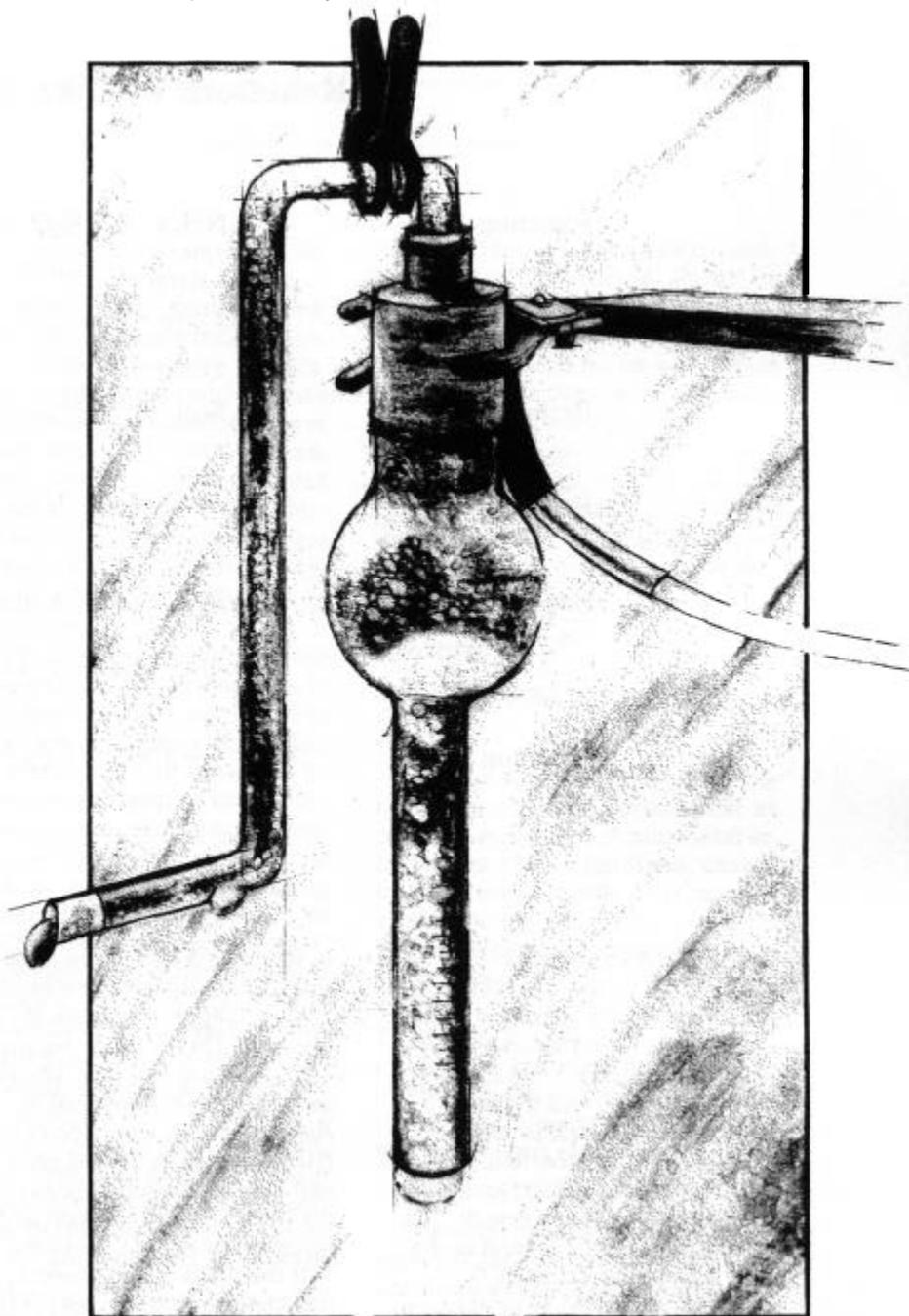


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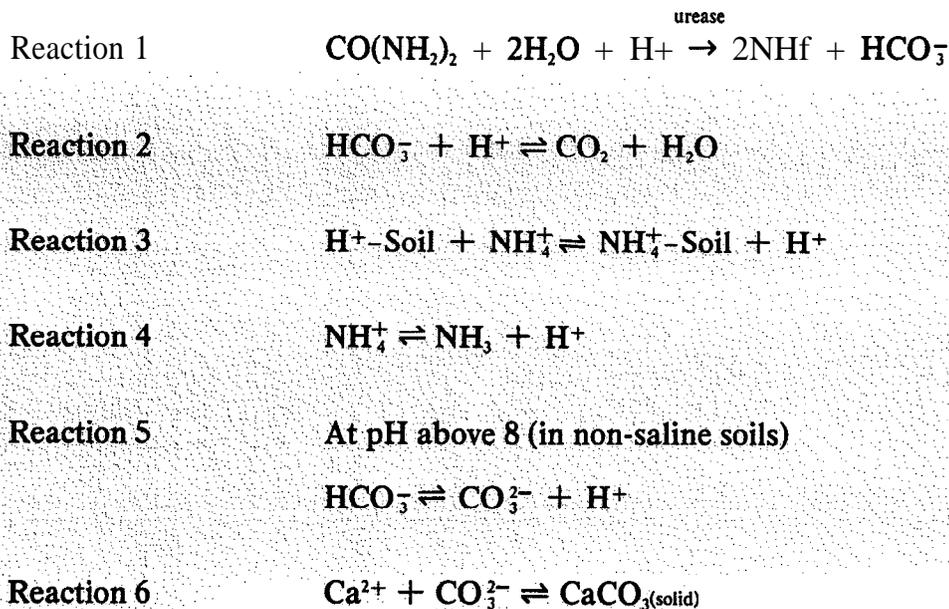


