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Managing Nitrogen

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Approximately 78% of the air above an acre of land is nitrogen (N). Unfortunately, grain crops such as corn and wheat cannot use this N because it is in N_2 form, which is very inert. This means that grain crops need to get their N from sources such as manure and fertilizer, in which the N is in forms that the plants can take up and use. Because plants have more N than any other element besides those that come from the air or water (carbon, hydrogen, and oxygen), nitrogen is the most limiting element in grain crop growth under most natural (unfarmed) systems and in many farming systems. Other than possible stress due to shortage of water, N deficiency in grain crops is also very visible. Finding ways to provide N to grain crops has been a major challenge to farmers in most parts of the world since the beginning of agriculture.

Nitrogen Rates for Corn

A bushel of corn contains about 0.8 pounds of nitrogen (N), so a 200-bushel corn crop removes about 160 pounds of N from the field. About two-thirds of the N in a corn plant ends up in the grain, so our 200-bushel crop would have about 240 pounds of N in the plants before harvest. This is 1.2 pounds N per bushel, which has been the factor that has been used to convert proven or expected yield into N rate recommendations—"1.2 is the most [we] should do." This has been the corn N rate recommendation in Illinois for more than three decades, with some minor adjustments over time. This guideline was not just made up; it resulted from early work showing how much N the plant needs rela-

tive to its yield, and it also was backed by N rate research showing that, averaged over trials, "optimum" yield (yield at the economically optimum N rate) divided by the optimum N rate came out to about 1.2 pounds of N per bushel.

At one time, the N rate recommendation was tempered by economic considerations. Thus it was suggested to lower the 1.2 pounds N/bushel to 1.1 or even 1.0 if the ratio of N price (dollars per pound) to corn price (dollars per bushel) rose from, say, 0.05 (10 cents/pound N: $2 per bushel) to 0.1 (20 cents/pound N: $2 per bushel) or higher. This makes economic sense, in that we usually try to apply an input like N at a rate where the last pound of N added produces enough extra yield to just pay for itself. Agronomically, there was incentive to apply N at the rate needed for maximum yield, plus some extra "just in case," in order to always have enough N. In fact, the development of the yield-based N recommendation provided a much-needed rationale to lower rates to more reasonable levels. Without it, N rates of 200 or more pounds per acre were used for corn not expected to produce more than 100 bushels per acre. In Illinois, the average corn yield exceeded 100 bushels per acre for the first time in 1967, and from the mid-1960s to the mid-1970s, corn yield averaged less than 100. Ammonia prices during that period averaged about $100 per ton, or about 5 cents per pound of N.

While yield-based N recommendations were appropriate and useful at the time they were developed, recent research results have shown that modern hybrids grown in Illinois soils may not need as much N as these recommendations suggest. In most studies, especially those where

corn follows soybean, there is little or no relationship between yield and the N rate it takes to reach those yields (**Figure 9.1**). Reasons for this discrepancy include the fact that the soil provides varying amounts of N, and also that modern hybrids may be better both at extracting N from the soil and at using this N efficiently to produce grain. The latter is true in part because the grain protein content of newer hybrids tends to be lower than that of older hybrids, so the removal of N with the grain is lower on a per-bushel basis.

A New Approach

One way to use data from a large number of trials is to average results over the trials, producing single curves that describe average N responses (**Figure 9.2**). This approach is straightforward, and we can apply economics to such response curves to find the optimum rate. However, it can be difficult to average data over different trials done differently, and there is usually little sense of, or adjustment for, variability among response curves.

Most N response data show a curvilinear (decelerating) response, usually (depending on highest rate) leveling off at some point, with a flat curve after that. Yield decreases at high N rates occur rarely now compared to trials a few decades ago, as a result of hybrid improvement. **Figure 9.3** shows such a response from one trial. After finding a line to fit the data, we can subtract the yield at zero N fertilizer and multiply the yield added by N at each N rate times the price of corn to produce the gross return from N. Subtracting the cost of N gives the "return to N" (RTN) line, which gives the profit from N at each N rate (**Figure 9.4**). The high point of this line is the "maximum return to N" (MRTN) point, where the yield increase from adding N just paid for the N added.

Similar RTN values are calculated for each trial in the N response dataset; then these values at each N rate are averaged to produce an RTN line for the whole dataset. The MRTN is the high point on this average line over all trials, and it shows the N rate at RTN at which the maximum return to fertilizer N is reached. **Figure 9.5** shows RTN based on a dataset containing results of many trials over years and locations. Because the RTN curve tends to be rather flat on top, we think it makes sense to use a "range" of N rates instead of a single rate. We arbitrarily chose this range to be the N rates over which the RTN is within $1 per acre of its maximum, at the MRTN. In the database we have, this range of N rates is usually about 15 to 20 pounds on either side on the N rate that produces the MRTN, so the range is about 30 to 40 pounds of N wide. Ranges allow some individual choice based on personal approach to risk, environmental fragility, and other factors.
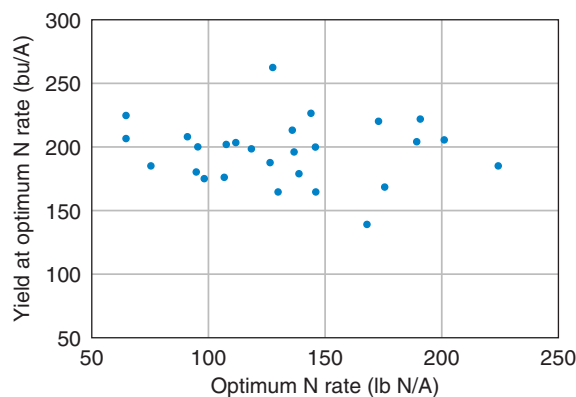

Figure 9.1. Optimum yields and optimum N rates from 27 separate N rate trials in Illinois. Trials were corn following soybean, and optimum N rates were calculated using the N price ($ per lb N) to corn price ($ per bushel) ratio of 0.1.
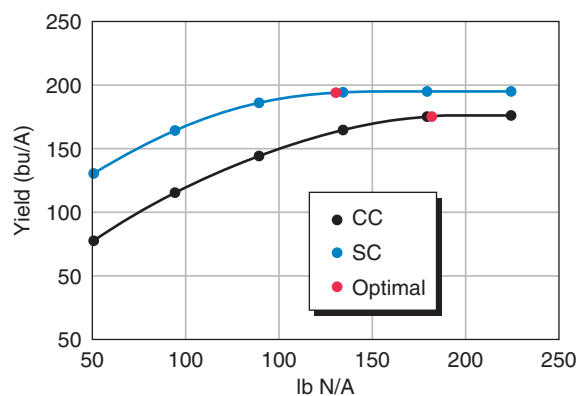

Figure 9.2. Response of corn to N rate, averaged over 27 trials with corn following corn (CC) and 27 trials with corn following soybean (SC). Optimal N rate-yield points are calculated based on the N price ($ per lb N) to corn price ($ per bushel) ratio of 0.1.

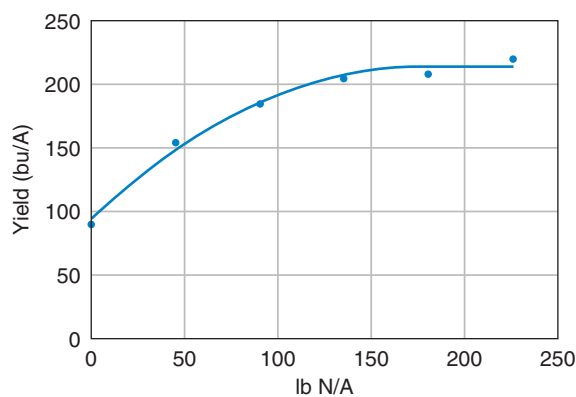

Figure 9.3. Corn yield response to N rate in a trial at Urbana where corn followed corn. The symbols are actual yields, and the line is computer-fitted as a "quadratic + plateau" line, where the curve rises then flattens out.
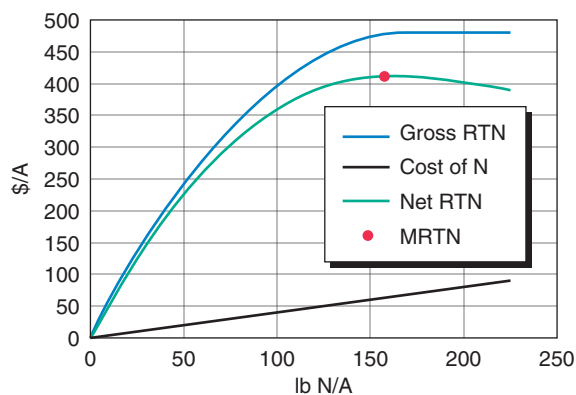
Figure 9.4. Return to N (RTN) at different N rates, using the data shown in Figure 9.3. The gross RTN is the yield increase (over the yield without N) times a corn price of $4 per bushel, and the N cost line is based on N priced at 40 cents per pound. Net RTN is the gross RTN minus the N cost. The point of maximum return to N (MRTN) is the highest point in the net RTN curve.
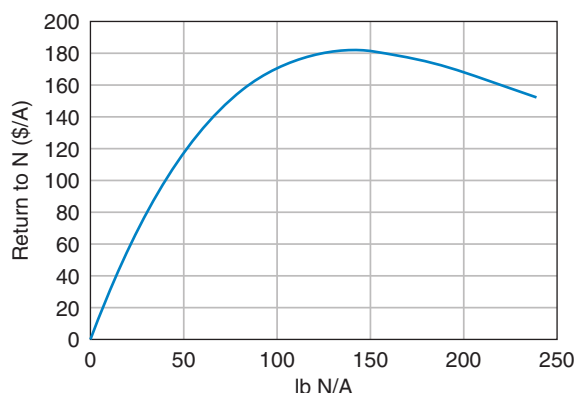

Figure 9.5. Return to N averaged over 40 trials with corn following soybean in northern Illinois.

The development of the MRTN approach was a cooperative effort among a group of scientists. Dr. John Sawyer at Iowa State University created a website where N rate guidelines can be calculated using this approach. The Illinois option on this website uses data generated from more than 400 trials in Illinois since the mid-1990s. Separate databases allow calculations to be made for northern, central, and southern Illinois, for corn following corn, and for corn following soybean. Calculations can be made for single N and corn price combinations, or different price combinations can be compared on the same graph. **Figure 9.6** shows the opening page of this website, and the output for corn following corn in northern Illinois as an example. New data are added each year, but the database in Illinois is large enough that calculated rates will not change a great deal as new data are added. The website is extension. agron.iastate.edu/soilfertility/nrate.aspx.

What Changes with the New Guidelines?

