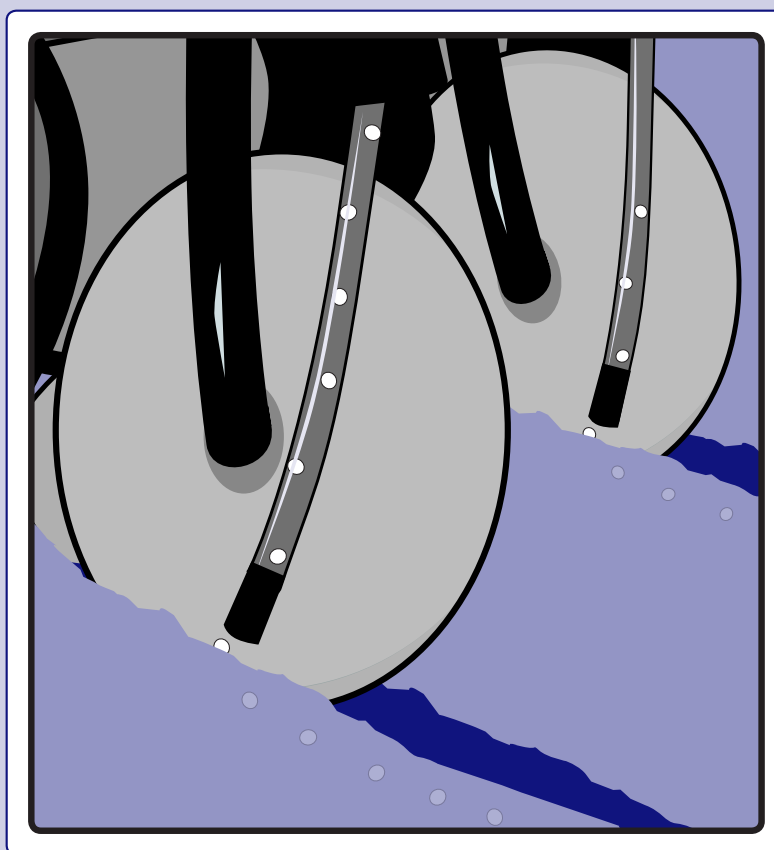# Management of Urea Fertilizer to Minimize Volatilization

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Introduction and Purpose

Urea (46-0-0), first introduced in 1935, is now the primary source of dry nitrogen (N) fertilizer in the U.S. due to its relatively high N content, ease of handling, and price. Although ammonium nitrate (34-0-0) may be superior in some situations to urea, due to liability concerns it is no longer available in many regions of the U.S. Fortunately, decades of experience and research suggest that urea and fluids containing urea are effective substitutes for ammonium nitrate when managed appropriately.

Widespread acceptance of urea was delayed in part due to its greater potential for N loss via ammonia volatilization (conversion from dissolved ammonia to ammonia gas). While all topdressed ammonia- and ammonium-based N fertilizers can volatilize, the potential is greatest with urea and fluids containing urea such as urea-ammonium nitrate (UAN; 28-0-0 or 32-0-0). While urea volatilization losses under worst-case conditions can be substantial, with proper management losses can be negligible.

With reduced availability of ammonium nitrate and increased reliance on urea, recent increases in N prices, and increasing environmental concern over atmospheric ammonia emissions, it should prove helpful to review conditions that affect ammonia volatilization and recommend ways to use urea effectively. The purpose of this publication is to summarize extensive research on urea use across a range of cropping systems and environmental conditions so practitioners can manage urea to minimize volatilization losses and maximize efficiency.