MANAGEMENT OF UREA FERTILIZERS



North Central Regional
Extension Publication

Reactions of Urea in Soil



The conversion of urea [$\text{CO}(\text{NH}_2)_2$] to plant-available ammonium (NH_4^+) can take place only if the urea is dissolved in the soil solution. Then it can react with water (H_2O) and the soil enzyme urease to release plant-available NH_4^+ in Reaction 1. Bicarbonate ions (HCO_3^-) also are formed through reaction with hydrogen ions (H^+) present in the soil. In Reaction 2, the HCO_3^- reacts with more H^+ to produce carbon dioxide (CO_2) which diffuses into the atmosphere. The consumption of H^+ by these two reactions raises soil pH. The H^+ consumed in Reactions 1 and 2 come from the soil particles, as shown in Reaction 3. The release of positive-charged H^+ from soil

in Reaction 3 (for use in Reactions 1 and 2) allows one negative charge to appear for each H^+ released. This or other negative charges in soil can then adsorb most of the NH_4^+ released in Reaction 1. A proportion of the NH_4^+ remains in the soil solution and may be converted to ammonia (NH_3). The proportion as NH_3 increases as the pH increases.

If the pH is raised above 8, sufficient carbonate ions (CO_3^{2-}) may be formed so they can react with calcium ions (Ca^{2+}) from the soil to form a precipitate of calcium carbonate (CaCO_3) as shown in Reaction 6. If Reaction 6 begins to occur following urea application due to sufficient Ca^{2+}

and CO_3^{2-} in the soil solution it causes more H^+ to be released from bicarbonate via Reaction 5. This sequence of reactions helps resist a further rise in pH, as does a reduction of CO_2 formation via reaction 2 when pH exceeds 8. A combination of reactions 5 and 6 can help resist a rise in pH, which is one of the reasons that L. B. Fenn and associates (Fenn et al., 1981) have advocated adding calcium salts with urea to reduce ammonia loss from surface-applied urea. Reaction 6 may begin below pH 8 in the presence of high soil solution calcium levels (from added calcium salts or from those present naturally in salty soils.

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Urea, an organic compound, occurs naturally in animals and some plants. It was first identified over 200 years ago and was prepared synthetically in the laboratory in 1828. Industrial facilities to produce urea in large commercial quantities were developed early in this century. Urea, produced by ammonia reacting with carbon dioxide, is often manufactured at facilities that use natural gas as feedstock. Carbon dioxide is a by-product of ammonia production at these facilities.

Urea fertilizers range in composition from pure, dry granular urea to fertilizer products that are mixtures of urea with other sources of nitrogen and/or phosphate and potash. The most common nitrogen mixture is the liquid urea-ammonium nitrate solution (UAN) commonly sold in the midwest as a solution containing 28 percent nitrogen. It may also be sold as a 32 percent nitrogen solution. Approximately half of the nitrogen in UAN is urea. Liquid UAN often is blended with liquid ammonium polyphosphate (10-34-0) to make N-P liquid blends. Dry muriate of potash may be dissolved in this mixture to make a complete liquid fertilizer. Also, dry urea may be blended with dry phosphate and potash products such as diammonium phosphate (18-46-0) and muriate of potash (0-0-60).

The tonnage of urea fertilizer sold (primarily dry urea and UAN solution) has increased markedly over the past three decades, due in part to the increased total tonnage of nitrogen sold. However, the proportion of total nitrogen sales as urea-containing fertilizer (urea and UAN) has increased from roughly 8 percent to 36 percent of the total nitrogen sold in the north central U.S. Of the dry nitrogen sold, urea tonnage is presently three times greater than ammonium nitrate. The increased use of urea is likely to continue as urea is less expensive to produce and transport because of its higher concentration of nitrogen. Although urea is presently less expen-

sive than ammonium nitrate, questions often are raised about its availability to crops compared to ammonium nitrate and its potential for loss when applied to the soil surface and not incorporated by tillage. Chemical reactions of urea and ammoniacal nitrogen (ammonia and ammonium) in soil, and also the soil, climate, and management factors that affect the performance of urea, need to be understood for proper use.