We have termed N rates calculated as described "guideline" rates, to reflect that this is a decision aid rather than a fixed recommendation. This does not mean that we don't have faith in this method—we recommend strongly that it be used, and we recommend that the yield-based N recommendation system no longer be used. We recognize that the use of a "sliding" N rate guideline and of ranges is not as comfortable for some as the single, fixed rate that could be calculated under the proven-yield (PY) system. The fact that rates can change with corn and N prices may also seem to some to be agronomically shaky, in that it might seem that there must be a "best" rate from a yield standpoint. The fact that guideline rates are not fixed also seems to allow the possibility that the crop could sometimes end up deficient in N. In truth, no reasonable N recommendation system can rule out N deficiency under some conditions. In research, we occasionally see yields respond to N rates above 250 pounds per acre. This makes it clear that it is unreasonable to use N rates high enough to guarantee that the corn crop will never be deficient.

While we know of no perfect system to set N rates under variable conditions such as those in the Corn Belt, we do think that this is the best way to use current research data to estimate N rates that are likely to provide the best return. It is clear that as corn yields continue to rise, N rates required to produce such yields are not rising at the same rate, if they are rising at all. As **Figure 9.1** shows, yields above 200 bushels can in some cases be produced with less than 100 pounds of N. From an environmental standpoint, the fact that most guideline N rates are lower than rates under the proven yield system would seem to be a positive.

We trust N rate calculations based on current N and corn prices, but if N prices drop and corn prices rise so that the ratio drops to 0.05 or less, calculated N rates could be very high. The N rate calculator has a built-in limit on this, and it will not calculate N rates with the top of the range above 240 pounds N per acre. For corn following corn in northern Illinois, this limit is reached at a ratio of about 0.03. Reaching such a ratio is unlikely; for instance, if the corn price were $8 per bushel, N would have to cost less than 25 cents per pound.

When using manure, sewage sludge, or other N sources that usually cost less per pound of N than commercial fertilizers, a conservative approach to assigning value to those products is to price the pounds of crop-available N the same as would be for a pound of N from commercial fertilizer. Usually about 50% of the total N in dry manure and 50% to 60% of the total N in liquid manure is available in the first year after application.

Corn Nitrogen Rate Calculator

Finding the Maximum Return To N and Most Profitable N Rate
A Regional (Corn Belt) Approach to Nitrogen Rate Guidelines

State: Illinois - North
Number of sites: 40
Rotation: Corn Following Soybean
Non-Responsive Sites Not Included

Nitrogen Price ($/lb): 0.40
Corn Price ($/bu): 4.00
Price Ratio: 0.10

MRTN Rate (lb N/acre):	**139**
Profitable N Rate Range (lb N/acre):	126 - 153
Net Return to N at MRTN Rate ($/acre):	$181.00
Percent of Maximum Yield at MRTN Rate:	99%
Anhydrous Ammonia (82% N) at MRTN Rate (lb product/acre):	170
Anhydrous Ammonia (82% N) Cost at MRTN Rate ($/acre):	$55.60

Most profitable N rate is at the maximum return to N (MRTN).
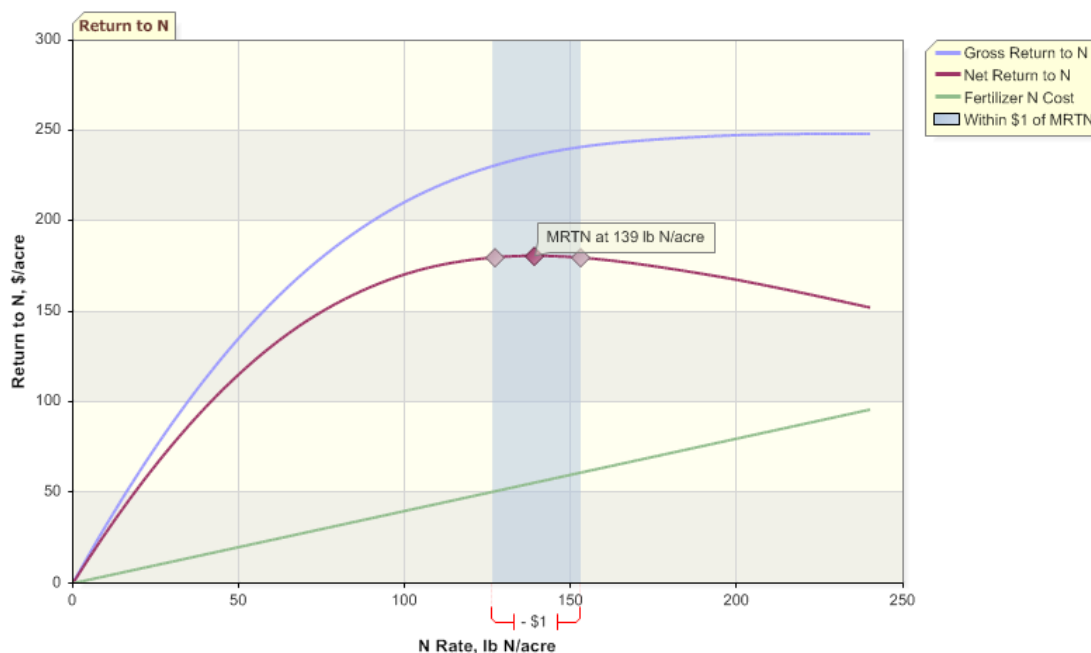Profitable N rate range provides economic return within $1/acre of the MRTN.

Figure 9.6. Output page from the online corn N rate calculator for corn following soybean in northern Illinois. Based on 40 different trials, 139 lb of N will maximize the return to N when the N price is 40 cents per pound and corn is $4 per bushel. The return to N is within $1 per acre of the maximum over the range from 126 to 153 lb N per acre. The profit produced by N at this rate is $181 per acre.

Guideline N rates in central Illinois are lower for corn following corn and similar for corn following soybean than under the PY method. In southern Illinois, N rates are somewhat higher than under the PY method, reflecting the fact that lower-yielding corn typically needs more N per bushel of yield than has generally been thought. In northern Illinois, N rates under these guidelines are considerably lower than under the PY method and are in line with those calculated for Iowa. We think that higher soil organic matter, more manure application in the past on many fields, and favorable weather have increased both yields and the supply of N from the soil in this part of Illinois.

One of the features of these new guidelines is that there is no longer a subtraction of a "soybean N credit." The guideline rates for corn following soybean are calculated based only on those trials where corn followed soybean, so there is no longer any consideration of how this rate compares to the rate for corn following corn. Do not make further subtractions from the calculated rates in order to include such "credit." In northern Illinois, corn following corn has a guideline rate about 40 pounds per acre higher than corn following soybean, so it is similar to the "N credit" previously used. In central Illinois, however, the difference is less than 10 pounds. This is not only because of different soils,
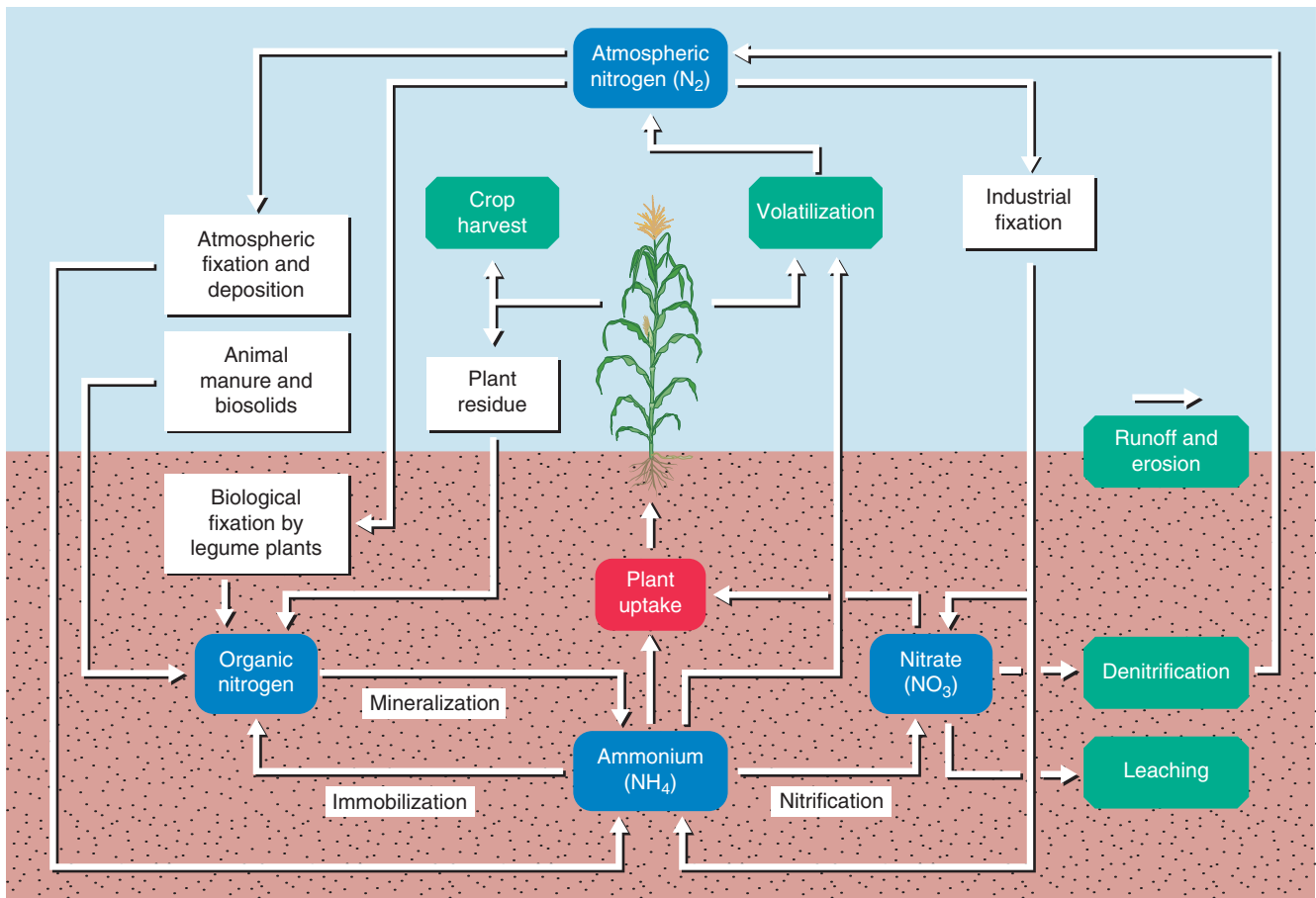
Figure 9.7. The nitrogen cycle.

but also because carryover N reduced the response to N for corn following corn in some trials following dry years. Many of the trials with corn following corn were done in different fields than those of corn following soybean, so some of this is due to chance. In any case, results for central Illinois overall indicate that corn following soybean simply needs N rates close to those needed by corn following corn. In southern Illinois, the difference is about 20 pounds.

Factors That Affect Nitrogen Availability

Soil N can undergo several transformations that influence its availability to plants. Understanding how N behaves in the soil is necessary to know how to improve its management. Key points to consider in the nitrogen cycle are the changes from inorganic to organic forms (immobilization), from organic to inorganic forms (mineralization), and from ammonium (NH_4^+) to nitrate (NO_3^-) as well as the movements and transformations of nitrate (**Figure 9.7**).

