Nitrogen Management for Corn

by Emerson Nafziger | Reviewed by Dr. John Sawyer, Iowa State University and Jean Payne, Illinois Fertilizer & Chemical Association

Approximately 78% of the air is nitrogen (N)—that's nearly 34,800 tons of N above every acre of land. Nitrogen exists in the air as N_2—two N atoms bound tightly together. This bond is so strong that plants can't break it, so can't make use of this N. One of the few natural ways that N is released from the air is through lightning bolts, which produce small amounts of N that may reach the soil with rainfall. Plants contain more N than any other element besides those that come from the air or water (carbon, hydrogen, and oxygen), and N is the most limiting nutrient in growth of non-leguminous crops, including corn, in most farming systems. Finding ways to provide the right amount of plant-available N to corn remains a major challenge in most parts of the world where corn is grown.

Nitrogen is so important to plants and animals because it is a chemical component of most of the important molecules that make life possible. These include proteins, which as enzymes help produce all other components in cells; genetic material (DNA); and chlorophyll, which enables the capture of carbon (as carbon dioxide) from the air and its conversion to sugars and other plant materials, which fuel most of the rest of life on Earth. The amount of N in forms usable by plants was adequate to sustain human populations as they hunted animals and gathered plants to use as food. Before the Industrial Revolution, farmers used animal manures and legumes to provide N for food crops, but as the worldwide population increased, the need for plant-usable N exceeded the supply.

In the early 20th century, the German chemist Fritz Haber invented a process to convert nitrogen and hydrogen into ammonia under high temperature and pressure. He and Carl Bosch scaled this process up to produce large quantities of ammonia. The Haber-Bosch process typically uses natural gas as the source of energy and hydrogen, along with N_2 from the air, to produce tens of millions of tons of ammonia annually for use in agriculture. The scale of crop production in the world would not be possible without this supply of plant-usable N.

Although N fertilizer enabled major growth in crop production, its use also brought some problems. It is a large expense for many farmers, and most countries have production plants and policies that make N fertilizer readily available, often at subsidized prices. The use of N fertilizer has also raised substantial environmental concerns: N in the nitrate form (NO_3^-) is mobile in soils and in the environment, is toxic to animals and humans at high levels, and can reach water systems to affect drinking water supplies and to stimulate the growth of algae and other undesirable forms of aquatic life in surface waters.

Providing N to crops through soils is a highly complex process, involving a number of different N sources in addition to fertilizer; the involvement of microbes in N uptake and release; and the influences of soils, weather, and other factors on quantities and timing of N needed by plants. This complex system is called the nitrogen cycle (**Figure 9.1**). The need to supply enough but not too much N, along with the complex interactions among soils, microbes, weather, and plants, make managing N for crops one of the enduring challenges in agriculture.

The "4R" approach to fertilizer management for crop production was developed in the early 2000s by the International Plant Nutrition Institute to bring attention to the challenges of managing fertilizer, with the goal of maximizing economic returns while minimizing environmental consequences. This approach identifies four "Right" products and practices—source, rate, time, and placement—for providing fertilizer to help achieve these goals. In principle, there is a "best" combination of these for each field each year. In practice, knowing enough to find the best combination for every field is nearly impossible, given the effects of unpredictable weather. But there are principles that can help guide the development of sound N management practices.