Reactions of ammoniacal nitrogen in soil

Most commercial nitrogen fertilizers either contain ammoniacal nitrogen (ammonium or ammonia) or, in the case of urea fertilizers, convert to ammonium shortly after they are applied to the soil. If the pH at the site of fertilizer placement is much above 7, a noticeable amount of ammonia can form from ammonium. The higher the pH, the more ammonia forms. Ammonia forms because of the equilibrium between ammonium and ammonia that can be represented by this equation.



Because hydrogen ions are the source of acidity, this equation can be summarized as follows: Under acidic conditions (low pH), more hydrogen ions are available to react with ammonia to form ammonium, whereas under alkaline (high pH) conditions (fewer hydrogen ions), a greater portion of the ammonium is converted to ammonia. The relative proportion of these two ammoniacal nitrogen species varies with pH as shown in Table 1. These proportions also vary with temperature, as will be discussed later.

Very little ammonia exists at pH 7 and below, but at higher pH the proportion of the nitrogen as ammonia increases greatly (Table 1). This equilibrium applies to the ammoniacal nitrogen that is present in the soil

Table 1. The percentages of ammoniacal nitrogen that would be present as ammonia and ammonium at 77°F.

Soil pH	Ammoniacal N	
	Ammonia	Ammonium
6	0.058%	99.94%
7	0.57 %	99.43%
8	5.4 %	94.6 %
9	36.5 %	63.5 %

Table 2. The pH of Haynie sandy loam and Kahola silt loam 13 hours after adding urea.

Urea-N concentration	Haynie	Kahola
ppm N	Soil pH	
0	5.74	5.42
140	7.17	6.05
280	8.13	6.67

Source: Kissel, Cabrera and Ferguson (1988)

solution and not adsorbed to the soil particles. Much of the ammoniacal nitrogen from the applied fertilizer is present as ammonium adsorbed to the negatively charged soil particles.

Although ammonium and ammonia differ physically only by one hydrogen ion, they are greatly different in their properties. Ammonium is present as a cation in soil and is generally adsorbed by soil and not subject to direct gaseous loss. Ammonium ions are also readily taken up by plants. Ammonia, on the other hand, is a gas whose properties make it toxic to plants (including plant roots) and animals in high concentrations. Ammonia that is applied directly to soil as anhydrous ammonia will react with hydrogen ions in soil to form ammonium ions as it diffuses away from the injection band in the soil. The tendency for ammonia to diffuse away from where it is placed or formed is enhanced by a large ammonia concentration gradient resulting from conversion of ammonia to ammonium as it reacts with hydrogen ions in soil at the outer edges of the placement zone.

The reactions of ammoniacal nitrogen in soil also apply to urea fertilizer since ammonium is formed from urea shortly after urea is added to soil.

Reactions of urea in soil

Urea applied to the soil reacts with water and the soil enzyme urease and is rapidly converted to ammonium. This conversion is called urea hydrolysis. In this reaction (shown as reaction 1 on the inside cover), hydrogen ions are consumed which causes the soil pH near the fertilizer to rise. If the pH rises above 7, a significant amount of ammonia can form in soil for a few days following urea application. When urea is surface-applied, the formation of ammonia at the soil surface from urea hydrolysis may allow some ammonia loss, and if urea is banded with the seed, some plant damage may occur because of ammonia toxicity. The severity of both processes depends largely on the concentration of ammonia formed.

The concentration of ammonia that forms depends on a number of

factors. The most important are:

- 1) The concentration of urea in soil immediately following application. Higher urea concentrations generally result in more hydrolysis and in higher ammonia concentrations in soil.
- 2) Soil pH for 3 to 5 days after urea application. The higher the pH during this time, the higher the ammonia concentration.
- 3) The rate of urea hydrolysis in soils. Fast urea hydrolysis reduces the time for urea and ammonium (and any gaseous ammonia) to diffuse deeper into the soil when surface-applied or away from the seed in the case of seed-placed urea. When diffusion time is reduced, the ammonium will be more concentrated, the pH will be higher, and more ammonia will form. The primary factors affecting the rate of hydrolysis that are most likely to change from field to field are the amount of urease enzyme in the soil, soil temperature, and soil moisture.

The combination of large amounts of urease, high temperature, and moist soil favors fast urea hydrolysis which results in more ammonia formation. Each of the three factors affecting ammonia formation will be discussed in more detail below.

Urea concentration

The concentration of urea in soil depends largely on two factors: 1) the amount applied per acre and 2) the method of application. Methods such as band application or surface application cause higher urea concentrations than urea that is incorporated and mixed with soil by tillage. Rainfall or irrigation immediately after fertilizer application also can move urea into soil and cause it to disperse and to be less concentrated. Hydrogen ions from the soil are consumed when urea is hydrolyzed, so it follows that the hydrogen ions will be consumed from less soil where urea is

more concentrated, provided there is enough urease enzyme and adequate temperature and water to sustain a fast reaction. Rapid hydrolysis and consumption of hydrogen ions from a small volume of soil will cause the soil pH at the site of application to increase further and cause more ammonia to form.

