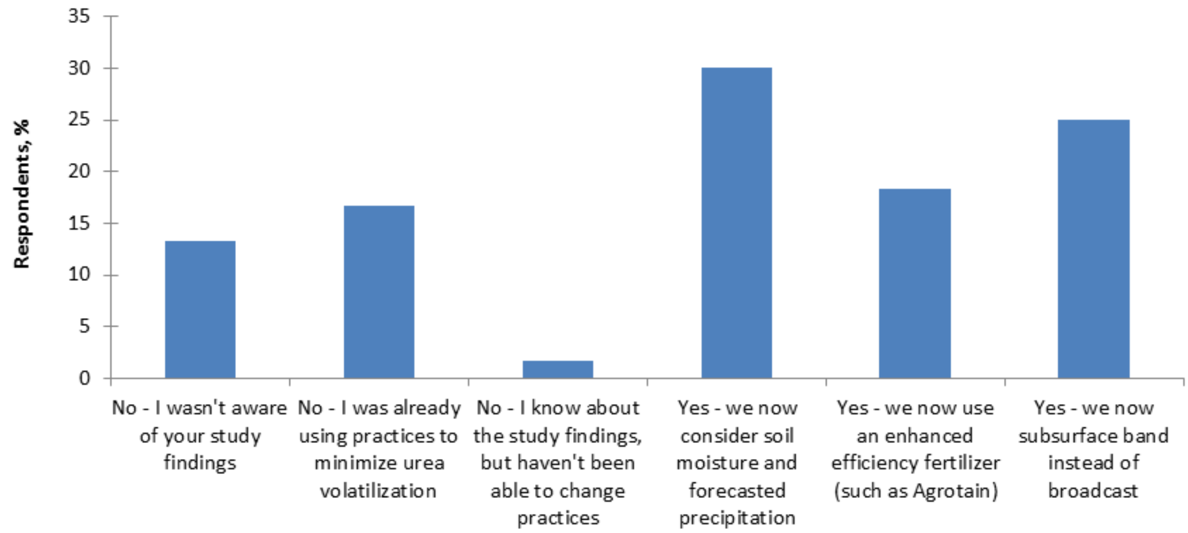

Figure 7. Montana online post-study survey responses to "Have you adjusted your management to minimize urea volatilization based on MSU's research findings on the topic?" n =60

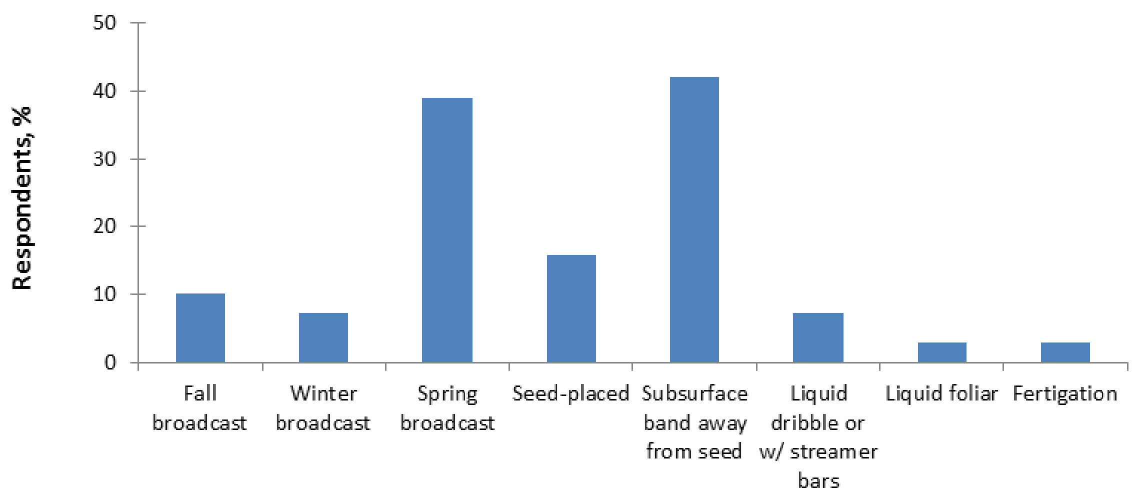

Figure 8. Montana online post-study responses to "Which of the following best describes how you apply the majority of your N on average?" n =69. The summed averages add up to somewhat more than 100% because multiple responses were allowed.