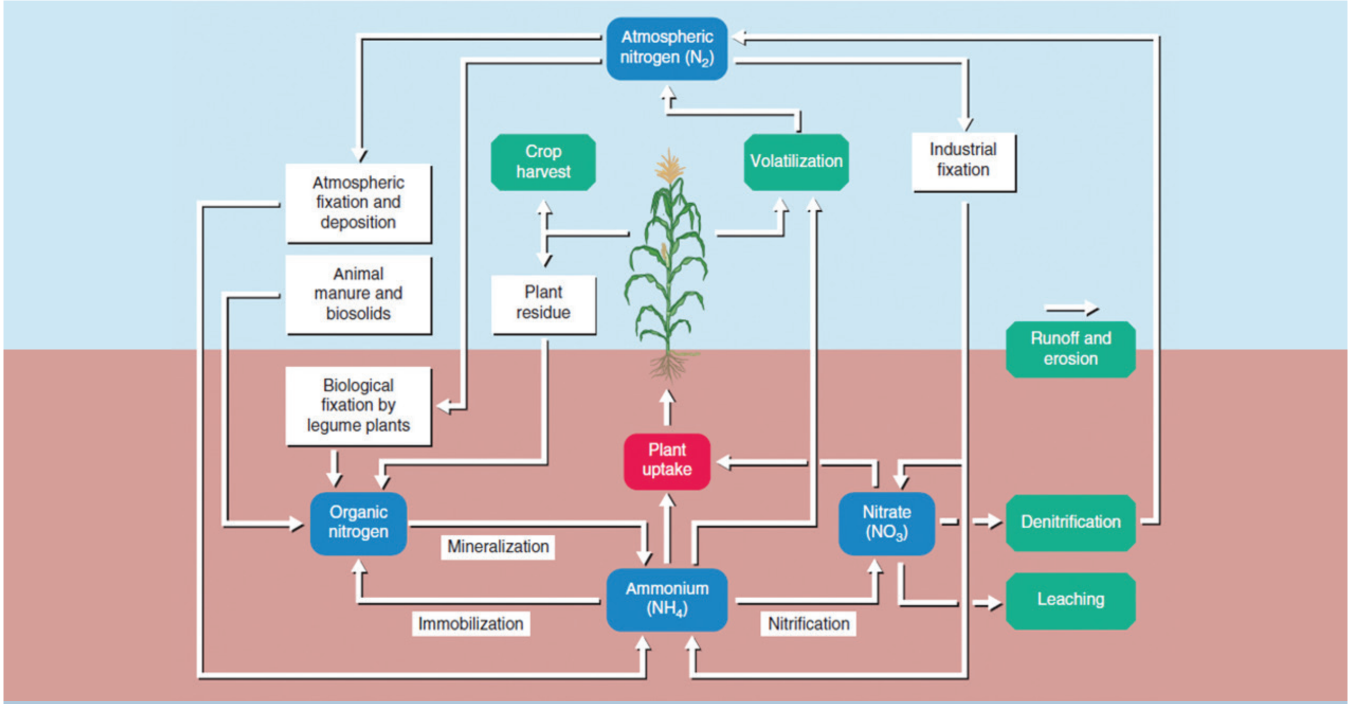


Fig 9.1. The nitrogen cycle.

Nitrogen Rate

A bushel of corn contains about 0.6 pounds of nitrogen, so a 200-bushel corn crop harvested as grain removes about 120 pounds of N per acre. About two-thirds of the N in a corn plant ends up in the grain, so a 200-bushel crop would have about 180 pounds of N in the plants at some point before harvest. Roots have some N as well, and we sometimes find more N in the plant than 0.9 lb per bushel of yield. So we will use 1 lb as an estimate of the amount of N the corn crop needs to take up to produce each bushel of grain. While this factor varies some depending on the soil, crop, and weather, a corn crop with high yields normally takes up more N from the soil than one with low yields. Because the soil supplies some N from organic matter and plants do not take up all of the fertilizer N that is applied, the only way to measure how much fertilizer N is needed is to run N rate trials, applying different rates of N and seeing how yields respond. Trials in the 1960s and 1970s showed that corn following corn needed about 1.2 pounds of fertilizer N for each bushel of yield: this led to the rule “1.2 is the most [we] should do” that tied N rate to expected yield, in Illinois and in other states. This recommendation system was in place for about three decades beginning in the 1970s in Illinois, and remains in place (with some useful refinements) in a number of states today.

Before the adoption of yield-goal-based N recommendations, high rates of N were used without much regard for corn yield level or how much N might be left in the soil after harvest. It was not unusual, in the 1950s and 1960s, to use N rates of 200 or more pounds per acre for corn that was not expected to yield more than 100 bushels per acre. Hybrids at the time were not great at taking up N, which increased the per-bushel N requirement. 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, the average corn yield was less than 100 bushels per acre. Low N prices also encouraged high application rates: anhydrous ammonia prices during that period averaged about $100 per ton, or about 6 cents per pound of N.

The use of manufactured fertilizer grew rapidly after World War II in the U.S., as rotations used in mixed farming (livestock-based, with most crops used for feed and forage) decreased rapidly. Soybeans were not yet a major crop, and so most N fertilizer was used on corn grown in the same fields for two or more years in a row. Early research to find the best N rates concentrated on corn following corn. The discovery that corn following soybean produced higher yields and needed less fertilizer N compared to corn following corn led to adoption of the

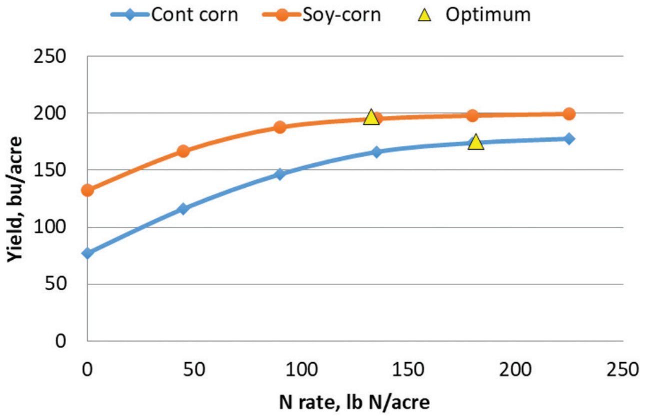


Fig 9.2. Responses of corn following soybean and corn following corn to nitrogen rate, averaged over 30 trials in northern and central Illinois, 1999-2008.

"soybean N credit," which in Illinois meant subtracting 40 lb of N from the yield-based N recommendation when corn followed soybean. This credit was not measured directly, but was taken from results such as those in **Figure 9.2**, showing that corn following soybean required substantially less fertilizer N even as it produced higher yields than corn following corn.

Corn following soybean needs less fertilizer N not because it receives a lot of the N fixed by nodules on soybean roots and carried over to corn; in fact, corn following a small grain or fallow responds to N much like corn following soybean. Instead, as microbes break down corn residue, they use N from the soil as their N source, thereby diminishing the amount of plant-available N in the soil, and increasing the amount of fertilizer N needed. Compared to corn residue, there is less soybean residue, and it contains much more N relative to the amount of carbon. Microbes that break down soybean residue use the N in the residue and don't need much from the soil, leaving more soil N available for crop uptake. Even so, adding higher rates of N to corn following corn often fails to bring yields up to match those of corn following soybean. This means that there are factors besides N availability—for example, cooler and wetter soils early in the season—that often limit yields in corn following corn.

