

Factors Affecting Nitrogen Fertilizer Volatilization

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This bulletin explains the various soil and climate factors that interact to affect ammonia volatilization from nitrogen fertilizers. Understanding these factors can help crop producers avoid applying urea and other nitrogen fertilizers in situations that may promote substantial volatilization, select best management practices to minimize loss, and increase nitrogen use efficiency.

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Any surface applied ammonia- and ammonium-based N fertilizer, including manure, can lose nitrogen (N) to the atmosphere via ammonia volatilization. The potential is greatest with urea and fluids containing urea such as urea ammonium nitrate (UAN; Table 1). Multiple and often interrelated factors make volatilization variable and difficult to predict under field conditions. However, the conditions that affect volatilization are relevant across climates and regions. This bulletin describes the processes and factors that influence volatilization potential. Understanding these factors helps managers better understand and select best management practices that minimize volatilization and maximize N use efficiency.

TABLE 1. Common N fertilizer sources and their grade.

Fertilizer	Grade
Urea	46-0-0
Urea ammonium nitrate (UAN)	28-0-0 or 32-0-0
Ammonium sulfate	21-0-0-24
Ammonium nitrate	34-0-0
Calcium ammonium nitrate	27-0-0

Suggested management practices for the inland Pacific Northwest and Montana are presented in *Management to Minimize Nitrogen Fertilizer Volatilization* (see “Extension Materials” at end of document).

Nitrogen Cycle Focused on Ammonia Volatilization

Nitrogen constantly cycles among different forms in the environment (Figure 1). The major forms of N include nitrate (NO_3^-), ammonia ($\text{NH}_3(\text{d})$) dissolved in water, ammonia gas ($\text{NH}_3(\text{gas})$), ammonium (NH_4^+), organic N (the N in organic matter and microbes), and N gas ($\text{N}_2(\text{gas})$). Only nitrate and ammonium 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 nitrate to N_2 gas), leaching (downward movement of nitrate out of the root zone), plant uptake and removal in harvested portions of the crop, and ammonia volatilization (from soils and 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. These processes are further explained in *Nitrogen Cycling, Testing and Fertilizer Recommendations*.

Ammonia volatilization from soil is the focus of this guide, yet all of the N cycling reactions shown in Figure 1 can affect volatilization by influencing the amount of ammonia available to volatilize. For example, plant uptake, immobilization, exchange, and nitrification all decrease volatilization potential by decreasing the amount of ammonium in soil solution.