To illustrate the effect of urea concentration on soil pH, the results of a laboratory study are shown in Table 2. In this study, urea was mixed uniformly with either Haynie sandy loam with initial pH 5.7 or Kahola silt loam with initial pH 5.4. Extra urease was added to insure that all added urea hydrolyzed. Two factors are important from the data: more urea caused higher pH, and the sandier Haynie soil had higher pH than the Kahola soil at both levels of added urea. While higher concentrations of urea cause higher pH, in many cases in the field, urease activity may limit hydrolysis rates at very high urea concentrations (such as surface band applications) thus allowing urea and ammoniacal nitrogen more time to diffuse into the soil and be adsorbed rather than lost to the atmosphere. The rate of hydrolysis strongly affects ammonia loss as discussed below.

Soil pH after urea application

The pH rise that occurs when urea hydrolyzes depends in part on the pH buffering properties of the soil. Soils vary in their ability to supply hydrogen ions (which resist a rise in pH) due to two factors: 1) their pH prior to adding urea and 2) their soil hydrogen ion buffering capacity which is a measure of the number of hydrogen ions released from soil clays and organic matter per one unit rise in pH. Soils with more hydrogen ion buffering generally have more clay and organic matter. Sandy soils, usually low in both, are typically very poorly buffered. The result is typically a higher pH when urea is ap-

plied to sandy soil. The primary sources of hydrogen ions in soils across the full range of soil pH, as described by Thomas and Hargrove (1984), are from hydrolysis of cation exchangeable aluminum, non-exchangeable hydroxy aluminum and iron, and organic matter that releases hydrogen ions due to addition of alkaline material to soil or, as in the present case, due to reactions that consume hydrogen ions in the soil.

The importance of hydrogen ion buffering capacity in ammonia loss is illustrated in Figure 1. In this study, soil mixes were prepared that differed in their hydrogen ion buffering but

had the same initial pH and cation exchange capacity. Urea fertilizer was then applied to the surface of each of these mixes. As would be expected, the ammonia loss was greatest from the soil mix that had the least hydrogen ion buffering (soil mix 1). Because this soil mix had the fewest hydrogen ions, it allowed the soil surface pH to be higher than the other soil mixes 3 to 4 days after urea was surface-applied. The higher pH allowed a greater proportion of the ammoniacal N to be in the gaseous ammonia form, which resulted in more loss. In turn, the soil mix with the most hydrogen ion buffering had the