Nitrogen Cycle

Nitrogen (N) constantly cycles among different forms in the environment (Figure 1). The major forms of N include nitrate (NO_3^-), ammonia (NH_3), ammonium (NH_4^+), organic N (the N in organic matter), and N gas ($N_{2(gas)}$). Only NO_3^- and NH_4^+ are considered to be "plant-available". By minimizing the loss of these plant-available forms to the air or water, crop yields and efficient fertilizer use will be maximized. Possible losses of N from fields include "denitrification" (conversion of NO_3^- to $N_{2(gas)}$), leaching (downward movement of NO_3^- out of the root zone), plant uptake and removal in harvested portions of the crop, and NH_3 volatilization (from soils and some plants). Two other reactions, "immobilization" (uptake by microorganisms) and "exchange" (binding to soil particles), are considered temporary losses because the N remains in the soil and most of it eventually becomes available. Ammonia volatilization from soil is the focus of this guide, yet all the N cycling
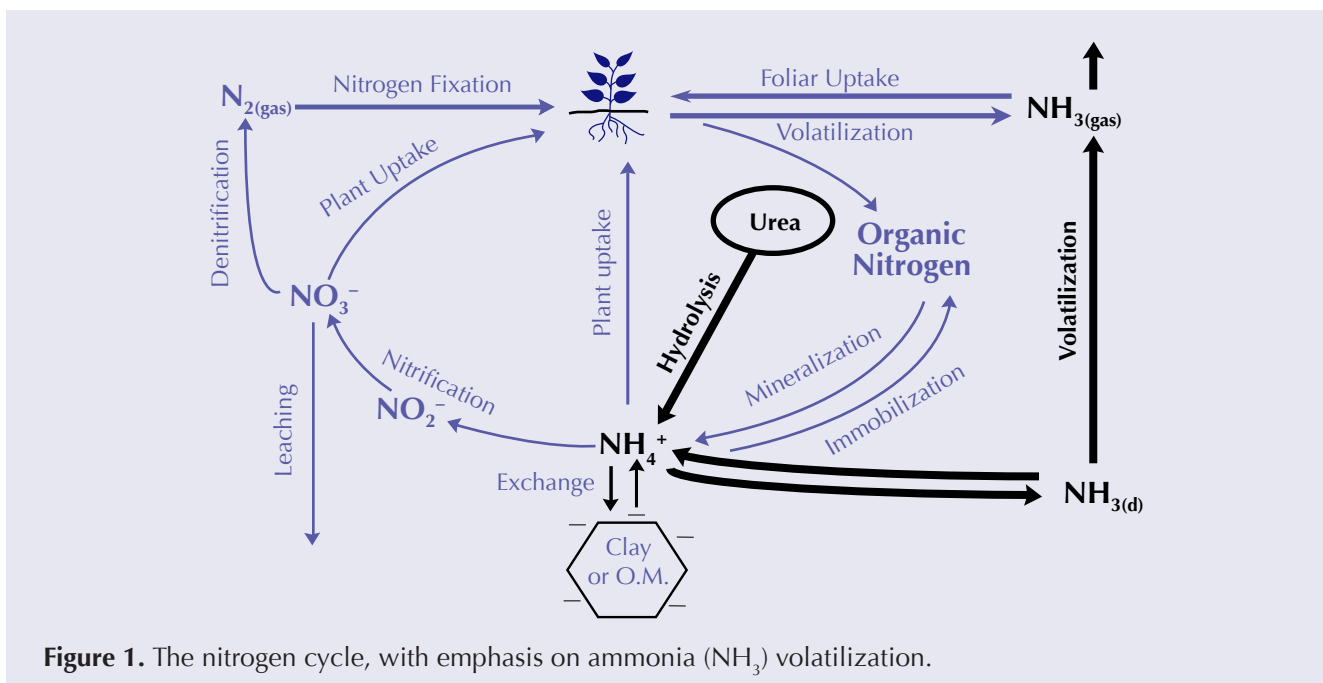

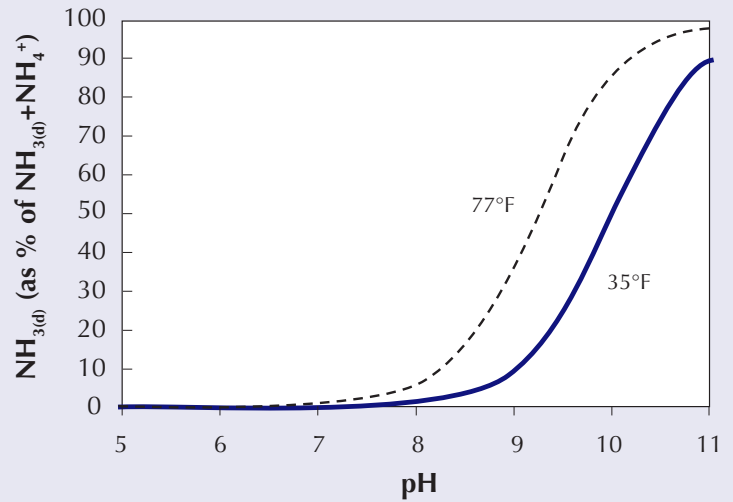**Figure 1.** The nitrogen cycle, with emphasis on ammonia (NH_3) volatilization.

reactions shown in Figure 1 can affect volatilization by influencing the amount of NH_3 available to volatilize. For example, plant uptake, immobilization, exchange, and nitrification all decrease the potential for volatilization by decreasing the amount of NH_4^+ in the soil solution. Complete N cycling reactions are described in more detail elsewhere (1).

Figure 2. Effect of pH and temperature on the concentration of $NH_{3(d)}$ as a percent of the total $NH_{3(d)} + NH_4^+$ concentration.

Volatilization Losses from Urea: Influencing Factors and Amounts

All NH_4^+ and NH_3-based fertilizers have the potential to volatilize. This guide focuses on NH_3 volatilization from urea ($CO(NH_2)_2$) and liquids made from urea, because topdressed urea fertilizers generally have the greatest potential for NH_3 volatilization. The most significant NH_3 volatilization from applied urea typically occurs during a two to three week period after application, assuming it is not incorporated by tillage, rain, or irrigation. The rate of NH_3 volatilization depends on the rate of urea hydrolysis (urea's conversion to NH_4^+), weather conditions following application, and several soil properties. *Multiple and often interrelated factors make volatilization variable and difficult to predict under field conditions.* This section reviews the factors that affect volatilization, describes the chemical reactions of urea hydrolysis and volatilization (see Chemical Reactions Box), and illustrates how soil properties such as pH affect volatilization.