Yield-based N rate recommendations were influenced in some cases by economic considerations: it was suggested to lower the 1.2 lb 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 per pound of N: $2 per bushel) to 0.1 (15 cents per pound of N: $1.50 per bushel) or higher. The maximum return to N occurs at the N rate where the last pound of N added produces just enough extra yield to pay for itself—this is called the "economic optimum N rate" or EONR. The maximum yield in N rate trials is typically only about a bushel more than the yield at the EONR; some call the N rate required to maximize yield the "agronomic" optimum N rate, or AONR, although such a rate is hardly "optimum" with regards to maximizing net profit. While most people are interested in applying enough N for maximum yield (perhaps plus some extra "just in case"), the amount of N needed to produce the last bushel or so of yield—the difference between the AONR and EONR—is typically about 20 pounds. At the price ratio of 0.1 (one bushel of corn equal in value to 10 lb of N), applying 20 pounds of N to produce that one added bushel means losing half of that investment of N. Not only does the extra N cost twice what that bushel is worth, but it also causes an environmental problem: only about one pound of the added N is taken up by the plant, and much of the rest is left after harvest and able to move out of the field in drainage water before the next growing season.

While yield-based N recommendations were appropriate and useful at the time they were developed, land grant university research in the 1980s and 1990s began to show that modern hybrids, especially when grown in higher-organic matter soils, did not need as much N as yield-based recommendations suggested. At the same time, corn grown in lower-OM soils often needed more N than the amount based on expected yield. Over a series of trials, corn in central and northern Illinois needed only 133 lb of N to produce 197 bushels per acre, while in southern Illinois, it took 155 lb of N to produce 144 bushels per acre (**Figure 9.3**).

Not only did data show that soils in lower-organic matter soils needed more fertilizer N to produce lower yields, but in a number of studies, especially those where corn followed soybean in higher-OM soils, there was little or no relationship between yields and the N rate it took to reach those yields. **Figure 9.4** summarizes results over a large set (274) of recent N rate trials conducted in central Illinois. Each symbol on the figure shows the EONR and

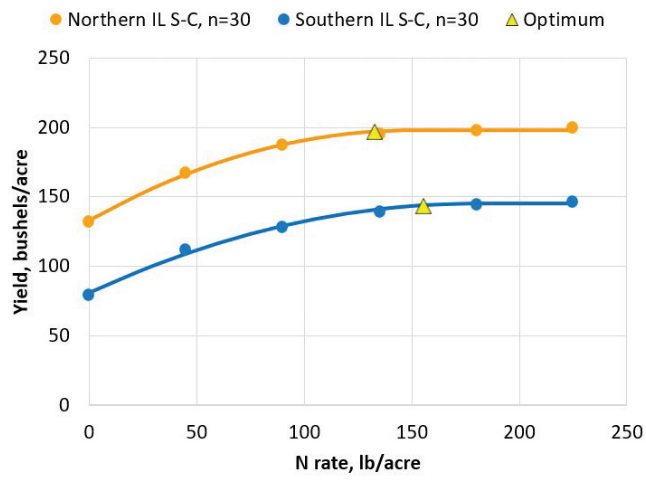


Fig 9.3. Response of corn following soybean to N rate averaged across 30 N trials in southern Illinois and 30 trials in northern Illinois, from 1999-2008.

the yield at that N rate from one trial. The average EONR was 166 lb N/acre, and the yield at the EONR averaged across these trials was 219 bushels per acre. Using the yield-goal-based formulation of 1.2 lb N per bushel and subtracting the soybean N credit (40 lb/acre) would have suggested using an average of 223 pounds of N per acre. In addition, the idea that higher yields require more N was not supported by the data. The average EONR value (166 lb N per acre) is 51 pounds less than the yield-goal-based N rate. Across 126 trials in southern Illinois over the same period, the average yield at the EONR was 185 bushels per acre, and the average EONR was 180 lb N per acre, almost the same as the yield-based N rate of 182 lb N per acre after subtracting the soybean N credit. There was a slight correlation between yield and EONR across the southern Illinois trials as well, suggesting that high yields in these soils with lower organic matter required more fertilizer N because the soil was unable to provide as much.

How is it possible to get high yields without needing to supply large amounts of fertilizer N? The main reason is that soil, especially soil with higher organic matter, can provide a large amount of N to the crop. The average yield without fertilizer N across the 274 trials in **Figure 9.4** was 112 bushels per acre, or just over half of the average yield (219 bushels per acre) at the EONR. If we estimate that corn took up 1 pound of N per bushel, the soil supplied 112 and fertilizer supplied 107 lb of the N taken up by the crop. The 107 lb of N that the crop took up at the (average) EONR of 166 lb N means that the average (fertilizer) nitrogen use efficiency (fNUE) was 107÷166 = 0.64; across trials, nearly two-thirds of the fertilizer N at the EONR was taken up by the plant.