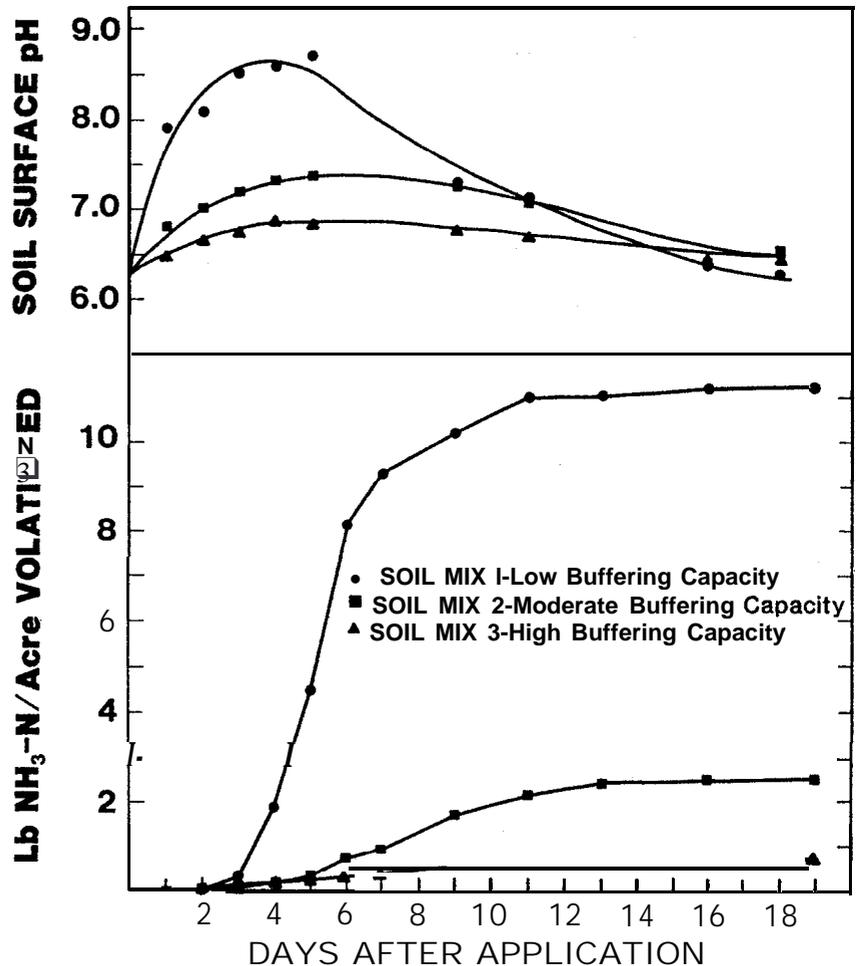


Figure 1. Soil surface pH and total ammonia loss with time after surface application of urea to soil mixes with various amounts of hydrogen ions (from Ferguson et al., 1984).

lowest pH 3 to 4 days after application and also the least ammonia loss. In related work, Izaurre et al. (1987) found that the retention of anhydrous ammonia by soils could be predicted from a soil's titratable acidity to pH 9. Their data showed that each H^+ released from soil upon raising the soil pH to 9 with NH_4OH allowed the adsorption of one molecule of NH_4^+ by soil. In summary, soils that have more hydrogen ions to buffer against a rise in pH will retain more ammonia as ammonium and will, therefore, lose less ammonia by volatilization from surface-applied urea.

Factors affecting the rate of urea hydrolysis

Three major factors—the concentration of urease enzyme in soil, soil temperature, and soil water content—work together to greatly affect the rate of urea hydrolysis.

Soil urease concentration. The greater the number of urease enzyme molecules in soil, the faster the hydrolysis of applied urea. The number of urease molecules in soil is highly correlated with the amount of soil organic matter. The urease enzyme is a large organic molecule that appears to be bonded with soil organic matter to soil clays. As a result, soils with more clay tend to have more urease enzyme molecules.

Crop residue also has been found to contain high levels of urease enzyme. In a couple of recent studies, the concentration of urease enzyme molecules was found to be 20 to 30 times higher in crop residue than in underlying soil (McInnes et al., 1986b, and Torello and Wehner, 1983). Therefore, urea placed directly on crop residue can rapidly form ammonium if temperature and moisture conditions are conducive to urea hydrolysis.

Soil temperature. The rate of urea hydrolysis is greatly increased by rising temperature. For example, a rise in

soil temperature from 44°F to 80°F will cause the rate of urea conversion to ammonium to be approximately four times faster. As an example, when urea is surface-applied at 80 lbs of nitrogen per acre to a typical silt loam soil with adequate moisture whose surface temperature is 80°F (as might occur when fertilizer is applied for grain sorghum production or as a sidedress for corn), it requires approximately 4 days for all the urea to be converted to ammonium (see Figure 2). In contrast, when urea is surface applied to the same soil at 35°F soil temperature (a temperature which might occur when wheat is top-dressed or fertilizer applied in early spring for corn), it requires approximately 12 days for all the urea to be converted to ammonium. Because more time is available for urea and its products to diffuse away from its application site at the lower temperature, the slower urea hydrolysis does not raise soil pH as high and results in less ammonia formed near the soil surface.

Temperature has an additional influence on ammonia formation during and following urea hydrolysis. Temperature affects the proportion of the total ammoniacal nitrogen in the soil solution that is present as ammonia. As the temperature rises, the proportion as ammonia increases. For example, at pH 8 the percent of ammoniacal nitrogen as ammonia is 5.4 percent at 77°F (see Table 1), but at 35°F the percentage as ammonia is about 1 percent. Less ammonia in the soil solution will result in less ammonia being lost.

These two principles are in agreement with observations of generally very little ammonia loss when urea is applied at cooler temperatures.

Soil water content. Soil water content has the greatest effect on the rate of urea hydrolysis when the soil becomes very dry. Urea hydrolysis is most rapid in moist soil, and the rate of hydrolysis does not change greatly at water contents that are readily available to plants. In the water con-

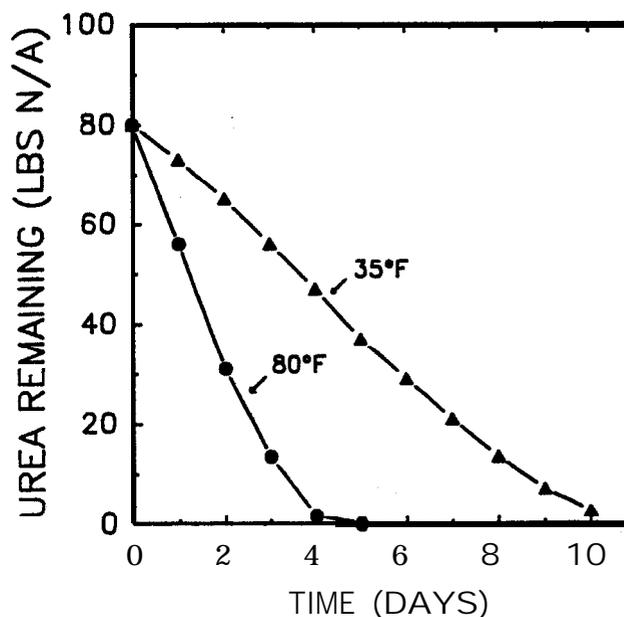


Figure 2. The conversion of urea to plant available ammonium as affected by temperatures of 35 and 80°F is illustrated for a typical Kansas silt loam soil. Each pound per acre of urea nitrogen is converted to one pound per acre of ammonium nitrogen.

tent range from wilting point to air-dry, the rate slows greatly, and essentially stops as the soil approaches air dryness.