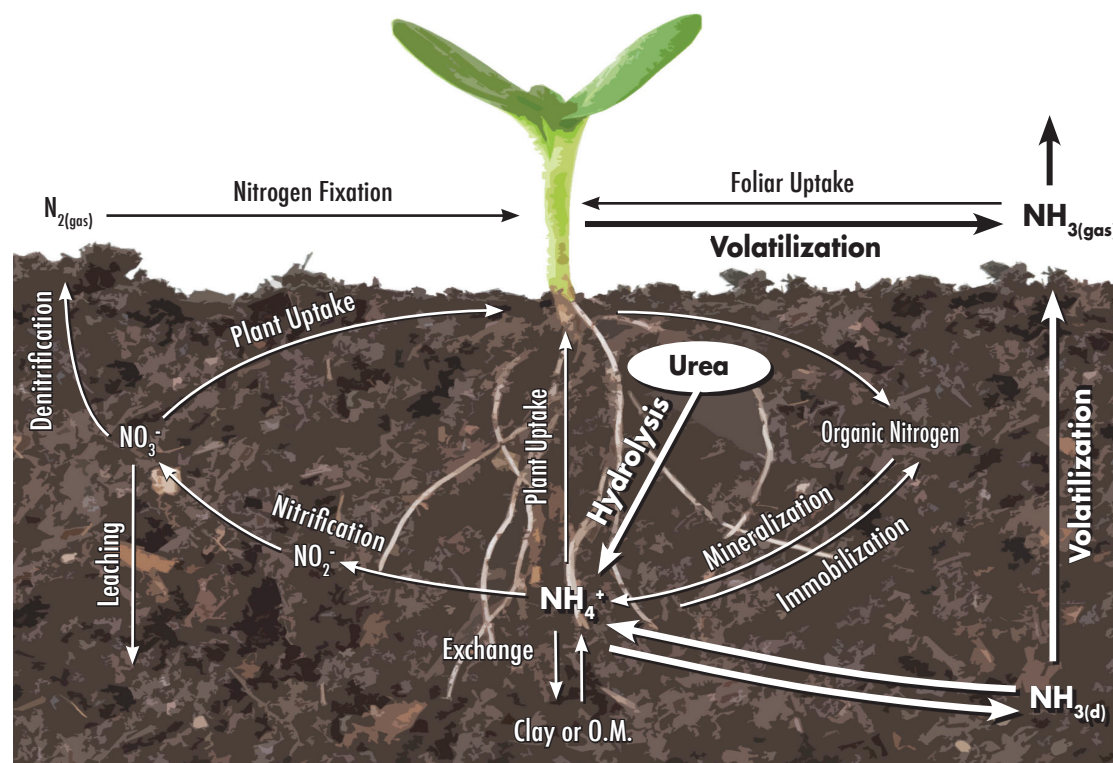


FIGURE 1. The nitrogen cycle, with emphasis on ammonia (NH_3) volatilization.

FIGURE 2. Urea (arrows) lost 40 percent of applied N when broadcast in late March on snow-covered soil with temperatures around freezing followed by slow drying. Losses were greatest during the first two weeks and were reduced or delayed by Agrotain® (see “Soil pH and Temperature” section; 5).

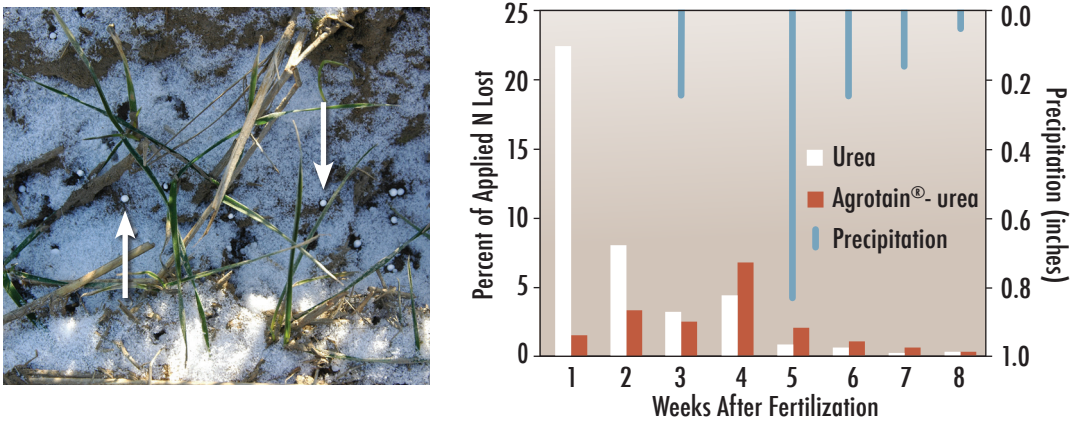


FIGURE 3. Volatilization was high from urea broadcast mid-March on moist soil with temperatures in the mid-40s (°F) followed by little rain. Irrigation with at least 0.45 inch (6) or the addition of Agrotain® (see “Soil pH and Temperature” section; 9), reduced volatilization to less than 5 percent of applied N.