Economic Analysis

Annual economic impacts were analyzed with two different methods: 1) fertilizer N savings ($) from mitigation of NH_3 loss and 2) increased gross revenue ($) from increased wheat grain yield and protein due to adoption of a best management practice (BMP). Most of the inputs for this analysis came from the surveys and some were estimated. Dr. Jones's yield, protein, and net revenue models (based on decades of Montana soil fertility trials) were used to estimate net revenue increases from the projected reduced losses (see http://landresources.montana.edu/soilfertility/small%20grains%20economic%20calculator.html). The estimates were only made for Montana because altered practices were low in ID (~13%) and we had insufficient information to conduct this analysis. Broadcast N rate was calculated as N application rate x fraction of N broadcast. Equations for each strategy are defined below and a list of parameters and their values are provided in Table 3.

1. NH_3 loss mitigation with BMP adoption (e.g. NBPT, considering weather, subsurface band) =
   (mean broadcast N application rate, lbs N/acre) x

   (acres of wheat) x

   (% growers adopting new practice)/100 x

   (reduction in N loss with BMP as a fraction)

   <u>Total N fertilizer loss mitigation (dollars)</u> =
   sum of NH_3 loss mitigation for the three BMPs (NPBT, weather, subsurface band) x
   urea cost ($/lb N)

2. Increased gross revenue ($) was calculated from the estimated difference in winter + spring wheat net revenue with the adoption of BMPs

Available N pre-study = Avail N/bu x yield goal – (broadcast N rate – broadcast N rate x fraction volatilized w/o mitigation)

Available N post-study = Avail N/bu x yield goal – (broadcast N rate – broadcast N rate x fraction volatilized w/ mitigation for each practice)

Gross revenue savings = sum of ((net revenue w/ pre-study available N – net revenue w/ post-study available N) x acres with adopted new practice

The savings for the two approaches were almost identical averaging approximately $5 million per year for the state of Montana. This estimate is likely <u>conservative for the United States</u> because we disseminated our results nationally with a focus in the west. Also, output from Dr. Jones's economic model shows a modest 0.2% boost in protein with the application of BMPs to reduce NH_3 volatilization. We have conducted replicated small trials in grower's fields to directly measure this effect. To date, our results have shown that deferring N application to early spring (reduced volatilization loss potential) will boost grain protein 0.5 to 1.5% over late-fall and winter applications (when volatilization loss potential is high), and addition of NBPT or Agrotain° to urea will boost grain protein 0.5 to 0.8% over untreated urea.

Table 3. Parameters, values and origin for economic analysis conducted using Dr. Jones yield, protein and net revenue model

Parameter	Value	Where obtained
broadcast urea fertilizer N loss,%†	18	average from 2008-2014 trials
% fertilizer N in Montana broadcast applied as urea in 2011	48	Pre-survey
% growers now considering timing urea applications according to weather b/c of study	22	Post-survey
% growers using enhanced products like Agrotain in 2014	16	Post-survey
% growers subsurface banding in 2014	16	Post-survey
% reduction in N loss by considering timing urea application according to weather	50	Study estimate
% reduction in N loss by using Agrotain	65	Study
% reduction in N loss by subsurface banding	100	Estimate from literature
mean N application rate, lbs N/acre	60	Survey, MDA 2012 (~300 million lb N as urea), and NASS
available N‡:spring wheat yield ratio, lbs N/bu	2.59	Pre-survey
available N:winter wheat yield ratio, lbs N/bu	2.33	Pre-survey
spring wheat acres (2013)	2.5 million	NASS
winter wheat acres (2013)	2.0 million	NASS
soil organic matter (affects N response),%	2.0	Estimate from variety of soil tests
spring wheat price for 14% protein (7/2014),	$6.00/bu	USDA Montana
winter wheat prices for 12.5% protein (7/2014)	$5.25/bu	USDA Montana
spring wheat discount below 14% (per quarter)	$0.15/bu	USDA Montana
winter wheat premium above 12.5% (per quar.)	$0.01/bu	USDA Montana
spring wheat yield goal	40 bu/ac	Somewhat higher than non-irrigated actual yield from NASS 2013 (35.6 bu/ac)
winter wheat yield goal	50 bu/ac	Somewhat higher than non-irrigated actual yield from NASS 2013 (42.2 bu/ac)
Fertilizer cost	$0.55/lb N	Estimate from retailers & growers

† We assumed a baseline NH_3 loss of 18% of the application rate for broadcast urea without consideration for practices that result in mitigation. This number comes from the combined results from this study (2010-2014), plus studies that pre-date this project (2008-2010).

‡ available N = soil N + fertilizer N

Publications/Outreach

Publications Scientific - refereed

Engel, R.E., C. Jones, and R. Wallander. 2013 Ammonia volatilization losses were small after mowing field peas in dry conditions. Can. J. Soil Sci. 93:239-242.