Soil temperature and soil water content often interact to affect urea hydrolysis rates and, therefore, the amount of ammonia loss from surface-applied urea. This interaction occurs because high temperatures increase the speed at which the surface layer of soil dries. Under conditions of rapid drying (usually associated with higher temperatures and dry atmospheric conditions), the surface layer of soil will reach air dryness much quicker and slow the hydrolysis rate sooner than under cooler and slower drying conditions. In some cases, the surface soil may become sufficiently dry within a day or two after fertilizer application to greatly slow or nearly stop urea hydrolysis.

This is illustrated by studies in which the conversion of applied urea to ammonium, the ammonia loss rate, and soil water content were all measured for 15 days following surface application of urea to a sandy loam soil that was relatively free of crop residue (McInnes et al., 1986a). Fertilizer was applied to the moist soil just after a rain in late June. As shown in Figure 3, about 30 percent of the 107 pounds of urea-nitrogen applied per acre was hydrolyzed in the first 2 days after application, but urea hydrolysis ceased for the next 4 days due to dry conditions in the top layer of soil. Soil water content in the top 0.4 inch of soil had declined from over 7 percent shortly after application to around 1.5 percent after 2 days. The field was sprinkler-irrigated with 0.2 inch of water late on day 186 (July 5) which caused the

water content of the surface soil to increase to about 14 percent again allowing urea to hydrolyze. Two more irrigations of 0.2 inch each were applied on days 189 and 193.

Loss of ammonia was also sensitive to soil water content, being greatest about mid to late morning each day just following the peak soil water content each day. The maximum soil temperatures each day occurred around 2 to 3 p.m. Although one might expect the maximum rate of ammonia loss to occur when the soil temperature is at its maximum for the day, apparently the dryness of the soil was the limitation to ammonia loss.

The amount of the applied urea lost in the first 6 days of this study was only 4 percent. The loss was increased greatly by the three light irrigations over the next 9 days so that by the end of the study, 17 percent of the urea had been lost. However, had these three irrigations not been applied to wet the surface layer of soil, the total loss probably would not have exceeded 5 to 10 percent of the applied urea.

Two other studies were carried out on a Muir silt loam with similar results (McInnes et al., 1986a). Losses were much less than previously believed based on laboratory studies, and the surface soil water content played a dominant role in controlling the amount of ammonia loss from surface-applied urea. In these two studies, 4 and 9 percent of the applied urea was lost, but in the study with 9 percent loss, light irrigations were used to increase loss over what it would have been normally.

Incorporating urea by tillage the day of application or leaching the fertilizer into soil by 0.5 inch or more of rain or irrigation water will nearly eliminate ammonia loss. Comparison studies of crop yields fertilized with urea that is incorporated versus urea left on the soil surface provides information on the severity of ammonia volatilization. Such a study was car-