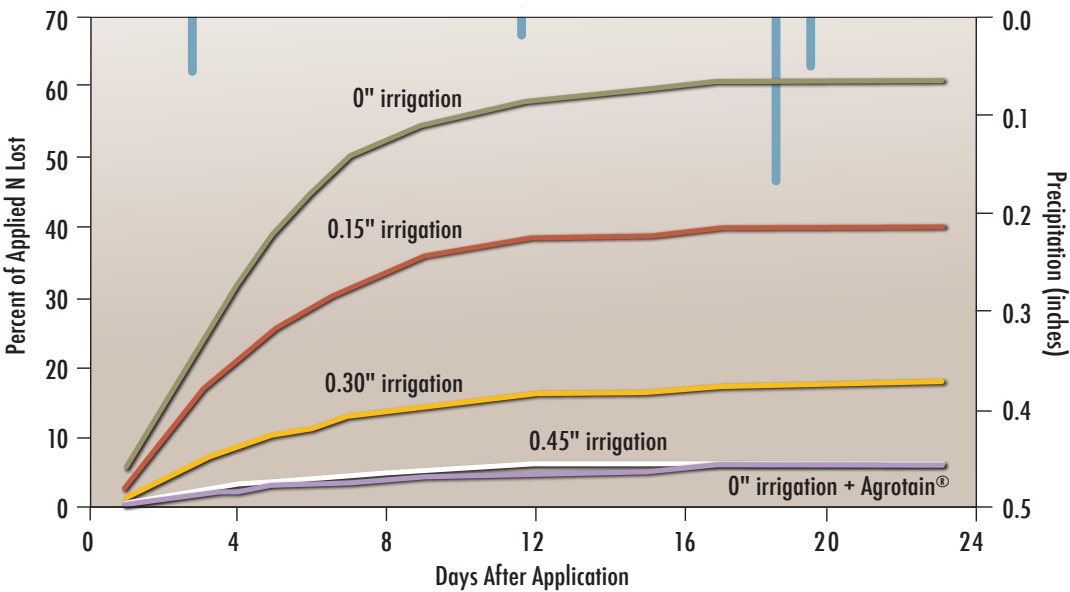
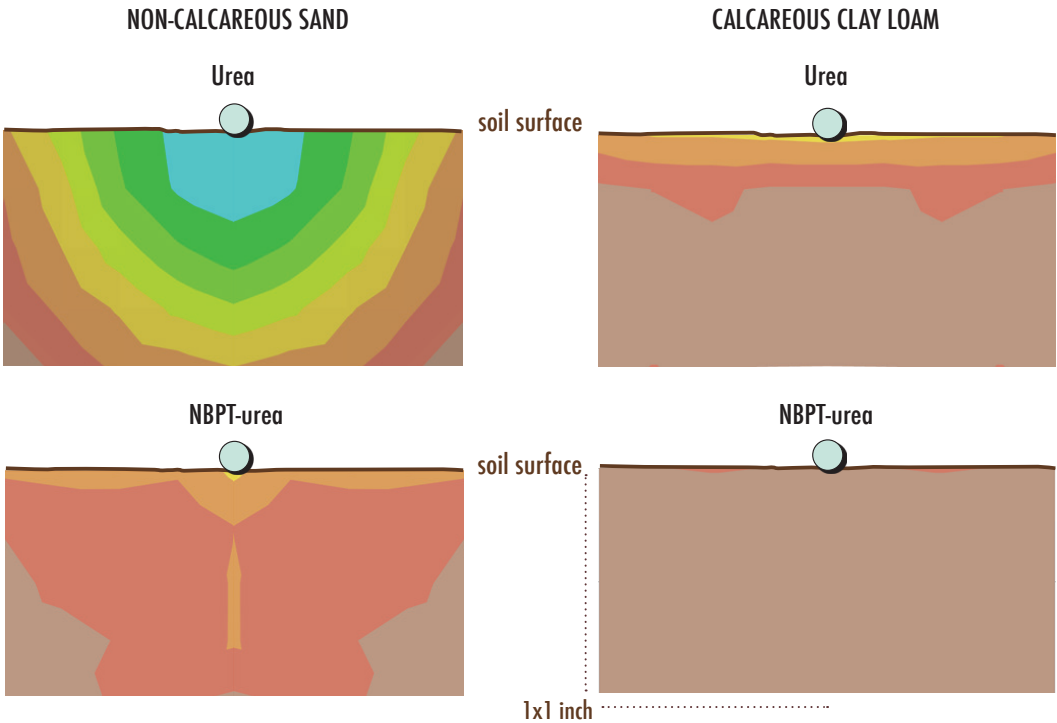


FIGURE 4. Increase in soil pH from the original pH by distance and depth six days after urea granule with and without NBPT was placed on non-calcareous sand (pH 5.2) and calcareous clay loam (pH 8.2) soil surface. Adapted from original (11).