Immobilization. Inorganic N, mainly in the ammonium (NH_4^+) and nitrate (NO_3^-) forms, is taken up by plants and

microorganisms to form organic compounds needed for various functions to sustain life. This process is referred to as immobilization, since it takes N "out of circulation." From a management standpoint, immobilization is important in relation to N availability and to processes such as breakdown of residues or other organic materials. The population of microbes is in equilibrium with the food (carbon) supply in the soil. When large amounts of residue are added to the soil, the microbial population increases rapidly, and the demand for N to help them grow increases as well.

Microbial growth has a carbon to nitrogen (C:N) ratio of 8:1 to 12:1, and microbes need to take in carbon and nitrogen in the ratio of about 20:1 (some C is used up in respiration) in order to grow. So when crop residue has a C:N ratio greater than 20:1 (corn stalks are 50:1 to 60:1), microbes take up some N from the soil in order to have enough N for growth. Conversely, residues rich in N, such as alfalfa and soybean (C:N less than 20:1), have more N than microbes need, so microbes will release some N to the soil as they break down such residues.

Mineralization. Mineralization is the process by which organic N is converted to NH_4^+ ions, thus becoming

available for plant uptake. This takes place during the decomposition of organic matter by microorganisms. Mineralization is a relatively slow process, and N release rates depend on organic source and the environment. Mineralization of N from dead microorganisms is three to four times faster than release from other organic N sources (such as organic matter) in the soil. Those conditions that promote plant growth (warm temperatures, adequate soil pH, good water content, and proper soil aeration) also enhance mineralization.

Each percentage point of organic matter content in the top 7 inches of the soil translates to about 20,000 pounds of organic matter per acre. Approximately 5% of soil organic matter is N; many Illinois soils contain large amounts of organic matter, and consequently large amounts of N. For example, a soil with 4% organic matter contains approximately 4,000 pounds of organic N in the top 7 inches, and deep soils will have considerably more than this in their topsoil. Because it is tied up in organic compounds, most of the N in organic matter is unavailable for uptake by crops at any given time.

Through the process of mineralization, about 1% to 3% of the organic N in the topsoil is converted annually into plant-available N. This would mean that a soil with 4% organic matter might be able to provide 40 to 120 pounds of N per acre per year. This range is wide because soil and weather conditions vary so much over years. Once N is in the NH_4^+ form, it is held by soil clay and organic matter and cannot move very far until it nitrifies.

Nitrification. Nitrification is the conversion of ammonium (NH_4^+) to nitrite (NO_2^-) and then to nitrate (NO_3^-). This is a bacteria-mediated process that accelerates as soil temperatures rise between 60 and 85 °F, when soil pH is slightly acidic to slightly basic, and when there is good soil aeration. The process of nitrification does not stop completely until soil temperatures are below freezing. The transformation of nitrite to nitrate is typically fast, so NO_2^- seldom accumulates. This is fortunate, because NO_2^- is toxic to plants and animals. Since the two steps in nitrification are done by different types of bacteria, it is possible to have accumulation of NO_2^- when soil conditions are very acidic or when a large amount of organic N is being nitrified under near-saturated conditions. Under such conditions, the bacteria that transform NH_4^+ to NO_2^- are active, while the bacteria responsible to transform NO_2^- to NO_3^- are not. In field conditions this can occur when manure is injected in poorly drained soils.

While NH_4^+ cannot be lost through leaching or denitrification, NO_2^- and NO_3^- can be lost in these ways. So it is advantageous to delay nitrification until as close as possible to the time crops start to take up large amounts of N. Since

NH_4^+ is transformed rapidly to NO_3^- under conditions favorable for crop growth, crops normally take up most of their N as NO_3^-. However, NH_4^+ is also important. Corn normally grows better when at least a quarter of the N supply is NH_4^+. In most fields, NH_4^+ needs are met by the normal process of mineralization, so there is generally no need to adjust fertilization practices to assure that plants have enough NH_4^+ to balance their uptake of NO_3^-.

Denitrification. Denitrification is the process by which N in the form of NO_2^- or (most commonly) NO_3^- is converted by bacteria into N_2 or N_2O gas. Both of these gases move up through the soil freely and are lost to the atmosphere, and neither can be taken up by crops. Denitrification is done by bacteria that are anaerobic, meaning that they are active when oxygen levels are low. This means that most denitrification occurs under saturated soil-water conditions. Since saturated soils are not uncommon in Illinois, denitrification is believed to be the main process by which NO_3^- and NO_2^- nitrogen are lost, except on sandy soils, where leaching is the major pathway.

The amount of denitrification depends mainly on how long the soil is saturated, the temperature of the soil and water, the pH of the soil, and the amount of energy material available to denitrifying organisms.

When water stands on the soil or the surface soil is completely saturated in late fall or early spring, N loss is likely to be small because much of the N (applied as fertilizer) is often still in the NH_4^+ rather than NO_3^- form and because the soil is cool, so denitrifying organisms are not very active. A different scenario occurs in late spring and early summer, when temperatures and microbial activity are high. The percentage of NO_3^- nitrogen in the soil (from fertilizer or nitrified from the soil supply) that can be lost through denitrification for each day the soil stays saturated varies by temperature. Nitrate losses through denitrification in Illinois are 1% to 2% when soil temperatures are less than 55 °F, 2% to 3% if soil temperatures are between 55 and 65 °F, and 4% to 5% at soil temperatures above 65 °F.

Leaching. Nitrate leaching depends on water movement, which is governed by several factors, including soil texture and structure, water status of the soil at the time of rainfall, and the amount and frequency of rainfall. An inch of water that enters a dry soil will move on average 4 to 6 inches down into a silt loam and slightly less in a clay loam. Some of the water will move farther down through preferential flow paths, such as through larger pores left by old roots or earthworms. In a loamy sand, each inch of rain that enters the soil will move down about 12 inches. By tasseling time, corn roots penetrate to depths of 5 and 6 feet in well-drained fields. So if the total rainfall at one time is more than 6 inches, little NO_3^- will be left within

the rooting depth on sandy soils. Conversely, if that same amount of rain occurs in a finer-textured soil, NO_3^- will be still within the rooting depth (approximately 3 feet) as long as it does not reach tile lines and drain from the field.

As soils dry out between rainfall events, evaporation of water from the soil surface and extraction by plant roots create a suction force that moves water and dissolved nitrate from deeper in the soil to shallower depths. So if another rain event occurs a few weeks later, the water will not carry NO_3^- down from the previous point, but from shallower depths. The next rainfall event will have to replenish soil water lost since the previous event, and nitrate will not move down again until after there has been enough rain to replace this water. If the soil is already wet at the time of rainfall, water (and NO_3^-) will not move uniformly along a wetting front, but rather will flow deeply through large soil pores. All these factors, along with the fact that some rainwater might run off the surface, make it difficult to predict how deep NO_3^- has moved based solely on total rainfall.

Estimating Nitrogen Availability

Because N can become available from organic matter in different amounts, can change forms, and can be lost from the soil, testing soil to determine N fertilizer needs for Illinois field crops is not nearly as useful as is testing to determine the need to add lime, phosphorus, or potassium fertilizer. Testing soil to predict the need for N fertilizer is complicated by the fact that N availability—both the release from soil organic matter and the loss by leaching and denitrification—is regulated by unpredictable weather conditions. Under excessively wet conditions, both soil and fertilizer N may be lost by denitrification or leaching. The amount of N released from organic matter is low under dry conditions but high under ideal moisture conditions. For these reasons soil tests designed to test how much N is available and how much more fertilizer N might be needed have not been very successful under Illinois conditions. Testing to estimate how much soil N is available to the crop close to the time of rapid N uptake by the crop has, however, been reasonably successful. This is because the N present in the soil at that time has less likelihood of being leached or denitrified before the crop can take it up. Even this approach presents some challenges, as we shall see.

Total soil nitrogen test. Because 5% of soil organic matter is N, some have theorized that organic matter content of a soil could be used as an estimate of the amount of supplemental N that would be needed for a crop. As a rough guideline, many assume that 2% of the organic N will be released each year. This would amount to a release of 100 pounds N per acre on fields with 5% organic matter. This estimate tends to be very inexact because mineralization of organic matter varies significantly over time due to variations in available soil moisture and in soil temperatures as well as in crop growth rates and the ability of the crop to take up N. Soils high in organic matter usually have a higher yield potential due to their ability to provide a better environment for crop growth, and so may need to take up more N.

Illinois soil nitrogen test (ISNT, or amino sugar-N test). This test was proposed to identify fields nonresponsive to N fertilization for corn by measuring organic amino sugar-N compounds that can mineralize during the growing season. Unfortunately, data from many sites in Illinois and the Midwest showed that this test was not able to predict nonresponsive sites with sufficient accuracy to prevent incidents of yield loss. Values produced by this test usually show high correlation to soil organic matter content, and many believe that this is because the test measures a relatively constant fraction of the total soil N, rather than only a readily mineralizable fraction. Researchers have found that relatively high ISNT values do not always mean that little fertilizer N need be applied, especially when cool soils limit mineralization into early June. This suggests that caution is needed in relying on this test.

Early spring nitrate nitrogen test. This procedure has been used for several years in the drier parts of the Corn Belt (west of the Missouri River) with reasonable success. It involves collecting soil samples in 1-foot increments to a 2- to 3-foot depth in early spring for analysis of NO_3^- nitrogen. This information is then used to reduce the total amount of N to be applied by the amount found in the soil profile sampled. Results obtained by scientists in both Wisconsin and Michigan have shown this procedure to work well, but research in Iowa indicated that the procedure did not accurately predict N needs.

Since samples are collected in early spring, the procedure measures mostly N carried over from the previous crop. It thus has the greatest potential for success on corn that follows corn, especially in fields where adverse growing conditions limited yields the previous year and where dry weather has reduced loss of N from the soil. Additional work is needed to find the sampling procedure that will best characterize the field conditions, especially when N has been injected in prior years. Heavy rainfall in late spring or early summer will reduce the usefulness of this test because much of the N detected earlier in the spring may be leached or denitrified before the plant has an opportunity to take it up from the soil.

Pre-sidedress nitrate test (PSNT). Work in several states has shown this test to be useful. The PSNT is typically

more accurate in high-yielding environments and in fields that have received manure or other organic fertilizers in the recent past or that have had legume crops with high N content, such as alfalfa. By sampling later in the season, this test provides a measure of the amount of N mineralized from organic N plus the amount of carryover N still present in the soil. However, if late spring temperatures are below normal, the test tends to overestimate N needs (lower soil test values), probably because of slow rates of mineralization in the soil. One of the limitations of this test is that it is useful only for fields that will receive sidedress N application. Usually a small starter rate (20 to 30 lb of N per acre) can be applied without compromising the usefulness of the test. Since N is applied at sidedress time, this brings the risks of a relatively short application window, which can be a challenge, especially in wet years, when applications may be delayed until plants are too large.