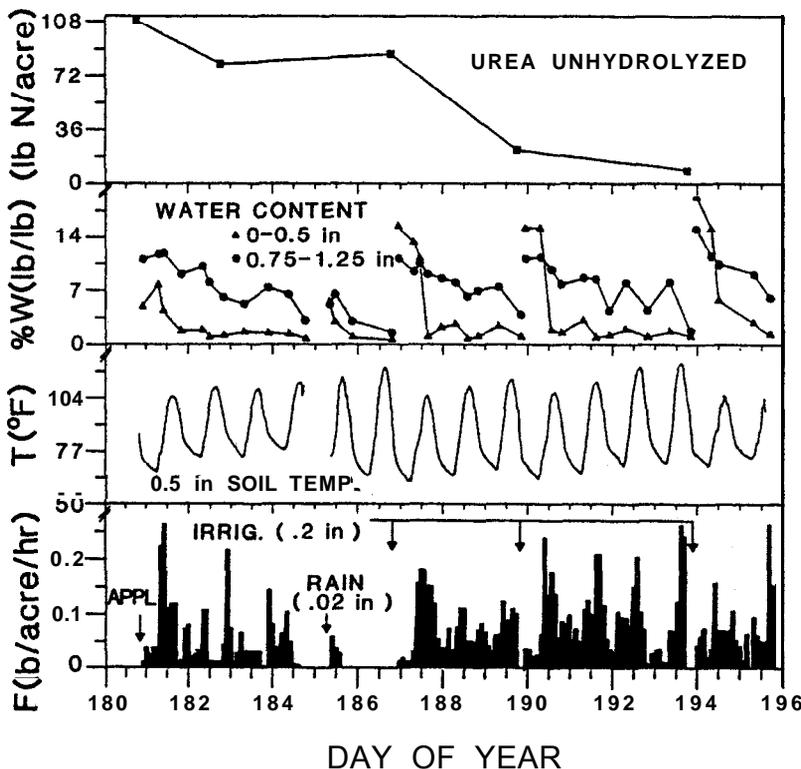


Figure 3. Results from a study of McInnes et al. (1986a) indicate how temperature and water content near the soil surface affect the conversion of urea to ammonium and loss of ammonia from surface applied urea.

ried out to compare the performance of irrigated corn fertilized with urea or UAN that was incorporated the same day versus that which was either not incorporated or incorporated 7 days after application. The resulting corn yields, an average for all nitrogen fertilizer rates and both sources for 8 site years of data, indicate that yields were not significantly different when the urea fertilizers were not incorporated when compared to incorporated the day of application (Table 3). These results indicate that ammonia loss was insignificant since a sizable ammonia loss would have caused the "not incorporated" treatment to have a lower yield. These data are reported in more detail by Maddux et al. (1984).

Management practices affecting ammonia loss

The following describes some cases when ammonia loss from urea fertilizers may be a problem and outlines possible practices to reduce losses. Other processes that reduce nitrogen fertilizer availability are also discussed.

No-till crop production. Ammonia loss from surface applied urea is likely to be greater under no tillage than for conventional tillage systems. Continued no-till crop production will result in a layer of crop residue on the soil surface that can enhance ammonia loss from surface applied urea or UAN solution. A layer of partially decomposed or undecomposed crop residue can increase loss because: 1) the urease activity of this residue layer is higher than in underlying soil, 2) undecomposed crop residue may reduce diffusion of fertilizer into the soil, and 3) crop residue at the surface often increases the water content of the surface soil layer, which can increase ammonia loss as discussed earlier. The layer of partially decomposed crop residue can tie up nitrogen temporarily, making it less

Table 3. Evaluation of the need for soil incorporation of urea and UAN solution applied to a slightly acid silt loam soil.

Time of incorporation	Grain Yield
No fertilizer	87 bu/a
8 hours	143 bu/a
7 days	146 bu/a
Not incorporated	145 bu/a

Source: Maddux et al, 1984.

Table 4. Average yield of grain sorghum produced by fertilization with three nitrogen source/placement method combinations.

N Source	Method	Yield	Flag leaf N
Ammonium nitrate	Broadcast	104 bu/a	2.19%
UAN	Broadcast	97 bu/a	1.97%
UAN	Knife	111 bu/a	2.28%

Source: KSU North Agronomy Farm (1986)

available to the crop as discussed below.

No-till row crops fertilized with surface applied urea or UAN solution have sometimes yielded less than when fertilized with a source of nitrogen such as ammonium nitrate which does not lose ammonia when applied to neutral pH or acid soils. Such data from a 1986 study at the KSU Agronomy Farm are shown in Table 4. In this study, yields of grain sorghum averaged across nitrogen rates and tillage methods were 97 bushels per acre for surface applied UAN solution, but 104 bushels per acre when ammonium nitrate was surface applied. Since ammonia is not lost from ammonium nitrate when applied to such an acid soil, the lower yields with broadcast UAN indicates that some ammonia may have been lost from the broadcast UAN, thereby lowering crop yields. However, when UAN solution was knifed 5 to 6 inches below the surface on 30 inch centers, the yields were even higher than for broadcast ammonium nitrate at 111 bushels per acre. The yields for the treatments correlated well with the percent nitrogen in the plant

leaves. Higher nitrogen in leaves indicates better nitrogen nutrition in the plant because of better fertilizer availability. Similar results have been obtained at other study locations.

Sufficient evidence has been collected to show that the differences in crop response to the various nitrogen sources are not always due to differences in ammonia loss from the various fertilizers. Decomposing crop residue can tie up surface applied nitrogen (making it unavailable to crops), whereas nitrogen placed below the decomposing crop residue is not as susceptible to this problem. In the above study, the knifed UAN treatment was better than the broadcast UAN in part because of less fertilizer nitrogen tie-up by decomposing crop residue. The amount of nitrogen fertilizer tied up by decomposing crop residue will depend on a number of factors, but two are especially important.

- 1) The percent nitrogen in decomposing crop residue. The lower the percent nitrogen, the greater the nitrogen fertilizer tied up.
- 2) The amount of crop residue per

acre. The greater the amount of residue, the more nitrogen can be tied up.