Highly productive soils contain thousands of pounds of N as part of their organic matter. Soil organic matter (SOM) contains about 5% organic N, and each percentage point of SOM in the top 7 inches of soil (weighing about 2 million lb) is about 20,000 lb of SOM, or 1,000 pounds of soil organic nitrogen (SON) per acre. So a soil with 3.5% SOM in the top 10 inches would contain about 5,000 pounds of soil organic N. Microbial action typically frees about 2 percent of this N for plant uptake during the growing season, which in this soil would be 100 lb of N per acre. Actual release (by the microbial process called “mineralization”) is affected by weather, soil drainage, and other factors, and is impossible to predict with precision before crop uptake is nearly complete. Modern hybrids have root systems that are better at extracting N from the soil and at using this N efficiently to produce grain compared to older hybrids. This efficiency comes from a combination of factors, including better standability, higher crop (including root) growth rates, better foliar disease resistance (or fungicide use), and lower grain protein concentration that lowers the amount of N in each harvested bushel.

A New Approach: Using data to predict best N rates

One way to use data from a large number of N rate response trials is to combine results over trials after fitting curves that describe 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

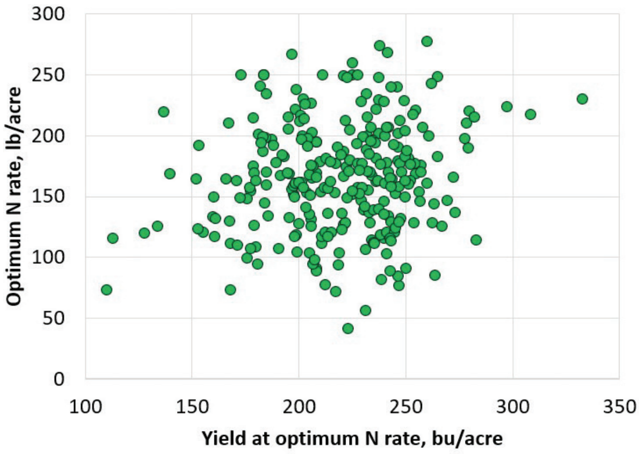


Fig 9.4. Optimum N rate and yield at the EONR in 274 N rate trials conducted in corn following soybean in central Illinois, 2006-2020.

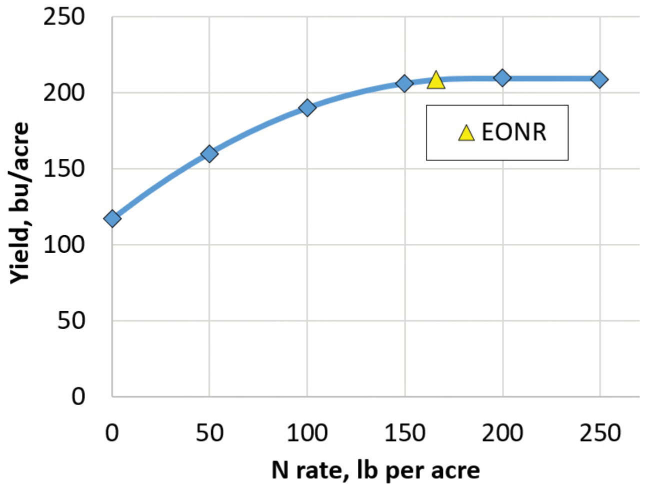


Fig 9.5. Example of an N response curve. The line is fitted to the data points using computer software. The optimum N rate is 166 lb per acre and the yield at that rate is 209 bushels per acre. Yield without N is 117 bushels per acre, so at the EONR, N added 209 – 117 = 92 bushels of yield.

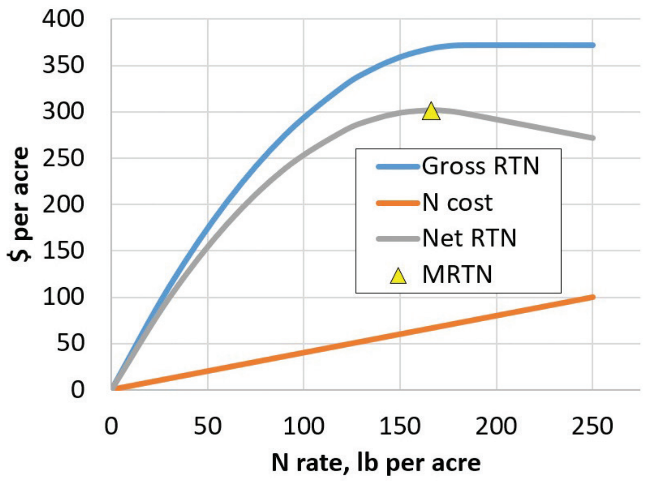


Fig 9.6. Response of gross return to N (RTN), N cost, and net RTN to N rate, using the yield data in Figure 9.5, with corn priced at $4.00 per bushel and N at $0.40 per pound. The Maximum RTN (MRTN) is the highest point on the RTN curve, which here is gross RTN (92 bushels added x $4.00 = $368) minus N cost (166 lb N x $0.40 per lb = $66) = $302 per acre.

be inaccurate 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 the highest N rate used) leveling off at some point, with a flat line after that. Yield decreases at higher N rates are sometimes found, but with the improvements in standability and other hybrid traits, this is relatively rare today compared to a few decades ago. **Figure 9.5** shows a typical response from an N rate trial. After finding a line (described by an equation) to fit the data, we subtract the yield at zero N to give the yield added by N, then multiply this added yield at each N rate times the price of corn to produce the gross dollar return from N. Subtracting the cost of N (N rate × N price) gives the "return to N" (RTN) line, which is the profit from adding N at that rate (**Figure 9.6**). The high point of this RTN line is the "maximum return to N" (**MRTN**) point, where the yield increase from adding N just paid for the N added. These calculations utilize the N:corn price ratio of 0.1. The MRTN and the EONR from a single trial are just different terms for the N rate needed to maximize profitability, which in this case is 166 lb N/acre.