The reliability of this procedure depends heavily on ensuring that samples are collected, handled, and processed correctly. A sample to 12 inches deep is collected when corn plants are 6 to 12 inches tall (V4 to V6 development stage), or in late May to early June when planting is delayed. If the field had a history of broadcast applications, randomly collect 20 to 25 samples from an area no greater than 10 acres. If band applications of fertilizer or manure were used to fertilize the previous crops, collect at least 10 sets of three cores each between two corn rows. The first core is collected 3 inches to the right of the corn row, the second core in the middle of the two rows, and the third core 3 inches to the left of the next corn row. In all cases, place all the cores in a bucket and obtain a subsample after the cores have been thoroughly mixed. If mixing the entire sample to produce a representative subsample is too difficult, it is better to use large sample bags and keep the entire sample. Collecting a sample less than the full 12 inches or not collecting all the cores will produce unreliable results. If the samples cannot be delivered to the laboratory the same day, either freeze or air-dry the sample. If you air-dry samples, dry them as fast as possible by spreading the samples out on a paper, crushing the cores, and blowing air with a fan. Since drying can be difficult without proper facilities, freezing samples is likely the best option for most people. Make sure to tell the laboratory that you want to measure NO_3^- nitrogen. If the entire sample is sent, request that the whole sample be dried and ground before a subsample is taken.

The general consensus is that no additional N is needed if PSNT test levels are above 25 parts per million, and a full rate should be applied if NO_3^- nitrogen levels are less than 10 parts per million. When test levels fall between 10 and 25 parts per million, N rates should be adjusted proportionally.

Measuring N Status by Plant Analysis and Sensing Technologies

Plant tissue testing. Plant tissue analysis can be useful in diagnosing N deficiency. For more information on tissue N levels and how to collect samples, see Chapter 8, page 95, under the heading "Plant Analysis."

SPAD meter. The SPAD meter is a device that measures relative greenness by determining how much light passes through a leaf. It is sometimes called a green meter or chlorophyll meter. Greenness is related to N level in the leaf. By comparing chlorophyll meter readings to those in a high N-rate strip of the same hybrid, the relative N status of plants, including degree of deficiency, can be estimated at any point during the season. The ability of this test to predict N deficiency improves as the plant starts to take up considerable amounts of N. Taking readings at about the V10 growth stage (plants typically about waist-high) is timely, because differences in leaf greenness are usually apparent then and there is still enough time to apply supplemental N if needed. If N is the factor that limits corn yield, then SPAD readings taken at about the time of pollination typically show a high correlation with yield. This is shown for an Illinois trial in **Figure 9.8**.

SPAD readings should be averaged from 20 to 30 plants from each area of interest in a field. Before tassels appear, collect readings from the top leaf with a fully visible collar. The same leaf of each plant should be measured, and readings are more uniform if taken at about the same position on the leaf, about halfway between the tip and the base and as far from the edge as the instrument allows.

Relative SPAD readings can be calculated by dividing the average reading from the portion of the field in question by the average reading from the reference strip. This relative value can be used to determine the rate of N needed to bring the corn crop to full yield potential. Work from Iowa showed that if the relative SPAD reading is 0.97 (97% of the reference strip) or lower, supplemental N is needed (**Table 9.1**).

Crop color sensing technology. Remote optical sensing technologies are being developed and used to determine the N status of the crop. These might include remote sensing (usually aerial photography) or sensors mounted on applicators, with changes in crop color used to adjust N application rate in different parts of the field.

The relative greenness of a crop canopy can be measured by seeing how much light of certain wavelengths (colors) the canopy reflects. Many crop sensors measure crop reflectance in the red (650 ± 10 nm) and near infrared (770 ± 15 nm) wavelengths and then calculate a "normalized difference vegetation index" (NDVI) based on these relative

Table 9.1. Relative SPAD values collected between V10 and VT corn development stages and corresponding N fertilizer rates when 100 lb N/acre is the maximum rate to be applied.

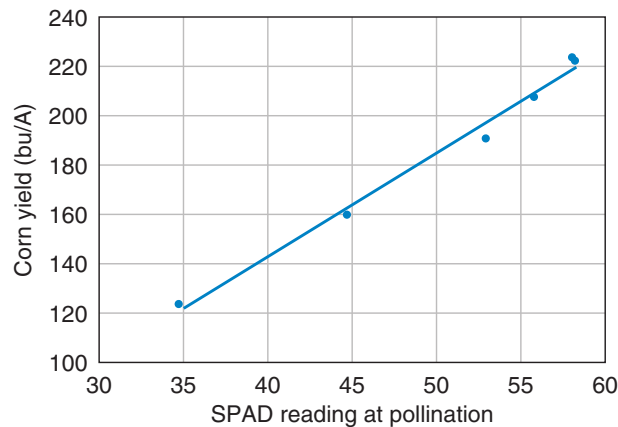| Relative SPAD values	N to be applied (lb/A)
<0.88	100
0.88–0.92	80
0.92–0.95	60
0.95–0.97	30
>0.97	0

Figure 9.8. Correlation between SPAD meter readings taken on the ear leaf at pollination and final grain yield in an Illinois trial.

readings. The need for additional midseason N fertilization is assessed by comparing readings to reference strips. In some cases, such readings are made on the go by sensors mounted on the applicator, and N rates are varied based on these readings in each part of the field. Readings from an aerial photo can be used to make a map, which can then direct different N rates to different parts of the field.

These techniques are often effective on irrigated fields where additional N can be applied through the irrigation system with little application cost and without damage to the crop. They can also be useful in rainfed systems where significant N loss has occurred or when the full rate of N has not been applied. For most Illinois fields, however, it is not yet clear that N rate adjustment based on crop color is cost effective, nor is it clear how it can best be done. As with other methods, the later such color measurements can be made, the more accurately they reflect crop N status and the soil supply, so the better they predict the need for additional N.

Nitrogen Fertilization

Most of the N fertilizer materials available for use in Illinois provide N in the forms of ammonia, NH_4^+, urea, and NO_3^- or in combinations of these. For many uses on a wide variety of soils, all forms are likely to produce about the same yield—provided that they are applied correctly.

Anhydrous ammonia (NH_3). This source of N is typically among the least expensive and contains the highest percent N by weight of all forms of N (82%). Anhydrous means "without water." Anhydrous ammonia is a liquid when kept under pressure, but it turns into gas when not contained in a pressure-capable tank. The weight of this fertilizer in liquid form is 5.9 pounds per gallon.

One of the drawbacks to the use of NH_3 is the danger it poses for living organisms in the event that it escapes into the air. It requires equipment than can handle high pressure (approximately 200 pounds per square inch), and its safe transport and handling represent real challenges. Because ammonia under pressure is a mixture of liquid and vapor, it is more difficult to ensure uniform application across a tool bar; average rates can usually be attained, but distribution is affected by such things as hose length and air temperatures. These problems can be minimized by using speed-control devices, using newer manifolds that are designed to distribute ammonia more evenly, and taking time to ensure that the applicator is properly configured. Variability among application knives can be reduced by taking certain steps: make sure the manifold is leveled and the openings used are evenly distributed around the manifold; do not have a hose opening directly opposite the entry of ammonia; avoid using dual manifolds with tool bars with less than 14 knives; cut all hoses to the same length; and use the same diameter hoses, hose barbs, and knife openings in all shanks.

Although anhydrous ammonia applications kill desirable microorganisms in the soil, this should not be a concern. With normal soil moisture, ammonia moves only a few inches from the point of release out into the soil, and only within this zone—normally less than 10% of the volume of the topsoil—will microbes be killed. The effect is also temporary in that N will, in the long term, enhance microbial growth once microbes move into the application zone.

Another concern is that ammonia will adversely affect the physical and chemical properties of the soil. Research has shown that other than lowering the pH, which is a feature common to most N fertilizer sources that contain or produce ammonium (replacing hydrogen atoms with oxygen atoms, in the conversion of ammonium to nitrate, releases hydrogen, which decreases pH), anhydrous ammonia does no lasting harm to soils whatsoever.

Ammonium nitrate (NH_4NO_3). This fertilizer material is 34% N (34-0-0). Half of the N is in the NH_4^+ form and half is in the NO_3^- form. Ammonium nitrate is highly soluble in water. Because 50% of the N is present as NO_3^-,

this product is more susceptible to loss from both leaching and denitrification. NH_4NO_3 thus should not be applied to sandy soils because of the likelihood of leaching, nor should it be applied far in advance of the time when the crop needs the N because of possible loss through denitrification. Ammonium nitrate is not easily volatilized, so it can be used for surface application where conditions are conducive to NH_3 volatilization. Because NH_4NO_3 has been used by individuals to produce explosives, it is no longer sold widely as a fertilizer material in the Corn Belt.

Urea ($CO[NH_2]_2$). This source is 46% N (46-0-0), and all of the N is in the urea form. As such, it is very soluble and moves freely up and down with soil water. After application in the soil, NH_2 changes to NH_3 either chemically or by the enzyme urease, and then to NH_4^+. The speed with which this conversion occurs depends largely on temperature. Conversion is slow at low temperatures but rapid at temperatures of 55 °F or higher.

If the conversion of urea to ammonium occurs on the soil surface or on the surface of crop residue or leaves, some of the resulting ammonia will be lost as a gas to the atmosphere. The potential for loss is greatest when the following conditions exist:

● Temperatures are greater than 55 °F. Loss is less likely with winter or early spring applications, but results show that the loss may be substantial if the materials remain on the surface of the soil for several days.

● Urea is left on the soil surface and not incorporated.

● Considerable crop residue remains on the soil surface.

● Application rates are greater than 100 pounds N/acre.

● The soil surface is moist but rapidly drying (under high temperatures).

● Soils have a low cation-exchange capacity.

● Soils are neutral or alkaline in reaction.

In the past, the manufacture of urea generated considerable amounts of biuret, a byproduct of urea formation that is toxic to plants. Modern manufacturing processes have reduced considerably the amount of biuret produced, and the concern about toxicity from it has subsided.

Ammonium sulfate ($[NH_4]_2SO_4$). This source is 21% N (21-0-0-24[S]) and supplies all N in the NH_4^+ form. This theoretically gives it a slight advantage over products that supply a portion of their N in the NO_3^- form, because the NH_4^+ form is not susceptible to leaching or denitrification. However, this advantage is usually short-lived because all NH_4^+-based materials quickly convert to NO_3^- once soil temperatures are favorable for activity of soil organisms (above 50 °F).

In contrast to urea, there is little risk of loss of the NH_4^+ contained in $(NH_4)_2SO_4$ through volatilization. As a result, it is an excellent material for surface application on no-till fields with a lot of crop residue on the soil surface. As with any other NH_4^+-based material, there is a risk associated with surface application in years when there is inadequate precipitation to allow for adequate root activity in the fertilizer zone. This can result in what is known as "positional unavailability," in which adequate N may be present but roots cannot reach it, usually due to dry soils that restrict roots and keep N from moving down to the roots.