Soil pH and Temperature

High soil pH and high temperature cause higher rates of NH_3 volatilization because they increase soil concentrations of NH_3 dissolved in soil water
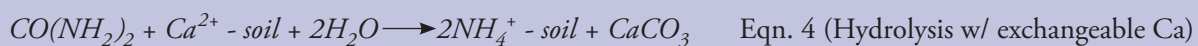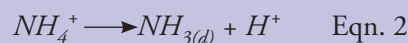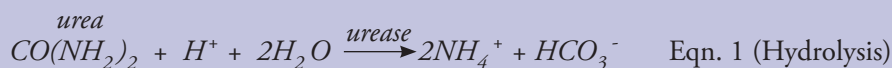
($NH_{3(d)}$). Figure 2 illustrates the importance of soil pH and temperature on $NH_{3(d)}$ as a percent of the total $NH_{3(d)}$ plus NH_4^+ concentration. The perecent of $NH_{3(d)}$ is near 0 when pH is below 7.5 for a range of temperatures, but as pH rises above 7.5, $NH_{3(d)}$ increases dramatically, especially at higher temperature. This is one reason why applying urea during periods with forecasted cool temperatures is recommended to reduce volatilization, especially on high pH soils. Other reasons are that urea hydrolysis rates are higher at higher temperatures, and $NH_{3(gas)}$, like all gases, is more volatile at higher temperatures.

The pH at which the percentage of $NH_{3(d)}$ becomes noticeably higher than 0 is higher than the surface pH of the majority of soils in our region. However, pH in the vicinity of a urea granule or fluid droplet can be substantially higher than the surrounding soil because urea hydrolysis raises pH by removing hydrogen ions (H^+) from the soil solution (Chemical Reactions Box:

Chemical Reactions

$$\overset{urea}{CO(NH_2)_2} + H^+ + 2H_2O \xrightarrow{urease} 2NH_4^+ + HCO_3^- \qquad \text{Eqn. 1 (Hydrolysis)}$$

$$NH_4^+ \longrightarrow NH_{3(d)} + H^+ \qquad \text{Eqn. 2}$$

$$NH_{3(d)} \longrightarrow NH_{3(gas)} \qquad \text{Eqn. 3 (Volatilization)}$$

$$CO(NH_2)_2 + Ca^{2+} - soil + 2H_2O \longrightarrow 2NH_4^+ - soil + CaCO_3 \qquad \text{Eqn. 4 (Hydrolysis w/ exchangeable Ca)}$$

Note: In the above equations, $NH_{3(d)}$ = dissolved ammonia ; Ca^{2+}- soil = exchangeable Ca^{2+}

Eqn. 1). Urea is not the only N fertilizer that raises pH; anhydrous ammonia, aqua ammonia (ammonium hydroxide), and UAN can similarly raise the pH of soil around the fertilizer; ammonium sulfate (AS), ammonium nitrate (AN), and diammonium phosphate can also have the same effect, but only in calcareous soils (soils containing lime). The pH increase resulting from urea hydrolysis is temporary because NH_4^+ is converted relatively quickly to NO_3^- (nitrification), or $NH_{3(d)}$ (Eqn. 2); processes that lower pH by releasing H^+ ions. However, the temporary increase in soil pH can result in NH_3 volatilization (Eqn. 3) from soils with an initial pH as low as 6.5 (2). Although volatilization has been measured from fields with even lower soil pHs, these fields had a stubble or sod surface cover, which likely had a higher pH than the underlying soil (3,4). The ash layer from recently burned fields generally also has a high pH (> 9). Volatilization can also occur at soil pHs below 6.5 if the soil buffering capacity is low (discussed later). As this research shows, caution is warranted when surface applying urea, as well as other NH_3-based N fertilizers, on warm, high pH soils.

Soil Moisture and Depth of Urea in Soil

Volatilization of topdressed urea increases linearly as soil water content increases, until the soil reaches saturation (5). Conversely, volatilization decreases dramatically as urea is moved below the soil surface, either through incorporation or movement by rainfall or irrigation. Specifically, in a study with a pH 6.5 silt loam soil at 75°F, only 5% of the urea-N that was incorporated into the upper 1.5 inches of soil volatilized compared to 17% for surface applied urea (2). Other studies have shown that ½-inch of rain moves urea deep enough into the soil to prevent volatilization (6) and yield reductions associated with N loss (7).

Soil Organic Matter and Residue

High concentrations of soil organic matter and crop residues increase urea hydrolysis rates (8, 9) and volatilization. This is largely because the urease enzyme, which is necessary for hydrolysis (Eqn. 1), is produced by microorganisms that are more active in the presence

of organic material than in mineral soil. Residue may also prevent urea and its hydrolysis product (NH_4^+) from entering the soil. As a result, perennial sod and no-till systems have higher surface hydrolysis rates than bare soil and conventional tillage systems, respectively (9, 10).