Engel, R.E., E. Williams, R. Wallander, and J. Hilmer. 2013. NBPT degradation occurs more slowly in alkaline soils. Soil Sci. Soc. Am. J. 77:1424–1429

Engel, R., C. Jones, and R. Wallander. 2011. Ammonia volatilization from urea and mitigation by NBPT following surface application to cold soils. Soil Sci. Soc. Am. J. 75:2348–2357.

Abstract and Proceedings at Professional meetings

Engel, R., C. Jones and R. Wallander. 2013. Improving fertilizer N recovery and mitigating NH3 volatilization from surface-urea applications in a semiarid climate. ASA-CSA-SSSA Conference Abstracts. Tampa, FL, November 3-6, 2013 (symposium, invited).

Engel, R.E., E. Williams, and R. Wallander. 2012. NBPT degradation and mitigation of ammonia loss from surface-applied urea in an acidic and alkaline soil. Great Plains Soil Fertility Conference, March 6-7, 2012. Denver, CO.

Engel, R.E., E. Williams, and R. Wallander. 2012. Degradation of the urease inhibitor N-(n butyl) thiophosphoric triamide) occurs more slowly in calcareous soils. 49th Annual Alberta Soil Science Workshop. Feb14-16, 2012. Edmonton, Alberta.

Engel, R. 2011. Volatilization losses from surface-applied urea during cold weather months. Manitoba Agronomist Conference, Dec 13-14, 2011. Winnipeg, Manitoba.

Jones, C., T. Rick, R. Engel, P. Miller, A. Moore, K.Olson-Rutz and S. Arnold. 2011. Comparison between online and hardcopy responses from a grower survey on urea volatilization. ASA-CSSA-SSSA 2011. International Annual Meetings. Oct 16-19, 2011. San Antonio, TX.

Engel, C. Jones, R. Wallander, T. Jensen. 2011. Cold weather volatility of NH_3 from surface-applied urea: A micrometeorological study to quantify losses in the Northern Great Plains. 48th Annual Alberta Soil Science Workshop. Feb 15-17, 2011. Calgary, Alberta.

Engel, R.E. 2010. Cold weather volatility of ammonia from surface-applied urea: A micrometeorological study to quantify losses in the Northern Great Plains of America. Yangling Int. Agri-science Forum. Nov 1-3, 2010. Yangling, China. (*invited*)

Ag-industry

Jones, C., R. Engel, D. Horneck, and K. Olson-Rutz. 2012. Minimizing urea volatilization in cool semi-arid regions. Crops and Soils. 45(6): 28-32. (15,000 readers)

Engel, R., C. Jones, and T. Jensen. 2012. Cold temperatures did not remove the risk of ammonia loss. Top Crop Manager – Western Edition. April 2012: page 28,30,36 (27,000 readers).

Engel, R., C. Jones, and T. Jensen. 2012. Cold temperatures did not remove the risk of ammonia loss from surface-applied urea. Better Crops. Vol. 96 Issue 1: 9-11 (11,000 readers).

Press releases

Factors contributing to N volatilization and BMPs to minimize loss. MSU Press release March 2013.

University Extension

Jones, C., B. Brown, R. Engel, D. Horneck and K. Olson-Rutz. Management to Minimize Nitrogen Fertilizer Volatilization. MSU Extension. EB0209. 5 p. 250 hardcopies delivered. Available online at http://landresources.montana.edu/soilfertility/PDFbyformat/publication%20pdfs/U%20vol%20BMP%20EB0209.pdf).

Jones, C., B. Brown, R. Engel, D. Horneck and K. Olson-Rutz. Factors Affecting Nitrogen Fertilizer Volatilization. MSU Extension. EB0208. 6 p. 250 hardcopies delivered. Available online at http://landresources.montana.edu/soilfertility/PDFbyformat/publication%20pdfs/U%20vol%20factors%20EB0208.pdf).

Engel, R. and C. Jones. 2012. Ammonia loss from urea surface-applied to cold soils. Montana Fertilizer Facts. Number 59. MSU Extension, Bozeman, MT. 2 pp. 700 hardcopies delivered and available online at http://landresources.montana.edu/FertilizerFacts/

Engel, R. and C. Jones. 2012. Mitigation of ammonia loss from urea applied to moist soils by Agrotain. Montana Fertilizer Facts. Number 60. MSU Extension, Bozeman, MT. 2 pp. 700 hardcopies delivered and available online at http://landresources.montana.edu/FertilizerFacts/.