Ammonium sulfate is an excellent material for use on soils that may be deficient in both N and sulfur. However, applying it at a rate sufficient to meet the N need will cause overapplication of S. That is not of great concern because sulfur is mobile and moves out of the profile quickly. Fortunately, there is no known environmental threat associated with sulfate sulfur in water supplies.

Most $(NH_4)_2SO_4$ available is a byproduct of the steel, textile, and lysine industries and is marketed as either a dry granulated material, a slurry, or a solution.

Ammonium sulfate is more acidifying—that is, causes greater drops in pH—than any other N source. In general, 5 pounds of lime are needed to neutralize 1 pound of N from ammonium sulfate, compared to 2 pounds of lime per pound of N from ammonia or urea. The extra acidity is of little concern as long as the soil is monitored for pH every 4 years and pH is corrected with lime as needed.

In areas where fall application is acceptable, $(NH_4)_2SO_4$ could be applied in late fall (after temperatures have fallen below 50 °F) or in winter on frozen ground where the slope is less than 5%.

Nitrogen solutions. The most common nitrogen solutions are NH_4NO_3 solutions that also contain urea. Urea-containing solutions (commonly called "UAN" for urea-ammonium nitrate) have 28% to 32% N. These materials have 50% urea, 25% ammonium, and 25% nitrate. The weight of solution per gallon is 10.70 and 11.05 pounds for the 28% and 32% solutions, respectively, meaning that one gallon of 28% has 3 pounds N and one gallon of 32% has 3.5 pounds N. Another common source is NH_4NO_3 solutions containing ammonia, which can have up to 41% N. The constituents of all these compounds will undergo the same reactions as described for the constituents applied alone. Urea-containing solutions can be dribbled or sprayed on the soil surface or injected to prevent urea volatilization. Ammonia-containing solutions, including aqua ammonia (ammonia dissolved in water, with an analysis of 21-0-0), have slight vapor pressure and must be injected 1 to 2 inches deep to prevent ammonia volatilization.

Ammoniated phosphate. Mono-ammonium phosphate (MAP; typically 11% N, for example, 11-51-0) and di-ammonium phosphate (DAP; 18% N, 18-46-0) are used mostly as phosphorus fertilizers (See Chapter 8, page 106, "MAP vs. DAP"). These sources have an acidifying potential similar to $(NH_4)_2SO_4$. Under warm soil conditions, the NH_4^+ from both products transforms quickly to NO_3^- and is subject to leaching or denitrification. Other less common sources available are liquid and dry ammonium polyphosphate (10% and 15% N, respectively). Like MAP and DAP, these are primarily considered P sources, not N sources.

Organic-N fertilizers. Manure, poultry litter, and other organic-N fertilizers can supply not only N but also phosphorus, potassium, and other nutrients. These products are excellent nutrient sources, and they often supply nutrients at lower cost than inorganic fertilizers. They should be incorporated to avoid N loss by volatilization or runoff. Most of the N is in uric acid and NH_4^+ forms that can rapidly transform to NO_3^-. Applications should be done as far as possible from environmentally sensitive areas, such as on steep slopes and near bodies of water.

Before application, these fertilizers should be analyzed for nutrient content. Many of these sources, if applied at rates needed to meet the N needs of the crop, will result in an overapplication of phosphorus, which can lead to environmental problems. For this reason, application should be based on meeting phosphorus requirements rather than the N requirements of the crop, with additional N applied using inorganic fertilizers. The soil phosphorus level and nutrient contents of these organic-N fertilizer sources must be known in order to determine the appropriate application rate.

Nitrogen Fertilizer Amendments

The critical need to supply adequate but not excessive N to crops, along with high N fertilizer prices, has resulted in the development of various products designed to make the use of N fertilizers more efficient. Most such products are designed to affect biological reactions in order to prevent changes in N form that can lead to N loss. For example, we described how microbial activity can affect N transformations and loss, and some of these amendments are designed to decrease microbial growth and activity.

Nitrification inhibitors. As **Figure 9.7** shows, once NH_4^+ is nitrified to nitrate (NO_3^-), N is susceptible to loss by denitrification or leaching. Nitrification inhibitors such as dicyandiamide (DCD) or nitrapyrin (known by its trade name N-Serve) can retard this conversion, reducing loss potential. When properly applied, inhibitors can significantly affect crop yields. In one experiment, 42% of the

applied ammonia remained in the NH_4^+ form through the early part of the growing season when the inhibitor was used, in contrast with only 4% when the inhibitor was not used. However, the benefit from using an inhibitor varies with soil condition, time of year, type of soil, geographic location, rate of N application, and prevailing weather conditions between N application and crop uptake. Yield increases of 10 to 30 bushels per acre are possible by using an inhibitor in years with excessive rainfall, but there is often no advantage when soil conditions are not conducive to leaching or denitrification.

Nitrification inhibitors are most often used with fall applications to help protect against N loss. In general, poorly or imperfectly drained soils that easily become water saturated and coarse-textured (sandy) soils with high potential for leaching probably benefit the most from nitrification inhibitors. Moderately well-drained soils that undergo frequent periods of 3 or more days of flooding in the spring also benefit. Although they are not commonly done, when springs are very wet and on nearly all types of soil from which N losses frequently occur, especially on sandy and poorly drained soils, spring preplant applications may benefit from the use of an inhibitor. Application of inhibitors is generally not recommended for sidedress applications. Soils typically do not stay saturated with water very long during the growing season after sidedress application, and only a few weeks elapse between sidedressing and rapid plant uptake, so there is little benefit to preventing conversion to nitrate. The longer the period between N application and absorption by the crop, the greater the probability that nitrification inhibitors will contribute to higher yields. However, the length of time that fall-applied inhibitors remain effective in the soil also depends partly on soil temperature. On a Drummer silty clay loam soil, an inhibitor application when soil temperature is 55 °F can keep close to 50% of the applied ammonia in NH_4^+ form for about 5 months. When soil temperature is 70 °F, the soil may retain the same amount for only 2 months.

Time of application and geographic location must be considered along with soil type when determining whether to use a nitrification inhibitor. Using inhibitors can significantly improve the efficiency of fall-applied N on the loam, silt loam, and silty clay loam soils of central and northern Illinois in years when the soil is very wet in the spring. At the same time, inhibitors do not adequately reduce the rate of nitrification in the low-organic-matter soils of southern Illinois when N is applied in the fall for the following year's corn. The lower organic matter content and the warmer temperatures of southern Illinois soils, both in late fall and early spring, cause the inhibitor to degrade too rapidly. Furthermore, applying an inhibitor on sandy soils in the fall does not adequately reduce N

loss because the potential for leaching is too high. Fall applications of N with inhibitors thus are not recommended for sandy soils or for soils low in organic-matter content, especially south of Illinois Route 16.

Nitrification inhibitors should be viewed as management tools to reduce N loss. Nitrification inhibitors are most likely to increase yields when N is applied at or below the optimal rate. When N is applied at a rate greater than that required for optimal yields, benefits from an inhibitor are unlikely, even when moisture in the soil is excessive. Finally, it is not safe to assume that the use of a nitrification inhibitor will make it possible to reduce N rates below the MRTN rate, because those rates were developed from fields where no significant amount of N was lost.

Urease inhibitors. The chemical compound N-(n-butyl) thiophosphoric triamide, commonly referred to as NBPT and sold under the trade name AgrotaiN, has been shown to inhibit the urease enzyme that converts urea to ammonia. This material can be added to UAN solutions or to urea and will reduce the potential for volatilization of such products when they are surface-applied. Experimental results collected around the Corn Belt over the last several years have shown an average increase of 4.3 bushels per acre when applied with urea and 1.6 bushels per acre when applied with UAN solutions. Where nonvolatile N treatments resulted in a higher yield than urea without the amendment, thus indicating high loss potential for urea, addition of the urease inhibitor increased yield by 6.6 bushels per acre for urea and by 2.7 bushels per acre for UAN solutions. In a year characterized by a long dry period in the spring, NBPT with urea resulted in yield increases as high as 20 bushels per acre compared to urea alone. These results clearly showed the importance of proper urea management techniques in years when it stays dry after surface application of urea.

Urease inhibitors have the greatest potential for benefit when urea-containing materials are surface-applied without incorporation at 50 °F or higher. Since the amount of urease is substantially greater in crop residue than in the soil, the potential benefit of the inhibitor is even greater if there is a large amount of residue remaining on the soil surface. In situations where the urea-containing materials can be incorporated within 2 days after application, either with tillage or with adequate rainfall (at least 1/2 in.), the potential for benefit from a urease inhibitor is very low.

Coatings and ureaform. Urea is available in the form of products designed to provide physical or chemical protection against volatilization loss that can follow transformation to NH_4^+ soon after application. Physical barriers can include polymer coatings and sulfur coatings. Chemical barriers can include the use of formaldehyde or other materials that inhibit the chemical breakdown of urea. The rate of N release from such products is dictated mostly by temperature and soil-water conditions. These products can be beneficial in years where substantial rainfall early in the spring may cause significant leaching or denitrification. On the other hand, if the season is dry, N may not be released in time to supply the crop's needs.

Time of Nitrogen Application

Fall applications. Because of concerns over environmental degradation and reductions in economic return on N brought on by higher fertilizer prices, fall applications should be done only in soils and regions with low N-loss potential. Fall N applications should not be done in soils that are sandy, organic, or very poorly drained or that have excessive drainage, or where soils rarely freeze or temperatures decline very slowly from 50 °F to freezing. Nitrogen, other than that included incidentally with the phosphorus application, should not be fall-applied for corn on any soil south of a line that approximates Illinois Route 16, or the terminal moraine of the last glacier. Soil maps may be used to determine where within this boundary area fall N can be safely applied. Most of the incidental N in phosphorus fertilizers should not be expected to be available the next spring. However, the amount of N in a typical P application is small, and so its loss would rarely translate into a significant yield loss. When applied properly, fall N on wheat is acceptable (see the discussion on page 129 on wheat, oats, and barley).

Fall N applications are often preferred because they are more economical to farmers and the fertilizer industry. Fall applications often lower the cost of fertilization by reducing transportation and storage expenses and by requiring less storage and application equipment. They also provide logistical advantages, such as saving time in the spring to allow for early planting, better distribution of labor and equipment, and generally better soil conditions in the fall to protect soils from compaction during fertilizer application.

In places where fall application is environmentally acceptable, farmers should apply N in forms that do not contain nitrate. The preferred source for fall application is anhydrous ammonia, because it nitrifies more slowly than other forms. Manure and poultry litter can also be applied in the fall as long as they are incorporated in the soil and the guidelines are followed on soil temperature and soil conditions as described for fall application of inorganic N fertilizers. Urea-containing fertilizers, even when incorporated, are not as effective as fall-applied anhydrous ammonia or spring-applied urea.