- Soil pH increase
- 1.4-1.6
 - 1.2-1.4
 - 1.0-1.2
 - 0.8-1.0
 - 0.6-0.8
 - 0.4-0.6
 - 0.2-0.4
 - 0.0-0.2



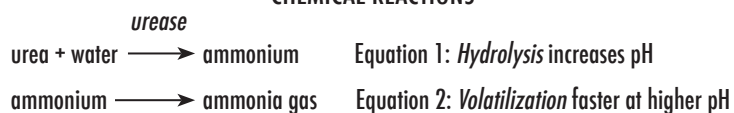
Until recently, volatilization loss from urea application was thought to be relatively low in the inland Pacific Northwest and Montana. This was based largely on grain yield and protein comparisons between N sources, rather than direct measures of volatilization. For example, Brown (1) found wheat grain yields in southern Idaho were equal between spring top-dressed urea and ammonium nitrate, and that yields were higher from spring broadcast than fall incorporated urea. Grain yield and protein were also similar between urea and ammonium nitrate applications in Montana (2, 3). Because ammonium nitrate and

incorporated urea have minimal volatilization, when yields and protein were similar between the two N sources and placements, minimal volatilization loss was assumed. However, another Montana study found sub-surface banded urea produced up to 40 percent higher annual forage yields than broadcast urea (4) suggesting significant volatilization loss from broadcast urea. Recent research in Montana (5) and Oregon (6) has directly measured substantial volatilization from broadcast urea applications. Results from these studies are summarized later in this bulletin.

Factors that Influence Ammonia Volatilization Losses

All ammonium and ammonia-based fertilizers have the potential to volatilize. This guide focuses on ammonia volatilization from urea and liquids containing urea because urea fertilizers generally volatilize more than other N fertilizers. Most volatilization from urea typically occurs during a two- to three-week period after application. Volatilization depends on the rate of urea hydrolysis (see Chemical Reactions; Equation 1), and the rate at which the ammonium is then converted to ammonia gas (Equation 2) that volatilizes if near the soil surface. The rates of these chemical reactions, including volatilization, are a function of the conditions described below.

CHEMICAL REACTIONS



SOIL MOISTURE AND PRECIPITATION

Volatilization of surface-applied urea increases linearly as soil water content increases, until the soil reaches saturation (7). Surface moisture conditions at the time of fertilization and the size and distribution of subsequent precipitation/irrigation events are the most critical factors that affect volatilization losses from cool season broadcast urea on fields monitored in semi-arid regions of Montana and Oregon (5, 6).

Largest losses in Montana (30 to 44 percent of applied N) occurred when urea was applied to a moist soil surface, followed by a period of slow drying with little or no precipitation (Figure 2). These are often the environmental conditions during fall to early spring broadcast applications. Generally, 0.5 inch or more of precipitation from a single weather event is needed to leach urea deep enough into the soil to protect it from volatilization. In the trial illustrated in Figure 2, volatilization was finally checked by an 0.8-inch rainfall event five weeks after urea application. In another Montana trial, 24 percent of

applied N was lost during the 10 weeks after urea was applied to a 5-inch snowpack (0.6 inch water) followed by light scattered rain. When urea was broadcast on dry soil, losses were 10 to 20 percent of applied N when followed by only light scattered rainfall (less than 0.33 inch). Losses were least (less than 10 percent of applied N) when followed within two weeks by at least 0.75 inch of rainfall (5). Reducing volatilization loss may or may not increase annual crop yields because N is not always the limiting factor. However, small grain protein is usually increased when volatilization losses are reduced (8).