We go through the procedure described above to calculate RTN values across the range of N rates for each trial in a set of N rate trials, then average these values across the trials to produce an RTN line for the whole dataset. The **MRTN** is the high point on this line,and it shows the N rate at which the dollar return to fertilizer N is at its maximum. **Figure 9.7** shows the RTN curve over the 274 trials in the current database for corn following soybean in central Illinois. This curve rises to its maximum point (the MRTN, which is 181 lb of N) then declines as N rates increase further; this happens because the average yield does not increase fast enough (many trials show no increase in yield) at higher N rates to cover the added cost of the N. Because the RTN curve tends to be rather flat on top, a "profitable range" of N rates is specified along with the MRTN. The low and high values of this range are the N rates at which the RTN is $1.00 per acre less than at the MRTN, both below and above the

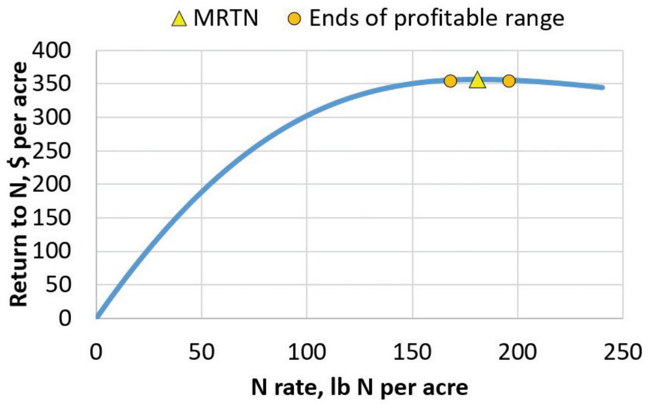


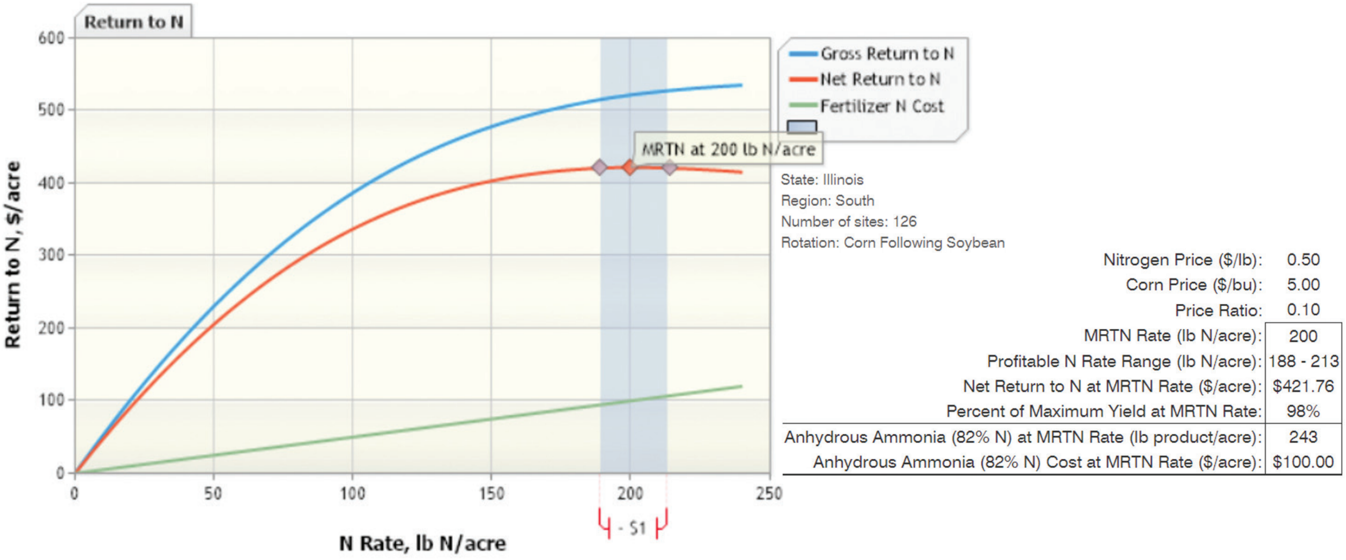
Fig 9.7. Return to nitrogen (RTN) curve over the 274 trials with EONR values and yields shown in Figure 9.4. The MRTN value (high point of the RTN curve, at 181 lb N per acre) and the ends of the profitable range (168 and 196 lb N per acre) are shown.

MRTN. These points are shown on **Figure 9.7**. This range of N rates is usually about 15 pounds on either side of the N rate that produces the MRTN, so the range is about 30 pounds of N wide. Ranges allow some individual choice based on personal approach to environmental concerns, economic risk, and other factors.