Fall N applications should be done when daily maximum bare soil temperature at 4 inches is below 50 °F. On

average, this temperature is reached after the first day of November in northern and central Illinois. However, this average date is not a satisfactory guide because of the great variability present from year to year. Current soil temperatures for different regions of Illinois are available at www.isws.illinois.edu/warm/soiltemp.asp. While these temperatures may be useful in most cases, soil temperature can vary due to many factors, including soil color, drainage, and amount of crop residue on the surface. For this reason the best method to determine soil temperature is direct measurement in the field to be fertilized. It is important to note that while the rate of nitrification is significantly reduced below the recommended 50 °F soil temperature, microbial activity continues until temperatures are below 32 °F. The 50 °F temperature for fall application is a realistic guideline for farmers. Applying N earlier risks too much loss (**Figure 9.9**). Waiting until later risks wet or frozen fields, which would prevent application and fall tillage.

In Illinois, most of the N applied in late fall or very early spring is converted to NO_3^- by corn-planting time because of nitrification during the long periods when soil temperatures are between freezing and the mid-40s. In consideration of the date at which NO_3^- is formed and the conditions that prevail thereafter, the difference in susceptibility to denitrification and leaching loss between late fall and early spring applications of NH_4^+ sources is probably small. Both are, however, more susceptible to loss than is N applied at planting time or as a sidedress application.

Large amounts of residue generated from corn or other crops can create challenges for planting and field operations in the spring. There is also concern that the high ratio of carbon to nitrogen in the residue means a high potential for tying up N and making it unavailable for the following crop when it needs it. A common question has been whether application of N, such as UAN, on the residue would help with the breakdown of corn stalks. Research has shown no benefit in fall application of N to increase microbial decomposition of corn residue or to improve N availability for the next crop. Typically, low temperature or dry residue, and not N availability, is the main limiting factor for microbial decomposition of residue in the fall.

Winter applications. Based on observations, the risk of N loss through volatilization associated with winter application of urea for corn on frozen soils is too great to consider the practice unless one is assured of at least half an inch of precipitation occurring within 4 to 5 days after application. Yield losses as high as 30 to 40 bushels per acre have been observed when urea is surface-applied on frozen soils during the winter months. On the other hand, in most years, application of urea on frozen soils has been an effective practice for wheat production. This difference is likely due to better protection under the wheat canopy
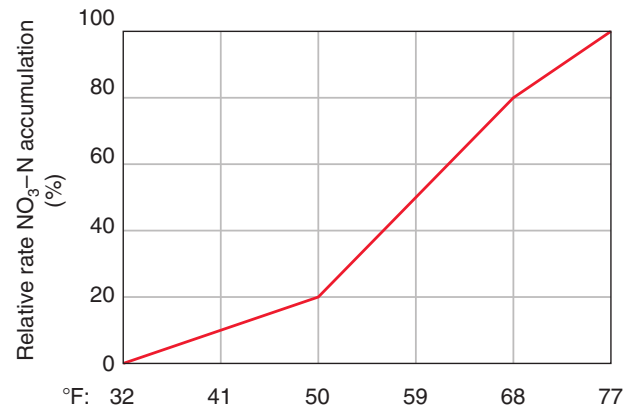
Figure 9.9. Influence of soil temperature on the relative rate of NO_3 accumulation in soils.

and to the fact that wheat takes up its N earlier than corn. If manure applications cannot be accomplished in the late fall, wait until the spring to do the application. Surface application of manure on frozen soils not only can result in substantial N loss, it could be an environmental hazard.

Spring (preplant) applications. Relative to fall applications, applying N in the spring reduces the time for N to be nitrified (and potentially lost) before crop uptake. Since this application is done before planting, it normally prevents damage to plants and eases the incorporation of urea fertilizers. Spring applications also have some drawbacks. Soils in the spring tend to be wet, and additional wheel traffic to apply N can result in soil compaction. Planting the crop in a timely fashion is important to maximizing yield potential. Since planting date is so important, it is advisable not to delay planting to apply N. It is better to plant on time and apply N later. If anhydrous ammonia is used after planting, it needs to be kept away from the seed rows to prevent seedling injury.

Sidedress applications. Sidedressing can help minimize N losses because N is applied close to the time of crop uptake. This application time can further increase N efficiency by allowing farmers to determine whether a full rate is needed or whether the rate can be reduced due to lower expected yields caused by poor growing season conditions and/or lower-than-expected corn stands. In some cases there might even be a decision to replace corn with a different crop, in which case N application might be avoided. Finally, this application time allows flexibility in the choice of N source.

While anhydrous ammonia and N solutions are preferred for sidedress applications, any common N fertilizer source can be used if proper care is taken. Potential drawbacks of sidedressing include not being able to apply N on time due to prolonged wet periods, root damage resulting from subsurface applications done after roots have grown out

into row middles, the need for sufficient rain to move surface-applied N into the root zone, and the need for high-clearance equipment if the application is delayed until the crop is too tall.

Many fields in east-central Illinois, and to a lesser extent in other areas, have low spots where surface water may collect at some time during the spring or early summer. The flat, claypan soils of south-central Illinois may also be saturated, though not flooded, during that time. Sidedressing would avoid the risk of spring loss through denitrification on these soils but would not affect midseason loss. Unfortunately, these are the soils on which sidedressing is difficult in wet years.

Sidedressing can be done any time between planting and tasseling. No corn yield reduction should be expected due to delayed N application, if application can be done before the 5th-leaf stage, or if there is enough N in the soil from starter or broadcast fertilizer to keep plants from becoming deficient before application can be done. Most soils in Illinois can provide sufficient N to satisfy the demands of young corn plants. Beginning at about V7 or V8 (8 leaf collars visible), N uptake is rapid until after pollination. So if supplemental N cannot be applied before the 5th-leaf stage, it is critical to apply it as soon as possible, especially if plants start to show deficiency symptoms. Application up to the time of tasseling will increase yields in most cases, unless the soils dry out and applied N does not reach the roots. While it is possible to increase yield by applying N after tasselling, this has only been observed in severely N-deficient fields when N was applied within two weeks after tasseling and when sufficient precipitation moved the applied N to the root zone. We would not expect such fields to yield as much as those with N applied early enough to prevent deficiency.

Methods of Nitrogen Application

Subsurface applications. Nitrogen materials that contain free ammonia (NH_3), such as anhydrous ammonia and low-pressure solutions, must be injected into the soil to avoid loss of ammonia in gaseous form. When released into the soil, ammonia quickly reacts with water to form NH_4^+. In this positively charged form, the ion is not susceptible to leaching or gaseous loss because it is temporarily attached to the negative charges on clay and organic matter. Some of the ammonia reacts with organic matter to become a part of the soil humus.

On silt loams or finer-textured soils, ammonia moves about 4 inches from the point of injection. On more coarsely textured soils, such as sandy loams, ammonia may move 5 to 6 inches from the point of injection. If the depth of application is shallower than the distance of movement, some ammonia may move to the soil surface and escape as a gas over several days' time. On coarse-textured (sandy) soils, anhydrous ammonia should be placed 8 to 10 inches deep, whereas on silt loam soils, the depth of application should be 6 to 8 inches. Except for sands or soils with very coarse texture, the soil can hold large amounts of ammonia, so there should not be concern about the capacity of the soil to hold ammonia when agronomic rates are applied at the appropriate soil depths.

Because anhydrous ammonia moves out into the soil until it is all dissolved in soil water, it is lost more easily from shallow placement than is ammonia in a low-pressure solution, which is already dissolved when applied. Nevertheless, low-pressure solutions contain some free ammonia and thus need to be placed into the soil at a depth of 2 to 4 inches. Some ammonia will escape to the atmosphere whenever there is a direct opening from the point of injection to the soil surface, so it is important to apply into soil conditions that allow good closure of the applicator knife track. It is common to see white puffs during application (water droplets, formed as ammonia lowers the temperature of the air surrounding the applicator knife) and to smell ammonia after application. The human nose is extremely sensitive to ammonia; a faint smell indicates too little loss to be of concern. If the soils dry out after application and the smell continues or grows stronger, then N loss is occurring.

Combining shallow tillage (field cultivation, disking, etc.) with ammonia application is possible in fine-textured soils as long as the soil has adequate moisture and ammonia is applied behind the tillage operation at least 4 inches below the soil surface. If deeper tillage is needed after the application, it is important to wait at least 5 to 8 days to allow sufficient time for the ammonia to react with soil water and form NH_4^+. This reaction is typically very fast, but its speed depends on soil conditions. The best and easiest way to test whether it is safe to till is by seeing if there is an ammonia smell immediately after tillage. If there is, then the transformation to NH_4^+ is not completed and tillage should be delayed. Free ammonia is harmful to living tissues, and application of fertilizers containing or forming free ammonia should be separated from seeds and seedlings by time or space. Most problems of plant injury occur when soils are wet at the time of application, the application slot does not close properly, and the ammonia moves only a very short distance from the release point and is thus at high concentration in the soil. If the soil dries quickly and cracks along the knife track, ammonia can move up to damage seeds or seedlings. This can also happen when applications are done in dry soils, thus allowing ammonia to move to the surface before it reacts with water, or when shallow applications allow ammonia to reach the surface soil.
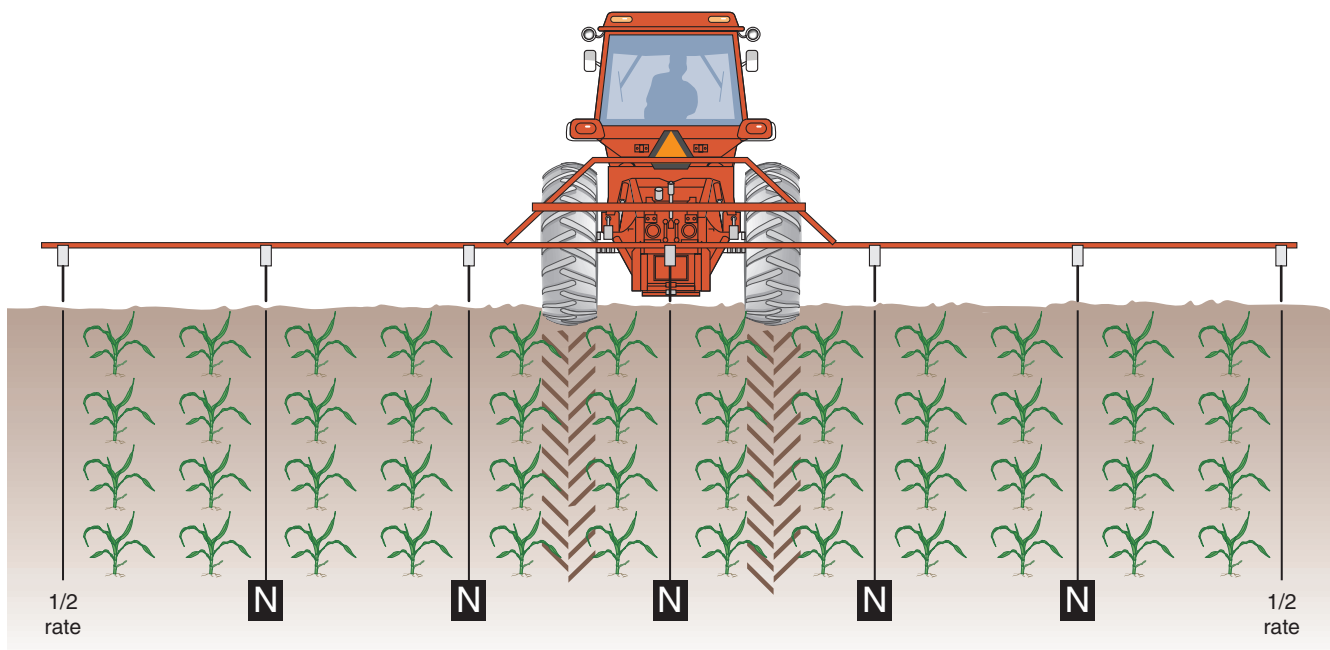
Figure 9.10. Schematic of every-other-row sidedress nitrogen injection. The outside two injectors are set at half-rate because the injector runs between those two rows twice.