In an Oregon trial, more than 60 percent of applied N was lost when urea was applied to freshly irrigated soil with no subsequent irrigation and only light scattered rain over the next 24 days, whereas 0.45 inch of irrigation applied immediately after urea application reduced the loss to less than five percent of the applied N (Figure 3).

Urea prills can absorb moisture from the air and begin dissolving; however, this requires more humidity than generally found in our semi-arid region. There are localized areas or situations where relatively high humidity exists or sufficient dew occurs to begin dissolving urea prills and start volatilization.

SOIL pH AND TEMPERATURE

High soil pH and high temperatures cause higher rates of volatilization because 1) they increase soil concentrations of ammonia dissolved in soil water and 2) warm soil water cannot hold as much ammonia gas. Most soils in our region have a surface pH lower than the pH necessary to produce a high percentage of dissolved ammonia. However, urea fertilizers can temporarily increase soil pH within an inch of the granule, sufficiently to increase volatilization loss (10). The pH increase is higher in poorly buffered soils (Figure 4). The rise in pH increases the rate of ammonium conversion to dissolved ammonia, which increases the supply of dissolved ammonia available for

4 volatilization. Although the increase in pH is temporary, it can result in substantial volatilization loss from soils with an initial pH as low as 5.5 (5).

Urea coated with N-(n-butyl) thiophosphoric triamide (NBPT), contained in Agrotain®, can reduce volatilization loss (Figures 2 and 3) because NBPT slows the conversion of urea to ammonium, minimizing the pH increase (Figure 4). NBPT reduces urea volatilization relatively more in non-calcareous acidic than in alkaline or calcareous (containing free lime) soils, but it loses its effectiveness more quickly in acidic than alkaline soils (12). Polymer-coated urea also reduces the increase in soil pH around the granule, and combined with a slower release of urea, reduces volatilization relative to conventional urea (10). See *Enhanced Efficiency Fertilizers and Management to Minimize Nitrogen Fertilizer Volatilization* for more information on these specialized fertilizers.

Ammonium sulfate has intermediate volatilization potential, with higher rates in calcareous than acidic soils because sulfate dissolves some calcium carbonate, increasing pH around the fertilizer granule. Losses from ammonium sulfate should be low when soil pH is less than 7.0, because low pH suggests calcium carbonate is absent. Anhydrous ammonia and aqua ammonia also temporarily raise pH around the fertilizer, increasing volatilization potential, but for a different reason than hydrolysis. Ammonium nitrate has relatively little effect on soil pH, and thus low volatilization, often similar to unfertilized controls. It is no longer readily available because of its potential use for making explosives. Calcium ammonium nitrate is still available in the U.S. and has similarly low volatilization potential (13). Common N fertilizers and their grades are in Table 1.

Warm temperatures increase the rate of urea hydrolysis and ammonium conversion to ammonia gas, and therefore volatilization. For example, an increase in temperature from 45°F to 60°F can double volatilization loss when moisture

content is kept the same (14). However, cool temperatures do not ensure reduced volatilization. Although cool temperatures decrease the rate at which ammonia is formed, they also decrease the rate that ammonium and ammonia are converted to nitrate, bound to clays, tied up (immobilized) by microorganisms, or taken up by plants. Soils also stay moist longer at low temperatures. These factors leave more ammonia in solution where it can volatilize slowly but over a longer period of time when temperatures are low. In 12 fields throughout Montana where urea was broadcast between October and April, volatilization loss averaged 20 percent of N applied. In all trials it took at least four weeks to reach 90 percent of the total loss and in one trial volatilization was still occurring 10 weeks after surface application. In two-thirds of the trials, peak loss occurred when soil surface temperatures were below 41°F (5). Frozen soils may be at higher risk because they have less ability to bind ammonium and the urea cannot move downward, where there is less risk for loss. The pH at these sites ranged from 5.5 to 8.4. Research in Montana and Oregon shows that caution is warranted when surface applying urea or ammonia-based fertilizers at all temperatures and soil pH levels.