Soil Buffering Capacity, Cation Exchange Capacity, and Calcium Concentrations

Due to the large effect of pH on NH_3 volatilization, soil properties that resist pH changes will decrease NH_3 volatilization from urea. These include high clay, organic matter, and/or bicarbonate contents. In addition, a high cation exchange capacity (CEC) will lower the NH_4^+ concentration in solution, decreasing the NH_4^+ available for conversion to $NH_{3(d)}$, and thereby reducing volatilization. For example, urea volatilization was almost three times higher in a sandy loam soil with a CEC of 7 meq/100 g than in a silt loam soil with a CEC of 12 meq/100 g (3). By comparison, soil CECs in Montana, Idaho, and Washington are generally in the range of 15 to 30 meq/100 g. In addition, soils with high CEC often have high levels of exchangeable calcium (Ca^{2+}), which can offset the pH increase caused by urea hydrolysis (Eqn. 4). Note that, unlike Eqn. 1, hydrolysis in the presence of free Ca does not use H^+ and thus does not raise pH as long as there is sufficient exchangeable Ca in the system. Not only does the reaction in Eqn. 4 minimize the pH increase, but it also opens two sites on clay particles for NH_4^+ to bind to, further decreasing NH_4^+ in solution and the potential for $NH_{3(g)}$ volatilization. Irrigated soils receive annual inputs of Ca and bicarbonate, which should also reduce the potential for volatilization.

Magnitude of NH_3 Volatilization

There are no known field studies that have directly measured urea volatilization in the Inland Northwest. In other regions of the United States, NH_3 volatilized from urea, UAN, and AS vary greatly (Table 1), emphasizing that volatilization is highly dependent on soil and environmental conditions. The selected research summarized in Table 1 includes some 'worst-case' scenarios, such as fields with residue at high pH and

Table 1. Volatilization amounts of surface-applied urea, urea-ammonium nitrate (UAN), ammonium sulfate (AS), and ammonium nitrate (AN) from selected studies.

| Study Conditions	Volatilization (% of N applied)*				Literature Reference
	Urea	UAN	AS	AN	
Temp. = 75°F, pH=7.8, calcareous silty clay loam, field capacity or wetter, with straw residue (2 t/ac)	17	21	10	5	6
Field experiment (May), pH=8.4, calcareous clay loam, CEC =24 meq/100g	11	—	14	4	20
Temp. = 65-85°F, pH=6, non-calcareous silt loam, CEC=14 meq/100g, orchardgrass sod	10-31	14-37	—	3-7	4
Field experiment (June), pH=5.5, silt loam, CEC=12 meq/100g, corn residue	18	9	—	3	3

Due to differences and difficulties in measuring volatilization, these data are shown to compare volatilization amounts between N sources, rather than comparisons between studies. Volatilization amounts in the controls (no N fertilizer) were generally only slightly less than for AN.

temperature, which are optimal conditions for volatilization. The results also show that volatilization amounts from AN are very low, and are often similar to unfertilized controls.