If planting is done about a week after application or when there is some rainfall after application, most ammonia should have been converted to NH_4^+ and plant damage would not be expected. But in extreme cases, there has been damage even after fall-applied ammonia. This has happened when application was in late fall on wet soils where serious compaction occurred along the side walls of the knife track, followed by dry winter and spring weather. When the surface soils dried in the spring, the soil cracked along the knife track and allowed the ammonia to escape into the seed zone.

Research has shown that a relatively small portion of corn root system can take up all the nutrients the crop needs, including N. Because every-other-row injection supplies N on one side of each row (**Figure 9.10**), N injected between every other row results in yields similar to those from injection between all rows, irrespective of tillage system, soil type, or nitrogen rate. Use of wider injection spacing at sidedressing allows for reduced power requirement for a given applicator width or use of a wider applicator with the same power requirement. From a practical standpoint, the lower power requirement frequently means a smaller tractor and smaller tire, making it easier to maneuver between rows and causing less compaction next to the row.

With this system, positions can be adjusted to avoid placing an injector in the wheel track, where N losses can be greatest. Since roots will reach the center of the row before rapid N uptake starts and applying N close to the row can damage roots, take care to keep injection midway between the rows. If it is necessary to match application to the planter width with the usual even number of rows, the outside two injectors must be adjusted to half-rate application, as the injector will go between those rows twice if one avoids having knives in the wheel track. This can be done by splitting the output of one port in the manifold with a T and connecting hoses to the two outer knives. To avoid problems of back-pressure that might be created when applying at relatively high speeds, use a double-tube knife, with two hoses in each knife; the outside knives would require only one hose to give the half-rate application.

The use of autosteer to plant and to apply sidedress ammonia in alternate rows will increase application efficiency by allowing all knives to apply the full rate rather than using half-rates on the outside knives. This means applying without regard to planter pass, and it will work only if planting was done with good accuracy, both in terms of driving straight and of maintaining uniform guess row width.

Although urea–ammonium nitrate (UAN) solutions do not have free ammonia and can be applied on the soil surface, many studies have shown that injecting UAN below the surface to avoid contact with crop residue is a technique superior to broadcast and surface-dribble applications. If UAN is applied as sidedress, it is recommended that it be applied 4 inches from the soil surface (especially in dry years) to ensure that the roots of corn will reach this N.

Urea is commonly broadcast on the soil surface and then incorporated with tillage. In recent years there has been some interest in subsurface banding of urea. Our data show

that subsurface banding is at least as effective as broadcast and incorporated placement. When doing subsurface banding it is important to avoid applying urea under the corn row, as this can result in substantial lower yield. This is likely the result of urea hydrolysis, which produces ammonia and inhibits root growth in the fertilizer band.

Corn responds very well to starter fertilizers under most conditions. The response is often greatest in soils with low fertility or when cool and wet early-season conditions slow crop growth. Although N typically provides the greatest benefit, starter fertilizers are often a mixture of several nutrients. For more information on starter fertilizers, see Chapter 8, p. 108, under "Starter or Row Fertilization."

Surface applications. Because of the high level of urease activity in crop residue in no-till fields, surface application of UAN solutions can result in significantly lower no-till corn yield than surface application of NH_4NO_3 or injection of UAN or anhydrous ammonia. Addition of a urease inhibitor can increase yield compared to broadcast urea, but yields are likely not going to be as high as those obtained with injected UAN or ammonia.

Dribble application of UAN solutions in concentrated bands on 30-inch spacings on the soil surface is also more efficient in reducing the potential for N loss compared with an unincorporated broadcast application. Such dribble applications are not superior to an injected or incorporated application of UAN solution, and they can result in some loss of N and unavailability of N to the roots if the weather stays dry after application.

If weather conditions do not allow sidedress with regular field equipment, it is possible to do a delayed application up to tasselling by using high-clearance sprayers with drop nozzles. If this method is used, it is important to keep the fertilizer off the plants—especially the green, active leaves above the third or fourth leaf below the ear leaf—in order to avoid leaf burning that can reduce yield. Many drop nozzles release only a few feet below the boom; an extra length of tubing to lower the release point should help minimize leaf burning.

In fields that have not received N applications or where there is insufficient N supply, aerial application of dry N fertilizers can increase yield. This practice should not be considered a replacement for normal N application, but rather an emergency treatment in situations where corn is too tall for normal application equipment. To avoid severe leaf burning, do not apply more than 125 pounds N per acre of urea or NH_4NO_3. Urea is often used for foliar applications because it produces low salt damage compared to other sources. Aerially applying N solutions on growing corn is not recommended, as extensive leaf damage likely results if the rate is greater than 10 pounds N per acre.

Nitrogen Rates for Crops Other Than Corn

Soybean

Soybean and other legume crops can access much of their N needs through a symbiotic relationship with bacteria that have the ability to transform N_2 from the air into forms that these plants can use. Legume crops also remove significant amounts of N from the soil if soils have plant-available forms, and N fixation requires the plant to expend energy. Research, however, has not shown consistent yield increases from N fertilization, including foliar fertilization, when legume crops are well nodulated. In fact, applying N fertilizer to legumes reduces nodulation and activity of existing nodules and thus reduces N fixation. This makes little economic sense, since N fixation provides N at relatively no cost. So rather than apply N fertilizer to legume crops, ensure proper nodulation by inoculating seed with the appropriate bacteria if the crop has not been grown in the field for 5 years or more. Also, maintain soil pH at optimum levels for crop production. If desired pH levels cannot be maintained, be certain that molybdenum availability is adequate.

On average, corn removes 0.8 pounds N per bushel of grain and soybean removes approximately 3 pounds N per bushel (amount can vary depending on protein content). Based on a corn yield of 180 bushels per acre and a soybean yield of 50 bushels per acre, the total N removed per acre by soybean (150 pounds) is greater than that removed by corn (144 pounds). When properly nodulated, symbiotic fixation of N accounts for 63% of the N removed in harvested soybean grain. Thus, the net N removed from the soil by soybean (56 lb/A) is less than that removed by corn (144 lb/A). Even though there is a large net N removal from soil by soybean, research at the University of Illinois has generally indicated no soybean yield increase from either residual N in the soil or N fertilizer applied for the soybean crop.

A four-location study showed no soybean yield increase from residual N in the soil even when rates as high as 320 pounds of N per acre were applied to the previous corn crop. Similarly, studies where N was applied to the soybean crop have not shown consistent yield increase. In some trials a tendency for higher yields has been observed, but the yield increase was not enough to pay for the additional N.

Studies in Illinois and elsewhere have shown very consistently that starter fertilizers do not enhance soybean yields compared to a broadcast application. Very few reports, all from other states, have shown benefit from the use of N in

Table 9.2. Recommended spring nitrogen application rates for wheat.

Soil situation	Organic matter	Amt of N that 1 bushel of wheat will "buy"			
		Very high (>13 lb)	High (9–13 lb)	Medium (5–9 lb)	Low (<5 lb)
		lb N/A			
Low in capacity to supply nitrogen: inherently low in organic matter (forested soils)	<2%	150	120–150	90–120	60–90
Medium in capacity to supply nitrogen: moderately dark-colored soils	2–4%	100–120	80–100	60–80	40–60
High in capacity to supply nitrogen: deep, dark-colored soils	>4%	70–90	50–70	30–50	30

Rates assume no more than 30 lb of fall-applied N and spring application at greenup.

a starter for soybean. In all cases, the advantage occurred when low temperatures slowed normal nodulation and N fixation early in the season. Because soybean is sensitive to salt, fertilizers should not be applied with the seed. Studies have shown as much as 50% stand loss when as little as 3 pounds of N per acre was applied with the seed.

Wheat, Oats, and Barley

The rate of nitrogen to apply on wheat, oats, and barley depends on soil type, crop and variety to be grown, future cropping intentions, and, in the case of wheat, time of spring application. Light-colored soils (low in organic matter) require the highest rate of nitrogen application because they have a low capacity to supply nitrogen. Deep, dark-colored soils require lower rates of nitrogen application for maximum yields. Estimates of organic-matter content for soils of Illinois may be obtained from soil surveys or from soil tests that include organic matter.

The amount of N needed for good fall growth of wheat is modest, since the total uptake in roots and tops before cold weather is not likely to exceed 30 to 40 pounds per acre. Twenty to 30 pounds of N in the fall is recommended; it can be supplied in the form of di-ammonium phosphate (DAP), which should also supply the maintenance levels of phosphorus needed.

Recent studies with wheat nitrogen management allow the incorporation of economics into the nitrogen rate decision process, similar to the approach taken for corn. The cost of fertilizer N and the expected wheat grain price are incorporated into the spring wheat nitrogen recommendations in **Table 9.2**. One needs only to calculate the amount of N equivalent in value to one bushel of wheat. For example, a bushel of wheat at $6 per bushel would "buy" 10 pounds of N if N costs 60 cents per pound. Use the column in the table that corresponds to this value, and determine the suggested N rate based on estimated soil organic matter.

Spring nitrogen recommendations in **Table 9.2** are based on applying no more than 30 pounds of N in the fall and on making the spring application at early green-up (Feekes growth stage 3 or 4). On soils low in organic matter in

southern Illinois, research has shown that N rates can be decreased by 10% when one of the following applies: spring application is delayed to late tillering (Feekes growth stage 5.0-6.0); spring N applications are split, with one at early green-up and one at late tillering or early jointing; or a nitrification inhibitor or a slow- or controlled-release nitrogen source is used. On soils with higher organic matter, spring application timing has had little impact. Research has also shown that a spring-split N application, with one-third early and two-thirds at late tillering to jointing, can increase yields by about 10% compared to a single spring application at green-up, especially when conditions favor N loss. Delaying all of the N application to late tillering or early jointing usually produces the same yield as splitting N applications in the spring.