Although the fertilizer nitrogen tied up through decomposition of residue may later be released for crop use, our studies indicate it is released very slowly, and very little of the tied up nitrogen will be released the same cropping season, Wagger et al. (1985). In summary, nitrogen fertilizer banded below the soil surface (and crop residue) will often be more available than surface applied nitrogen, even for non-urea fertilizer sources.

An alternate method of applying liquid nitrogen sources with little or no tillage is to apply the fertilizer in surface bands or strips. When differences occur, this method of placement provides better nitrogen availability to row crops or small grains than surface broadcast applications, but not as good as fertilizer bands placed below the soil surface.

Cool-season grass fertilization.

Grasses such as bromegrass or tall fescue cover the soil surface with a layer of partially decomposed litter. These residues are comparable to no till cropland with regard to the amount of organic litter on the soil surface. When urea fertilizers are applied to these grass sods, they are potentially subject to ammonia loss much the same as when urea fertilizers are applied in no-till crop production. They are also subject to nitrogen tie-up in this decomposing litter. Other non-urea sources of nitrogen may also be tied up by this process.

When urea fertilizers are not used efficiently by forage grasses, it is difficult to determine in traditional soil fertility studies whether poor use of the applied nitrogen is due to ammonia loss or nitrogen tie-up. An additional complication is the root systems of these forage grasses which are quite large and serve as a storage reservoir for much nitrogen.

In some forage fertilization studies, we have compared the production

of bromegrass and fescue on plots receiving urea with those receiving ammonium nitrate. In a study with bromegrass, these two sources were applied to their respective plots for several years, and forage production was measured. In the second year of the study, forage production was better with ammonium nitrate than urea, but in the other years of the study, production was equal from the two sources. Total forage production for the seven years of the study was about equal for the two sources of nitrogen. Other research has found better carry-over of nitrogen from urea fertilization than from ammonium nitrate for use by the next year's forage crop.

In summary, in most cases there is little ammonia loss from urea surface applied to cool-season grasses on well drained soils. Over several years of fertilization, the production of forage using urea will be the same as that from using ammonium nitrate, when applied during the recommended time from November through early March.

When UAN solution is used as the nitrogen source, we have observed better performance (about 15 percent more forage production) when it is applied in surface bands than when applied broadcast. Representative data from one of these studies are given in Table 5. In this study, N uptake from the surface band treatment was about 24 percent greater than from the broadcast treatment. Band

spacing was 10 inches. If surface bands are used, the bands should be spaced no more than 10 to 12 inches apart in order to obtain maximum forage production.

Environmental conditions at the time of and shortly after application

The two weather related factors of the environment, temperature and moisture, were shown earlier to greatly affect urea hydrolysis rates and ammonia loss from surface applied urea fertilizers. Knowledge of how these two factors affect loss of ammonia can be used to the farmer's advantage in making fertilizer application decisions.

When a choice is possible, apply urea fertilizers when temperatures are cool. Wheat, cool-season grasses, and corn can be fertilized in late winter to good advantage rather than later in the spring when temperatures begin to warm up. Even though losses are usually not large with later application, the early application is preferred.

While application under cool or cold conditions is preferred, there is potential for loss of fertilizer in storm runoff should an unusual winter rainstorm or quick snowmelt occur when soils are frozen. We have observed poor fertilizer performance in a few instances when these somewhat rare weather events occur. Separately, we

Table 5. Forage yields, N content of forage, and N uptake by forage as affected by application method.

Application method ¹	Forage yield at 12.5% H ₂ O	N content	N uptake
No N	3,220 lb/a	0.92%	26 lb/a
Broadcast	5,906 lb/a	1.19%	62 lb/a
Knife	5,607 lb/a	1.36%	68 lb/a
Surface Band	6,791 lb/a	1.28%	77 lb/a

¹Values presented are the means over N rates of 10 inch spacing for knifed and surface band.

Source: KSU-North Agronomy Farm (1984).

studied loss of nitrogen in runoff when one inch of sprinkler irrigation water was applied to a frozen soil (with air temperature about 35°F) just following application of urea and ammonium nitrate. Losses were about equal for both sources, being 25 percent of the fertilizer applied. Therefore, it is best to avoid application of fertilizer to frozen soils if there is a high probability of rapid warming conditions with rainstorms and runoff. If the surface soil is partially thawed at fertilizer application time or if it thaws soon after application, the fertilizer will dissolve and diffuse into the soil within a day or two. If storms and runoff then follow, losses will be small.

Application under dry surface soil conditions is also better than wet conditions to avoid ammonia loss. Usually, the surface of a well-drained soil dries quickly. Soils with high water tables, however, may stay moist near the surface for longer periods of time. Lower parts of a field that stay wet for long periods of time may also experience some problems with ammonia loss, whereas well drained areas of a field may not experience loss. Somewhat higher rates of application, or later sidedress applications on these wetter areas could increase production by offsetting or avoiding some nitrogen loss.

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