Several studies in the region have compared small grain yields among urea, AN, and AS fertilizers as an indirect estimate of volatilization and found little or no difference (Figures 3 and 4). It is important to recognize when evaluating these studies that, if yields were similar between these N sources when a crop was N-limited, there likely was little or no urea or AS volatilization because AN volatilization is low or nonexistent. In southern Idaho, irrigated winter wheat and winter barley grain yield was lower with fall incorporated compared to spring topdressed urea in four out of six crop-years (Figure 5). Preplant incorporation in the fall should minimize volatilization, so yield differences were likely due to fall or winter N immobilization or leaching losses, and suggest minimal volatilization from spring topdressed urea. In Montana, urea topdressed at 30 lb N/ac in March produced 15% higher winter wheat grain yield than urea topdressed in November, but there were no significant differences in yield between application times at 60 or 90 lb N/ac (11). In another Montana study, fall surface banding produced almost identical winter wheat yields as spring topdressed urea (Figure 6). Finally, urea applied before,
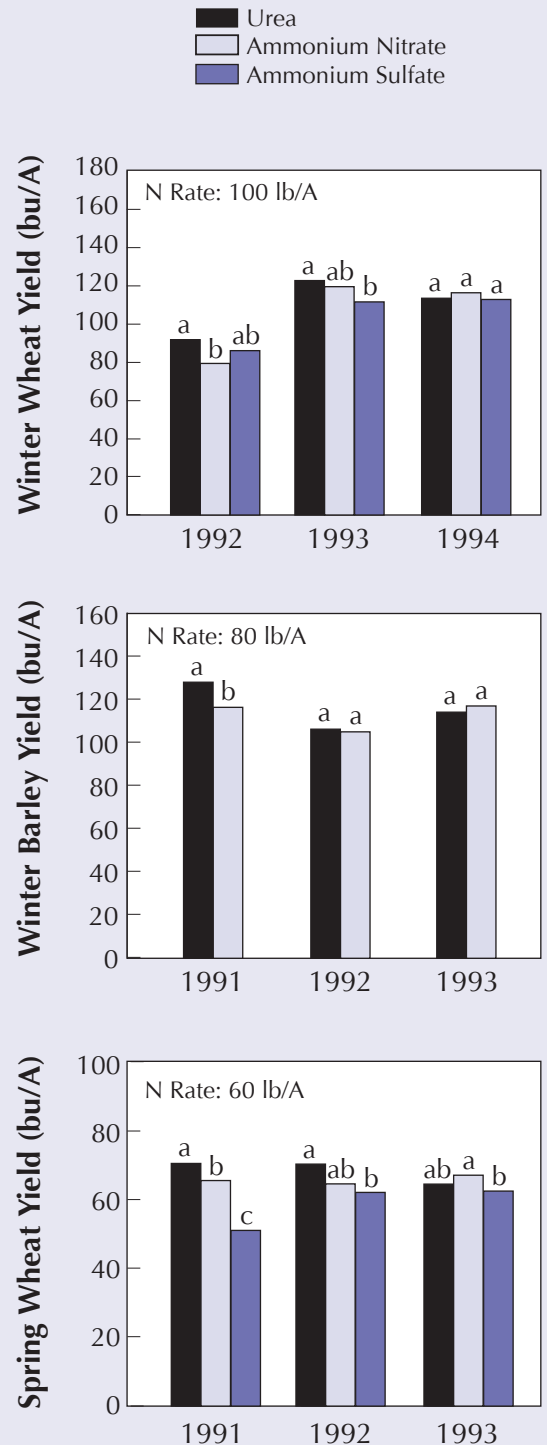
Figure 3. Irrigated grain yield response to spring topdress fertilizing (Brown, unpub. data). Different letters indicate significantly different yields.
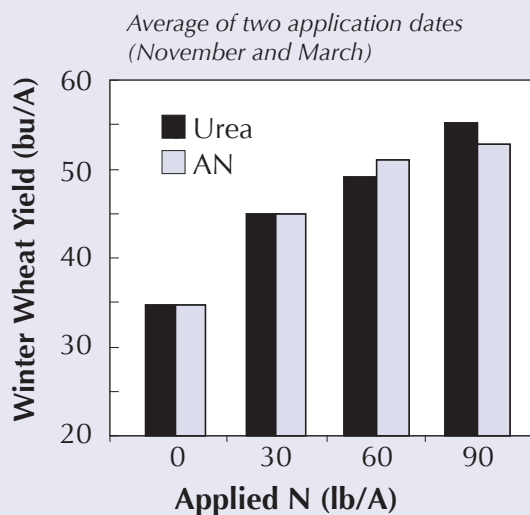
Figure 4. Dryland winter wheat yield response in north central Montana (Christensen and Mients, 1982). Each bar represents average yields from both fall and spring urea and ammonium nitrate (AN) applications. No significant N source effects.
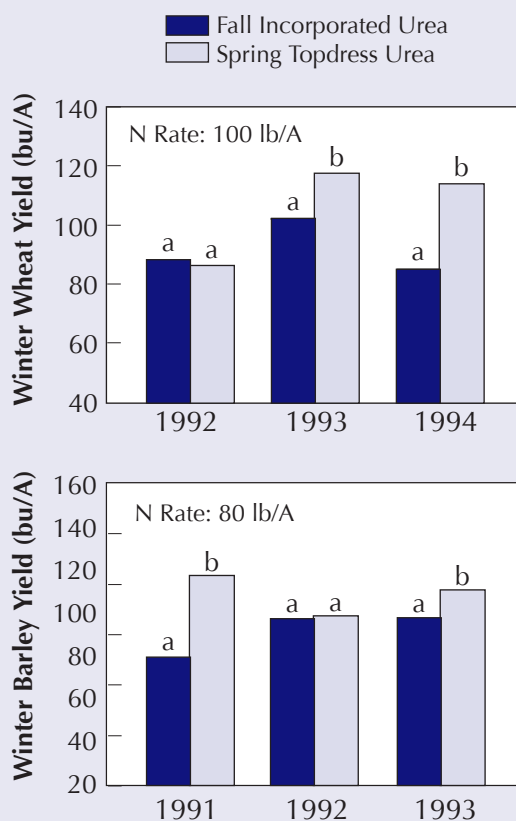

Figure 5. Comparison of irrigated winter wheat and winter barley yield response to urea timing and placement (Brown, unpub. data). Different letters indicate significantly different yields.

during, or after planting or at tillering in Montana had similar effects on spring wheat yield and protein (12). The combined results of these source and timing studies indicate that the potential for urea volatilization in the Inland Northwest, at least in small grain production systems, is lower than in other regions of the country.