Across the set of 274 trials used to produce the curve in **Figure 9.7,** the average EONR value was 168 pounds of N and the average yield at the EONR across trials was 221 bushels per acre. This same set of trials, though, produced an MRTN value of 181 pounds of N per acre and a yield of 219 bushels per acre. Why these differences, especially the higher N rate using the MRTN? This is because N rate trial responses vary widely in shape, from those with steep yield increases to those that respond up to high N rates, but with modest yield increases as N rate increases. In fact, the MRTN is a conservative number—it is influenced more by large yield responses up to high N rates (trials with high RTN values) than by trials with only modest yield responses to increasing N rate. There are fewer of these highly responsive trials, but they produce high return to N, so are important to include in the database.

The development of the MRTN approach was a cooperative effort among a group of scientists that began in 2004. Dr. John Sawyer at Iowa State University created a website where N rate guidelines can be calculated using this approach. The Illinois part of this website uses data generated from more than 700 trials in Illinois since the mid-2000s, with separate databases and calculations for northern, central, and southern Illinois, and for corn following corn and 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 9.8** shows a screen shot of the output for corn following soybean in southern Illinois as an example. New data are added each year, and older data deleted, making this approach a dynamic one that responds to annual weather and changes in corn productivity.

MRTN rates have risen in each region of Illinois over the past five years as new data have been added. Southern Illinois currently has the highest MRTN rate for corn following soybean, at 200 lb per acre, followed by central Illinois (181 lb per acre) and northern Illinois (171 lb per acre). The higher rates in southern Illinois stem from having data from recent years with high yields and higher demand for fertilizer N, and in soils that have lower organic matter than in central and northern Illinois. But this change only was uncovered due to the emphasis on conducting N rate trials in farmer fields in southern Illinois, with most of the work carried out by the Illinois Fertilizer & Chemical Association with funding from the Illinois Nutrient Research & Education Council using fertilizer tonnage fees.



State: Illinois
Region: South
Number of sites: 126
Rotation: Corn Following Soybean

Nitrogen Price ($/lb):	0.50
Corn Price ($/bu):	5.00
Price Ratio:	0.10
MRTN Rate (lb N/acre):	200
Profitable N Rate Range (lb N/acre):	188 - 213
Net Return to N at MRTN Rate ($/acre):	$421.76
Percent of Maximum Yield at MRTN Rate:	98%
Anhydrous Ammonia (82% N) at MRTN Rate (lb product/acre):	243
Anhydrous Ammonia (82% N) Cost at MRTN Rate ($/acre):	$100.00

Fig 9.8. Screen shot of the N rate calculator (http://cnrc.agron.iastate.edu/) output for corn following soybean in southern Illinois, with a corn price of $5.00 per bushel, and N at $0.50 per lb of N, or $820 per ton of anhydrous ammonia.

One important feature of the MRTN approach is that it does not include the need to make an adjustment based on whether the previous crop was corn or soybean. This is not because N responses are considered the same for corn following soybean as for corn following corn, but because the data used to generate the MRTN database are from different trials: the corn-following-soybean MRTN is based only on trials done with corn following soybean, and the corn-following-corn MRTN is based only on trials done with corn following corn. The N rates are still higher for corn following corn—by about 35 lb in northern Illinois and 20 lb in central Illinois—but are about the same in southern Illinois. With less continuous corn in Illinois in recent years, we have not generated as much data from corn-following-corn N trials. It's also possible that current hybrids may be less affected by previous crop than older hybrids.

If the previous crop was neither corn nor soybean, we suggest using the corn-corn MRTN only if the previous crop was grain sorghum or another grass crop that left behind low-carbon crop residue; this may include cereal rye used as a cover crop with dry matter of more than 1 ton per acre at termination. If the previous crop is wheat or another small grain, the months of warm weather following harvest allow residue to break down by the next spring, so the soybean-corn MRTN is more appropriate. If the corn crop was preceded by a multi-year forage legume such as alfalfa, decrease the soybean-corn MRTN by 125 to 150 pounds if the established legume stand was good, down to no reduction if there were few forage legume plants remaining. Leguminous cover crops such as clover planted in late summer and allowed to grow to mid- to late April contain a considerable amount of N at termination, but it is not clear how much of this N will become available in time for the corn crop to make use of it. If termination of a cover crop legume is more than a few weeks before corn planting, using the low end of the soybean-corn MRTN range, and subtract 20-30 lb from that rate if the cover crop is already breaking down when corn is planted. If termination was closer to the time of planting, the fertilizer N rate should be the MRTN. If there was no crop in the field the year before corn, use the soybean-corn MRTN.

The N rate calculator (MRTN) website is currently at http://cnrc.agron.iastate.edu/. Work is underway to develop a separate calculator to use Illinois data, along with added features: this may be available in 2022. Six additional states utilize the Iowa State website to produce N rate guidelines based on data from each state.

What Changes with the MRTN Approach?

We have termed MRTN rates as "guideline" rates, to reflect that this is a decision aid rather than a fixed "recommendation." This does not mean that we lack confidence in this method—we recommend strongly that it be used, and that the yield-based N recommendation system no longer be used. We recognize that the use of a "flexible" guideline N rate and ranges is not as comfortable for some as the single, fixed N rate from the yield-goal-based system. The fact that rates can change with corn and N prices may also seem to some to be questionable, given that the agronomic response to N doesn't change with prices. 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 fact, no N rate recommendation system exists that is capable of making exact N recommendations before the season; getting to zero chance of having less N than the crop needs would require using the highest rates shown in **Figure 9.4**—some 275 lb of N per acre—in every field. That would mean over-fertilizing nearly every field, which would greatly increase the loss of N from fields through tile lines or leaching, and would mean a loss of millions of dollars every year from applying more N than the crops need or can use, as well as sending many tons of paid-for N down the river systems and into the Gulf of Mexico, and affecting local water supplies.