CROP RESIDUE AND THATCH

Thatch and crop residue increase urea hydrolysis rates and volatilization (15). This is largely because: 1) the urease enzyme necessary for hydrolysis is produced by microorganisms that are 40 times more active in surface residue than in mineral soil (16); 2) crop residues often have higher pH than soil, which increases ammonia in solution; 3) thatch and residue may locally increase moisture, which also increases ammonia in solution and available for volatilization; and 4) residue can prevent N from moving into soil. As a result, perennial sod and

TABLE 2. Environmental and soil conditions with high and low risk for ammonia volatilization. The risk of volatilization increases as the number of high risk conditions increases, with soil moisture likely being the most important risk condition.	
High risk conditions	Lower risk conditions
Moist soil or heavy dew	Dry soil
High soil pH (>7.0)	Low soil pH (<6.0)
High soil temperature (>70°F) or frozen soil	Cool soil temperature
Crop residue, perennial thatch or sod	Bare soil
Low cation exchange capacity soil (sandy)	High cation exchange capacity soil (silt or clay-dominated)
Poorly buffered soils (low soil organic matter, low bicarbonate content, high sand content)	Highly buffered soils (high soil organic matter, high bicarbonate content, high clay content)

no-till systems have higher volatilization potential and require more irrigation or rainfall sooner after urea application than bare soil and conventional tillage systems to minimize loss (15, 17, 18). A 0.50-inch rainfall within three hours of urea application on pasture can be sufficient to protect urea from volatilization, whereas a 0.50-inch rainfall two days later may not (19). Three days after UAN was applied to straw residue, 1.2 inches of rainfall was needed to minimize further ammonia loss (16). Nine days after fertilizer was applied to established fescue, ammonia volatilization from UAN and Nitamin® (a slow release liquid urea polymer) became nearly undetectable after more than two inches of rain, while volatilization continued from urea after the rain (20). As on bare soil, scattered rainfall (less than 0.1 inch) every few days on thatch (with urea; 19) or straw residue (with UAN; 16) can cause small bursts of ammonia production resulting in increased volatilization loss.

SOIL BUFFERING CAPACITY, CATION EXCHANGE CAPACITY, AND CALCIUM CONCENTRATIONS

Because urea hydrolysis increases pH around the fertilizer granule, soil properties that resist (buffer) pH changes decrease volatilization. These include high clay, soil organic matter, and/or bicarbonate content. Soils with high cation exchange capacity (CEC) also reduce volatilization by lowering the ammonium concentration in the soil solution available for volatilization. Volatilization loss from urea 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 (21). By comparison, soil CECs in Idaho, Montana, Oregon and Washington are generally in the range of five to 30 meq/100 g. In addition, soils with high CEC often have high levels of exchangeable calcium, which can offset the pH increase caused by urea hydrolysis. It pays to know the soil conditions where urea is being applied.

Summary

Ammonia volatilization 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, moist soils, thatch or crop residue and higher temperature and soil pH increase the potential for volatilization (Table 2), while incorporation with tillage, rain, or irrigation decrease volatilization potential. Recent regional research suggests that surface soil moisture at time of application and rainfall or irrigation amounts after application play the biggest roles in affecting volatilization loss. High CEC soils and cool conditions during major fertilizer application periods reduce the potential for high volatilization in many cropping systems

of the inland Pacific Northwest. However, substantial volatilization has been measured in semi-arid fields in Montana under cool, relatively dry, no-till conditions. Areas with tilled, low-residue soils that dry out quickly may have lower potential for volatilization. By understanding how soil and climate factors influence volatilization, producers can apply urea in situations or with best management practices that minimize volatilization loss (see *Management to Minimize Nitrogen Fertilizer Volatilization*).

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