Summary

Volatilization of NH_3 from urea and other N fertilizers is controlled by a number of diverse soil properties and environmental conditions that make losses difficult to predict in the field. In general, higher pH, temperature, crop residue, and moisture conditions increase the potential for volatilization, while increased incorporation depth from tillage, rain, or irrigation decrease volatilization potential (Table 2). Due to soil characteristics such as high CEC and buffering capacity, substantial inputs of bicarbonates and Ca on irrigated land, and generally cool conditions during major fertilizer application periods, the potential for substantial urea volatilization in many cropping systems of the Inland Northwest is likely relatively low. Nevertheless, the lack of direct field measurements of NH_3 volatilization in the Inland Northwest coupled with the complexity of fertilizer management practices for the many diverse crops grown in the area is reason to exercise caution and use good urea management practices. Understanding the factors that
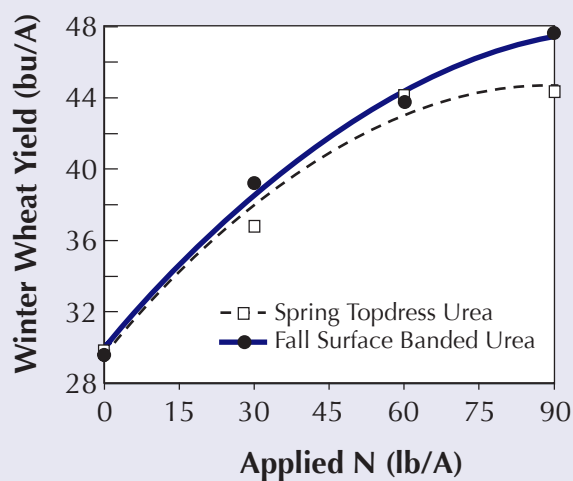
Figure 6. Winter wheat yield response to spring topdress urea or fall surface banded urea based on a four year study. Rotation for the study used no-till winter wheat following barley with 2 years fallow. No significant differences between treatments (Jackson, unpub. data).

Table 2. High and low risk conditions for volatilization. The risk of volatilization increases as the number of high risk conditions increase, with temperature being the most important risk condition.

High risk conditions	Low risk conditions
High soil temperature (>70°F)	Low soil temperature (<50°F)
Moist soil or heavy dew	Dry soil
High soil pH (>7.0)	Low soil pH (<6.0)
Low cation exchange capacity soil (sandy)	High cation exchange capacity soil (silt or clay-dominated)
Crop residue, perennial forage, or ash layer from recent burn event	Bare soil

Table 3. Summary of urea management practices to minimize or prevent volatilization.

- Evaluate relative risk for volatilization (Table 2).
- At higher risk, either delay application, subsurface band, OR incorporate with:
    - o   Tillage (> 2 inches deep)
    - o   Irrigation (> 0.5 inches)
   - o   Rainfall (when > 0.5 inches is expected)

  Incorporation should take place within 1 to 2 days. If incorporation is not possible within that period, and application cannot be delayed, consider using a coated urea product or urease inhibitor.

- At lower risk
    - o   Surface broadcast OR
    - o   Subsurface band/incorporate to further minimize the potential for volatilization

influence volatilization will allow urea users to select management practices that minimize volatilization. These practices are discussed in more detail in the following section.

Urea Management

The first step in managing urea is to evaluate relative volatilization risk for a specific application situation (Table 2). The second step is to adopt practices that are appropriate for the relative volatilization risk (Table 3). The following sections review management practices intended to reduce volatilization from urea.

Source

Urea is found in three common fertilizer formulations: dry granular urea (46-0-0), UAN (28-0-0 or 32-0-0), and liquid urea (see *Liquid Urea* side bar). All three urea sources have similar potentials to volatilize; therefore, the decision on which source to use should be based primarily on cost per unit of N, equipment available to apply the material, and convenience of application.

Placement

Urea-based fertilizers can be broadcast, subsurface banded, or surface banded. Broadcasting urea without incorporation increases the potential for NH_3 volatilization and should be avoided, if possible, under high-risk conditions (Table 2). If this is unavoidable then delaying the application, applying prior to an irrigation or a rain event, or banding beneath the

Liquid Urea

Dry urea can be mixed with water to produce a fluid containing 15 to 23% N by weight. Dissolution is slow and should be done in a large tank with an external source of heat. The final solution may recrystallize depending on urea concentration and temperature. An even mixture of urea and water by weight (e.g. 5000 lb of urea and 625 gal of water) results in a 23% N solution which will recrystallize below 60°F, whereas a 15% N solution will recrystallize below 10°F (13). The final product must also be filtered (40 mesh) to prevent nozzle plugging.