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 most-profitable N rates. It is clear that as corn yields have risen, N rates required to produce these yields are not rising at the same rate, if they are rising at all. From an environmental standpoint, the fact that most guideline N rates are lower than rates under the yield-based system would seem to be a positive. Will depending on soil N to provide N to the crop eventually mean a decline in soil organic matter and organic N?

Some scientists suggest that the amount of fertilizer N applied should not exceed the amount of N removed when the crop is harvested. At 0.6 lb N per bushel, that would mean applying no more than 120 to 150 lb of N per acre in high-yielding fields, and even less in lower-OM fields with lower yields and less N from organic matter. Such N rates would be substantially less than optimal, thus lowering profits from corn production unless corn prices remained low and fertilizer N prices rose substantially; in central Illinois, the MRTN would fall to 140 lb N/acre with corn at $5.00 per bushel only if N cost rose to more than $1.25 per lb, or $2,050 per ton of anhydrous ammonia. Some organic matter is produced as residue (especially root residue) from the corn crop as it breaks down, and this process incorporates some of the N left in the soil into organic matter. Applying only the amount removed would lower the yield and the return to N, and would also lower the amount of N left over after harvest. But growing corn, and perhaps following it with a cover crop that takes up some of this N, will likely be preferable to using N rates well below those needed to maximize return to N.

Some have wondered whether unexpected price distortions—very high or low prices for corn or N—might cause calculated N rates to fluctuate widely, even within the same season. The default ratio of 0.1 ($/lb N:$/bu corn) wasn't chosen arbitrarily: it turns out that the actual ratio has remained close to this value over time, with price changes in corn and in N tending to move in the same direction. The N rate calculator does not compute MRTN rates above 240 pounds N per acre. For corn following soybean in central Illinois, it takes a price ratio less than 0.03 to reach this limit, which would take doubling the corn price and cutting the N price in half at the same time. That large a change rarely happens, and when it does, it tends to be short-lived.

When using manure, sewage sludge, or other N sources that cost less per pound of N than commercial fertilizers, a conservative approach to assigning value to those products is to price a pound of crop-available N the same as a pound of N from commercial fertilizer. Usually about 40-50% of the total N in dry or liquid cattle manure, 50-60% of the N in poultry manure, and 90-100% of the total N in liquid swine manure is available in the first year after application. Manure or other non-chemical sources of N often are used at rates that supply less than the full amount of N, in which case the total N rate should be calculated using the fertilizer N:corn price ratio, then subtracting the amount of N applied with the other source or sources and only applying enough fertilizer N to "top off" the rate.

Nitrogen in the Soil

Soil N can undergo several transformations that influence its availability to plants. Understanding what happens to N in the soil helps us 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^-) (nitrification) as well as the movements and transformations of nitrate (**Figure 9.1**).

Nitrogen processes in the soil

Immobilization. Inorganic N, mainly as ammonium (NH_4^+) and nitrate (NO_3^-) ions, is taken up by soil microorganisms (mostly fungi and bacteria) as they multiply and grow; in the process, N is incorporated into proteins and other molecules in microbial biomass. This process is referred to as immobilization, since it takes N "out of circulation" in the soil and makes it unavailable for plant uptake. 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. Adding large amounts of residue to the soil causes microbial populations to increase rapidly, and the demand for N needed for microbial growth increases rapidly as well.

Microbial biomass 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 inorganic N from the soil in order to have enough N for growth. Conversely, materials rich in N, including some manures, forage legumes, and immature cover crops, have C:N ratios less than 20:1, and so have more N than microbes need. In that case, some of the N will be released by microbes as they break down such residues.

Mineralization. Mineralization is the process by which organic N—N in protein and other organic compounds in the soil—is converted to inorganic N (first as NH_4^+ ions), thus becoming available for plant uptake. This takes place during the decomposition of soil organic matter by microorganisms, and as microbes die off and their N is released. Mineralization is a biological process, so N release rates depend on soil temperature and moisture, as well as on the organic N source. 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, appropriate soil pH, good water content, and proper soil aeration) also enhance mineralization. Once N is in the NH_4^+ form, it is held by soil clay and organic matter "exchange sites" (which are negatively charged, and so attract cations like ammonium) and cannot move very far until it is converted to NO_3^-.

The large amount of soil organic matter in many soils, such as soils that developed under tallgrass prairie, is the legacy of thousands of years of slow accumulation, as plants took up N from wildlife droppings and carcasses, biological N fixation by microbes in soils or plants, and N produced by lightning. Some of this N was incorporated each year into soil organic matter. This process was aided by lack of aeration by tillage. Most of the N in soil organic matter is tied up in organic compounds, and is unavailable for uptake by crops. It is estimated that 1% to 3% of the organic N in the topsoil is mineralized annually into plant-available N. As described above, this can make up a substantial amount of the crop's N requirement. While this explains how fertilizer N rates can be lower than crop uptake, the amount of N mineralized in a growing season is highly variable due to soil and weather factors. It is also unpredictable, which makes it difficult to adjust fertilizer rates based on how much N the crop will receive from mineralization.