Nearly all modern varieties of wheat have been selected for improved standability, so concern about lodging under high N rates has decreased considerably. But it is still recommended that no more than 150 pounds of spring N be applied to wheat grown on soils with low organic matter soils and no more than 90 pounds to wheat grown on soils with high organic matter. Varieties of oats, though substantially improved with regard to standability, will still lodge occasionally, and N should be used carefully. Barley varieties, especially spring barley, are prone to lodging, so rates of nitrogen application shown in **Table 9.3** should not be exceeded.

Nitrogen recommendations are based on equipment delivering a uniform application of nitrogen across the spread path. If there is not uniform application, significant lodging can occur at the higher rates of N application, along with significant yield losses.

For wheat grown after corn in rotation, there can be a significant amount of residual soil N following the corn crop, depending on rate of N application, corn yield, and the amount of rainfall during the summer. The breakdown of corn residue may tie up some of this N, but depending on whether the residue is tilled into the soil and on the amount of soil moisture in the fall, this might take place mostly in the spring after soils warm up, which is often af-

ter wheat has taken up most of its N. Though it is not often done, it is possible to test soils for nitrate after corn harvest and to use this to adjust N rates for wheat, especially if the weather has been dry enough to reduce corn yields substantially. If little residual N is available for wheat seeding after corn, then using 25 to 30 pounds per acre of fall N is important to provide enough N for fall growth. If significant amounts of carryover N are found or suspected, it might be helpful to test residual N just prior to spring N application, with rates adjusted accordingly.

Some wheat and oats in Illinois serve as companion crops for legume or legume–grass seedings. On those fields, it is best to apply N fertilizer at rates 20% to 25% below the optimal rate to limit vegetative growth of the small grain and thus produce less competition for the young forage seedlings. Seeding rates for small grains should also be somewhat lower if they are used as companion seedings.

The introduction of nitrification inhibitors and slow- or controlled-release nitrogen (such as polymer-coated urea) combined with improved application equipment provides two additional options for applying nitrogen to wheat. In northern and central Illinois, research has shown that when the entire amount of nitrogen needed is applied in the fall with a nitrification inhibitor, the resulting yield is equivalent to that obtained when a small portion of the total need was applied in fall and the remainder in early spring. This has been much less successful in southern Illinois. Producers who are frequently delayed in applying nitrogen in the spring because of wet soils may wish to consider fall application (or early green-up applications in southern Illinois) with a nitrification inhibitor or a slow- or controlled-release nitrogen source. For fields that are not usually wet in the spring, either system of application will provide equivalent yield.

Most available forms of N fertilizer will work for spring application to the wheat crop, but care needs to be taken to minimize loss potential. Cool or cold soils at the time of application help slow the transformations that make N more susceptible to loss, but the weather can also turn warm quickly, and the potential for loss increases if that happens. Heavy rainfall on sloping soils, especially when they are still frozen, can cause runoff of N. Fertilizer materials containing urea (UAN, dry urea) can experience loss following breakdown by urease, though this is rare given the low soil temperatures typical at the time of application. Nitrate can leach at any time and can undergo denitrification if soils warm up and stay wet. Using UAN can also cause some damage to plants, though this is relatively rare on small plants when the weather is cool or when it rains soon after application. Uniformity of application can also be affected by the equipment used to apply different forms.

Table 9.3. Recommended total N application rates for oats and barley.

Soil situation	Organic matter	lb N/A
Low in capacity to supply nitrogen: inherently low in organic matter (forested soils)	<2%	80–90
Medium in capacity to supply nitrogen: moderately dark-colored soils	2–4%	60–80
High in capacity to supply nitrogen: deep, dark-colored soils	>4%	40–60

When oats and barley are used as a companion seeding for forage legume, rates can be reduced.

There is no risk-free way to apply N to wheat in the late winter and early spring, but be aware of potential for loss and try to apply in a way that minimizes loss.

Grass Hay

The species grown, period of use, and yield goal determine optimal N fertilization for grass hay (**Table 9.4**). The lower rate of application is recommended on fields where production is limited by inadequate stands or moisture.

Kentucky bluegrass is shallow-rooted and susceptible to drought. Consequently, the most efficient use of N by bluegrass is from an early-spring application, with September application a second choice. September fertilization stimulates both fall and early-spring growth.

Orchardgrass, smooth bromegrass, tall fescue, and reed canarygrass are more drought-tolerant than bluegrass and can use higher rates of N more effectively. Because more uniform production is obtained by splitting high rates of N, two or more applications are suggested.

If extra spring growth can be utilized, make the first N application in March in southern Illinois, early April in central Illinois, and mid-April in northern Illinois. If spring growth is adequate without extra N, the first application may be delayed until after the first harvest to distribute production more uniformly throughout the summer. Total production likely will be less, however, if N is applied after first harvest rather than in early spring. Usually the second application of N is made after the first harvest; to stimulate fall growth, however, this application may be deferred until August or early September.

Legume–grass mixtures should not receive N if legumes make up at least 30% of the mixture. Because the main objective is to maintain the legume, the emphasis should be on applying phosphorus and potassium rather than N. See **Table 8.6** in Chapter 8 for phosphorus and potassium maintenance required.

After the legume has declined to less than 30% of the mixture, the objective of fertilizing is to increase the yield

Table 9.4. Nitrogen fertilization of grass hay.

Species	Time of application of N (lb/A)			
	Early spring	After first harvest	After second harvest	Early Sept
Kentucky bluegrass	60–80			See text
Orchardgrass	75–125	75–125		
Smooth bromegrass	75–125	75–125		50*
Reed canary grass	75–125	75–125		50*
Tall fescue for winter use		100–125	100–125	50*

*Optional if extra fall growth is needed.

of grass. The suggested rate is about 50 pounds N per acre when legumes make up 20% to 30% of the mixture.

Pasture

The productivity of the grazing animals, the plant species present, and the management level and goals for the pasture must be evaluated to determine N fertilization for pasture. If legumes comprise 30% or more of the sward, do not apply N fertilizer because an adequate amount will be contributed through fixation. If the legume portion is less than 30%, grass will probably respond to N fertilizer. If applying 100 pounds N per acre, apply the first 50 pounds in early to mid-June when the spring flush of grass growth is over; apply the second 50 pounds in late July to early August. Because early-season growth is generally excessive, an early-spring application is not suggested unless the first harvest can be efficiently grazed or will be harvested as hay or silage. Nitrogen application early in the season can make grazing management of the spring flush more difficult.

Source of N is important for summer application. Use a dry N source such as NH_4NO_3, $(NH_4)_2SO_4$, or urea. Do not apply liquid UAN solutions to actively growing pasture.

Nitrogen Rate Adjustments

Once a rate of N has been determined, it is important to consider agronomic factors that influence N availability and N use by the crop to further adjust the planned rate. These factors include past cropping history and the use of manure (**Table 9.5**), as well as the date of planting.

Previous Crop

Corn following another crop typically yields better than corn following corn, although there is some evidence that the continuous corn "yield penalty" might be decreasing, in part because of improvement of hybrids, including the incorporation of traits that provide rootworm control.

Still, most trials show somewhat higher yields when corn follows a legume, such as soybean or alfalfa. This may be due partly to the residual N provided by the legume.

Since the N rate calculator already accounts for the effect of soybean on corn, there is no need to adjust the rate when corn follows soybean. For corn following a good alfalfa stand, it is not unusual to have sufficient N available from the alfalfa crop to supply a large portion of the N needs of corn. Often, when the alfalfa stand is destroyed and manure is applied, it is possible to grow the following corn crop without additional N. To assess the amount of N available in the spring, use the preplant or pre-sidedress soil nitrate test described earlier.

The contribution of legumes to the N supply for a following wheat crop will be less than the contribution to corn because the release N from legume residue will not be as rapid in early spring, when N needs of small grain are greatest, as in late spring and early summer, when N needs of corn are greatest (**Table 9.5**).

Idled Acres and Carryover Nitrogen

Depending on the crop grown, the N credit from idled acres may be positive or negative. Plowing-under a good stand of a legume that had good growth will result in a contribution of 60 to 80 pounds N per acre. If either stand or growth of the legume was poor or if corn is no-tilled into a good legume stand, thus delaying availability to the corn crop, the legume N contribution could be reduced to 40 to 60 pounds N per acre. Because most of the net N gained from first-year legumes is in the herbage, fall grazing will reduce the contribution to 30 to 50 pounds N per acre.

In years where a full rate of N was applied but yields were lower than expected, it is possible to have unused N carried over to the following year. The amount of carryover N will depend on weather conditions. Under unusually wet conditions, denitrification and leaching can reduce the amount of carryover N. But if the weather remains dry through the fall and winter, it could be very useful to take a soil test in March or April and analyze it to determine how much nitrate might be already present.

Manure

Nutrient content of manure varies with source and method of handling (**Table 9.6**). The availability of the total N content also varies by method of application. When manure is incorporated during or immediately after application, about 50% of the total N in dry manure and 50% to 60% of the total N in liquid manure will be available for the crop that is grown during the year following manure application.

Table 9.5. Reductions in nitrogen rates resulting from agronomic factors.

		1st year after alfalfa or clover			2nd year after alfalfa or clover		
	After soybean	5 plants/sq ft	2–4 plants/sq ft	<2 plants/sq ft	5 plants/sq ft	<5 plants/sq ft	Manure
Crop to be grown	Nitrogen reduction (lb/A)						
Corn	N/A	100	50	0	30	0	5*
Wheat	10	30	10	0	0	0	5*

*Nitrogen contribution in pounds per ton of manure. See Table 9.6 for adjustments for liquid manure.

Table 9.6. Average composition of manure.

	Nutrients		
Manure type	Nitrogen	P_2O_5	K_2O
Solid handling systems: no bedding; nutrients in lb/ton			
Dairy cattle	9	3	6
Beef cattle	11	7	10
Swine	11	8	5
Chicken	33	48	34
Liquid handling systems: nutrients in lb/1,000 gal			
Dairy cattle—liquid pit	31	15	9
Dairy cattle—lagoon	4	3	4
Beef cattle—liquid pit	29	18	26
Beef cattle—lagoon	4	3	4
Swine—liquid pit	36	25	22
Swine—lagoon	5	3	4
Poultry—liquid pit	60	45	30

Time of Planting

If planting is delayed, it may be possible to adjust side-dress N rates to reflect both lower corn yield potential and also the fact that late-planted corn takes up its N sooner after planting, so there is less chance of N loss. This needs to be done cautiously, since heavy rainfall and warm soils can create high N-loss conditions even after late planting. Late-planted corn that is planted into wet soil conditions can also struggle to take up N due to restricted roots, especially if it turns dry after planting. But if corn is planted a month or more after the optimum planting date—that is, after mid- to late May—and soils are warm and average rainfall is expected, it might be more profitable to reduce sidedress N rates by 20 to 40 pounds per acre. A pre-side-dress N soil test might help with this decision, especially if some N was applied before planting and if conditions have been favorable for mineralization before planting.