Presentations to Growers, Commodity Groups, Ag-Industry, and Scientific

Since the project's inception (July 2010), we have presented the study findings 33 times to a range of audiences that included growers, crop advisers, Extension Agents, and scientists (Table 4). Total direct contact at these presentations has totaled approximately 1400 people or 140% of our performance target of 1,000 direct contacts for the entire study. In addition, our research project was also mentioned at seven grower meetings in Idaho in February 2011, five ID grower meetings in 2014, and at the Wyoming Wheat Growers Association annual meeting in December 2010.

Table 4. Oral presentations given over the course of this project.

Meeting	Location	Date
International Agricultural Forum	Yangling, China	02-Nov-2010
American Society of Agronomy National Meeting	Long Beach, CA	03-Nov-2010
Grower Meeting	Glasgow, MT	16-Nov-2010
Montana Grain Growers Conv.	Great Falls, MT	02-Dec-2010
Nitrogen Conference	Havre, MT	12-Dec-2010
Grower Meetings (3)	Choteau, Shelby, Ft. Benton, MT	3-4 Jan-2011
Crop Pest Management School	Bozeman, MT	06-Jan-2011
Montana Agri-Business Convention	Great Falls, MT	26-Jan-2011
Grower Meeting	Malta, MT (via web)	07-Feb-2011
Alberta Soil Science Workshop	Calgary, AB	16-Feb-2011
Grower Meeting	Denton, MT	02-Mar-2011
Agriculture Extension Agent Update	Bozeman, MT	13-Apr-2011
Northern Ag Res Center Field Day	Havre, MT	28-June-2011
Central Ag Res Center Field Day	Moccasin, MT	07-July-2011
Grower Farm Tour	Poplar, MT	24-July-2011
Grower Meeting	Glasgow, MT	25-July-2011
Willow Creek Crops School	Willow Creek, MT	22-Feb-2012
Northern Ag Research Center field day	Havre, MT	12-July 2012
MSU Post Farm field day	Bozeman, MT	July 2012
Crop Pest Management School	Bozeman MT	02-Jan 2013
Sugarbeet and Barley Symposium	Billings, MT	09-Jan 2013
Golden Triangle Workshops (4)	Denton, Ft Benton, Chester, Shelby	14, 15-Jan 2013
Montana Agri-business Association	Great Falls, MT	01-Feb 2013
Grower Meeting	Denton, MT	05-March 2013
American Society of Agronomy National Meeting-Symposium – Practices that Improve Fertilizer N use Efficiency	Tampa, FL	05-November 2013
Great Plains Soil Fertility Conference	Denver, CO	05-March 2014
Grower Meeting	Denton, MT	11-March 2014
Northern Ag Research Center field day	Havre, MT	02-July 2014

Farmer Adoption

This project, in particular our studies with urea, has garnered considerable interest and support by the agricultural community in Montana and neighboring states. Over the past four years we have conducted formal surveys of grower to gauge producer attitudes about this project and its results. The results indicate that a majority of Montana producers have altered, or plan to alter, their management practices to minimize volatilization. Adoption in Idaho has been much lower, only 12% of 230 growers at talks earlier in 2014 knew about the research and had altered practices. Though now all of those 230 growers know about the research and the take home messages, so adoption may increase in ID as well.

Anecdotal evidence from our numerous contact hours with growers has always demonstrated to us that producers have adopted changes to their management practices. For example, we know of several growers who now apply all their urea N in a subsurface band as seeding, rather than surface apply urea during cold weather months. Crop advisers tell us they now pay far more attention to weather, and target more spring time applications or enhanced efficiency fertilizer products.

The results of our surveys, evaluations, and discussions with growers indicate this project is having a large impact on growers in this region. There are several reasons why this may be so. First, the information presented is relevant to management practices in the region (i.e. 50% of our survey respondents say they applied urea without incorporation). Second, nitrogen fertility and nitrogen inputs typically represent a grower’s largest annual cost input. Third, nitrogen is the fertilizer nutrient most often limiting crop yield and quality in NGP cropping systems. Therefore, management of this input to maximum crop efficiency is important to a grower’s bottom line as well as environmental quality. Most importantly, several growers and crop advisers have told us that they have changed, or plan to change, their urea management practices to minimize volatilization. This has likely increased their grain yield, grain protein, and net revenue.

Areas Needing Additional Study

In the future we would like to investigate ammonia losses from other N fertilizer N sources, e.g. UAN and/or ammonium sulfate. Also, the fertilizer industry is developing and releasing new urease inhibitors that should provide protection from volatilization losses and which should be tested in the field. Finally, the impact of ammonia N losses on production and quality, fertilizer N recovery, and nitrogen used efficiency in crops is not well defined and is of concern to many farmers. We made some attempts to address this issue in this project, but additional investigations should be conducted.