The primary advantage of a liquid urea compared to a UAN solution is that it produces less leaf burn when applied as a foliar spray (14). However, because the percentage of N in liquid urea is lower than UAN, transportation costs are normally higher per unit of N.

surface should be considered (Table 3). In perennial grass systems, subsurface placement of urea by drilling or knifing reduces NH_3 volatilization (15) but may not be feasible or may cause excessive stand disturbance. Alternatively, surface banding fluid UAN in perennial grass systems may result in lower volatilization than spraying UAN on the surface (16). In annual cropping systems, wet soil conditions may preclude deep banding, and the soil above the deep band may dry out preventing germination until a precipitation event. In
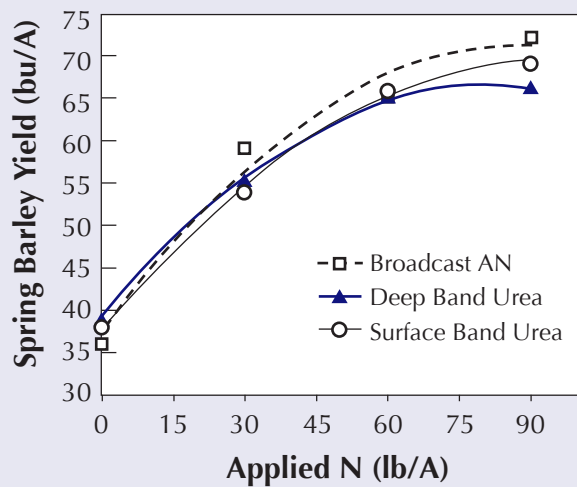
Figure 7. Spring barley yield response to different N sources (ammonium nitrate (AN) and urea) and placement. No significant differences between treatments (Jackson, unpub. data).

addition, draft requirements increase when fertilizer is deep banded in the same pass as seeding. Although surface banding of urea may increase the potential for volatilization compared to deep banding, a research study in Montana found no yield differences between the two placement methods (Figure 7), suggesting losses with surface banding were minimal.

Timing

Throughout the Inland Northwest, optimum times for N application vary due to the diverse climate and cropping systems involved. Therefore, base N application timing decisions primarily on local research and recommendations. Where possible, time broadcast applications of urea during periods where soil temperatures are low and the likelihood of a significant rainfall is high, or when irrigation or tillage can be used to incorporate the N.

With irrigated spring small grains, urea can be pre-plant incorporated or topdressed and incorporated with sprinkler or basin irrigation once the water is available. Furrow irrigation may exacerbate urea volatilization by increasing surface evaporation from the ridges. Applications on irrigated winter small grains are more problematic. Effective post-emergence incorporation depends on the availability of irrigation water frequently unavailable during tillering stages (fall through early spring) when yield potential is largely

determined. To avoid N immobilization, leaching, and volatilization losses with early fall-applied N, yet provide N for early season vegetative growth, topdress urea from late fall through early spring.

Dry or liquid fertilizer may be applied in season; however, foliar-applied UAN solution can burn plant leaves if the N rate exceeds approximately 40 lb/ac. In southern Idaho, foliar-applied urea solutions resulted in only about ½ the flag leaf burn of UAN solutions in hard red winter wheat, though leaf burn did not consistently decrease yield (14). Using drop nozzles with drag hoses (20-inch spacing) to minimize foliage exposure, UAN was applied at rates as high as 140 lb N/ac on irrigated small grains without damaging the crop (17). In northern Idaho, leaf burn was lower and grain yield higher when fluid UAN was foliar-applied at the rate of 90 lb N/ac early in the growing season (second tiller stage) for winter wheat compared to applications made later in the growing season when air temperatures were higher (18).

It was previously noted that high temperatures could greatly increase the potential for volatilization. This suggests that urea topdressed after wheat flowering, when temperatures are generally high, may not be as effective as less volatile N sources. However, in a study conducted at four locations in Montana, average spring wheat grain protein responses were very similar between urea and ammonium nitrate topdressed in July (Figure 8), suggesting minimal volatilization of urea even under warm conditions. In heavy canopies, some of the NH_3 is trapped in the foliage and used by the plant (19); therefore, volatilization becomes less of an issue with full canopies.

Broadcast urea applications are common in perennial grass seed and forage production systems. Due to high amounts of surface residue and the potential for rapid urea hydrolysis in perennial systems, avoid applications when the soil is moist and temperatures are above 50°F unless they occur within two days of a significant (>½-inch) rainfall or irrigation event. When temperatures are above 70°F, postpone applications or make them within one day of an irrigation or rain event. Applying urea to perennial grass stands when the soil is dry reduces the potential
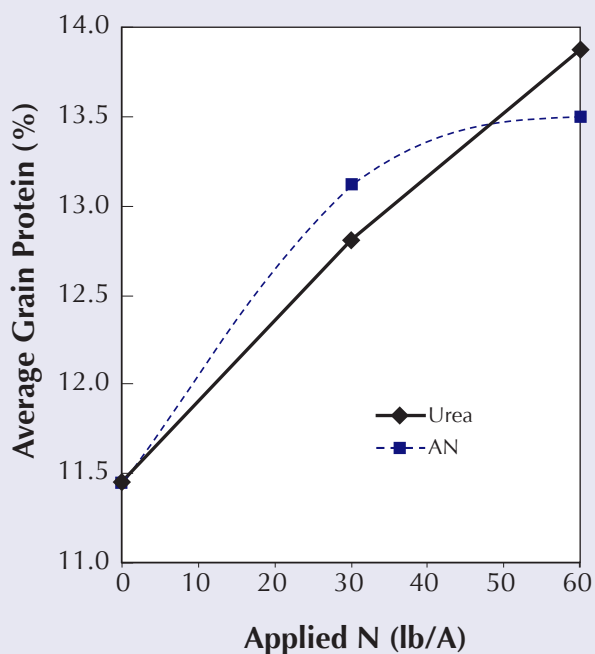
Figure 8. Average dryland spring wheat grain protein response to urea or ammonium nitrate (AN) applied after flowering in 1993. Four sites were tested in north central Montana with no significant differences between treatments (Jackson, unpub. data).

for volatilization since hydrolysis rates are lower with dry conditions. This may extend the safe window between application and a rainfall or irrigation event by several days. There are unknowns regarding the timing of urea application after burning perennial grass systems since burning reduces urease activity but creates a high surface pH condition. Regardless of other conditions, delaying fall applications of urea on perennial crops until soil surface temperatures fall below 50°F greatly reduces the potential for NH_3 volatilization.

Coatings and Inhibitors

Urea can be encapsulated in various coatings or treated with chemicals to inhibit transformations that result in N losses.

Coatings

The goal of fertilizer coatings is to slow the rate that granules dissolve, and hence reduce losses. The oldest and most common coating is elemental sulfur. Once applied, soil bacteria oxidize the sulfur coating, allowing the granule to dissolve and undergo hydrolysis. To ensure that urea is released over an

extended period of time, granules are coated with sulfur layers of varying thickness. Nitrogen release from sulfur-coated urea depends on soil moisture and temperature and therefore is somewhat unpredictable. Substantial N may not be released until later in the season, creating problems for high N demand crops like potatoes and sugarbeets.

Polymer coatings also control the release of N but use a different mechanism than sulfur coatings. Polymers act as a semi-permeable membrane that permits water to move in through the coating and dissolved urea to move out. The permeability of polymer-coated products depends primarily on soil temperature. A variety of polymer coatings are available to match release rates to specific crop N needs. Development and research on polymer coatings for urea are ongoing and more information will be available in the near future.

In the past, the cost of coated urea products has limited their use to intensively managed horticulture crops and turf. In the last ten years, however, new technology has made these coatings less expensive. For example, current polymer coatings may add 20% to the cost of urea fertilizer compared to 100% or more as little as 10 years ago. As a result, coated urea is being targeted for lower value crops and environmentally sensitive situations.

Inhibitors

Chemical compounds can also be added to urea fertilizers to inhibit transformations of N. Urease inhibitors are one class of compounds that prevent the conversion of urea to NH_4^+ (Eqn. 1). Inhibitors can delay the hydrolysis of urea for 2 to 10 weeks. In general, the longevity of urease inhibitors declines as soil temperature and moisture content increase. Inhibitor formulations are available to treat both dry and liquid forms of urea. Inhibitors have met with varied success because they affect only one reaction (hydrolysis) in the process of NH_3 volatilization from urea, depend on rainfall (or irrigation) to move the urea into the soil before hydrolysis begins and, similar to coatings, may delay the availability of N to the crop.

Conclusions

Various soil and climate factors interact to affect urea volatilization. As a result, it is nearly impossible to predict how much urea will be lost in a given field application situation. By understanding how soil and climate factors influence volatilization, crop producers and their advisers can avoid applying urea in situations that may promote volatilization, or adopt best management practices to minimize the potential for loss. Recommended best management practices include incorporating urea with equipment, irrigation, or rainfall; topdressing urea when temperatures and soil moisture levels are low; and avoiding topdress applications under high risk conditions unless there is an opportunity to incorporate the urea within one to two days of application.

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Acknowledgments

Web Resources

http://www.oznet.ksu.edu/library/crpsl2/NCR326.pdf

Management of Urea Fertilizers (for the North Central Region). A Kansas State University publication by Dr. David Kissel.

http://landresources.montana.edu/soilfertility

From this site, access 1) Nutrient Management Modules: Module 3 is on Nitrogen Cycling and Module 11 is on Fertilizer Placement and Timing, 2) Presentations on ammonia volatilization, and 3) Fertilizer Guidelines for Montana.

http://cru84.cahe.wsu.edu/cgi-bin/pubs/EB1987.htm

Winter wheat fertilizer guidelines for Eastern Washington.

http://cru84.cahe.wsu.edu/cgi-bin/pubs/search.html

Washington State University Extension Catalog (order information).

http://www.extension.uidaho.edu/crops.asp

Northern and Southern Idaho Fertilizer Guidelines (under "Fertilizers and Soils").