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, from near zero at freezing to a maximum at about 85 °F; when soil pH is slightly acidic to slightly basic (6.5 to 7.2); and when there is good soil aeration. 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 N fertilizer is in subsurface bands, soil conditions are very acidic, or when a large amount of organic N is being nitrified. Under such conditions, the bacteria that transform NH_4^+ to NO_2^- are more active than the bacteria responsible to transform NO_2^- to NO_3^-. This can occur when manure is injected in poorly drained soils.

While NH_4^+ is safe from loss by leaching or denitrification, NO_2^- and NO_3^- can both 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 usually take up most of their N as NO_3^-. Corn has been found to grow better, however, when at least some of the N it takes up is NH_4^+. In most fields, this need for NH_4^+ is met by the ongoing process of mineralization as plants grow, and 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, both of which are gases that can move up through the soil freely and be lost to the atmosphere. Neither of these gases can be taken up by crops, so their formation means a loss of crop-available N. Denitrification is mainly 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 conditions. Since saturated soils are not uncommon in Illinois, denitrification is believed to be the main process by which N (as NO_3^-) is lost, except on sandy soils and in some tile-drained fields, where leaching may be the main loss pathway. While quantities of N_2O produced during denitrification are low, N_2O is a potent greenhouse gas, so its release is a serious environmental problem. Severe oxygen limitations may cause more N_2 and less N_2O to be produced; because N_2 is not a greenhouse gas, this lowers the environmental risk.

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-supplying material available to denitrifying microbes. When water stands on the soil or the surface soil is completely saturated in late fall or early spring, N loss to denitrification is small because some of the N (applied as ammonia) is often still in the NH_4^+ rather than NO_3^- form, and because the soil is cool, which limits the activity of denitrifying microbes. In late spring and early summer, when soil temperatures and microbial activity are high, N losses can be substantial. The percentage of NO_3^- nitrogen in the soil (from fertilizer or nitrified from mineralized soil N) that can be lost through denitrification for each day the soil remains saturated increases with temperature. Daily nitrate-N losses through denitrification in Illinois soils are 1 to 2% when soil temperatures are 45 to 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 wet the top 4 to 6 inches of a silt loam soil, 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; in heavier-textured soils developed on dense parent materials, roots may reach depths of only 2.5 to 3 feet. If more than 5 to 6 inches of rain falls in a single event, little NO_3^- may 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 active rooting depth (about 3 feet) as long as it does not reach tile lines to move out of the field, and as long as soils don’t become saturated to allow denitrification to take place.

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. Subsequent rainfall first replaces the water that left the soil since the previous rain, and will carry NO_3^- down further from its previous position only if the amount of water entering the soil exceeds the amount that was removed. If the soil is already wet at the time of rainfall, water (and NO_3^-) will not move uniformly into the soil: some will run off or collect on the surface, and some will move deeper into the soil through large soil pores. All these factors make it difficult to predict how deep NO_3^- might have moved, or the extent to which it might have left the rooting zone altogether, either to depths well below rooting depth, or through tile drainage.

Estimating Availability of Soil Nitrogen

Because N can become available from organic matter in different amounts and at different times, can convert from ammonium to nitrate at different rates, and can be lost from the soil, testing soil to determine N fertilizer needs for corn in regions, including Illinois, where rainfall often exceeds crop water uptake, is not as useful as is testing to determine the need for less mobile nutrients such as lime, phosphorus, or potassium. Testing soil to predict the amount of N fertilizer needed is complicated by the fact that N availability—both the release from soil organic matter and loss by leaching and denitrification—is regulated by unpredictable weather conditions. Under very wet soil conditions, both soil-supplied and fertilizer N may be lost by denitrification or leaching. The amount of N released from organic matter is also unpredictable: it is high when soils are warm and neither too dry nor too wet; the supply may not be synchronized well with crop needs; and it can be lost from wet soils. For these reasons, soil tests designed to test how much N is available—and therefore how much 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, when there is less time for soil N to leach or denitrify before the crop can take it up, might better help guide rate decisions, but this also provides a short window in which to get N applied.

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 N supplied by the soil, and by subtraction, the amount of fertilizer N that will be needed for a crop. Soils with 3 or 4% SOM might supply half (100 lb or more per acre) of a corn crop's N needs. The estimate of 2% availability is, however, very inexact: the rate of N mineralization from organic matter varies significantly over time due to changes in available soil moisture, soil temperatures, crop growth rate, and the ability of the crop's root system 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 often take up more N. The soil under such conditions also supplies more N, resulting in the lack of correlation between yield and N rate shown in **Figure 9.4**.

Illinois soil nitrogen test (ISNT, or amino sugar-N test). This test was proposed to identify soils unlikely to respond to N fertilizer by measuring a fraction (organic amino sugar N compounds) of the soil organic N more likely to mineralize during the growing season. Unfortunately, data from many sites in Illinois and the Midwest showed that this test does not consistently identify nonresponsive sites, and it is unable to predict, with sufficient accuracy, how much N is needed in soils with lower ISNT test values. Relatively high ISNT values have not always meant that little fertilizer N is needed, especially when cool soils limit mineralization into early June. 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. The test does not measure nitrate, so can overestimate the need for N in fields that have received some fertilizer or where N has been mineralized and has been converted to nitrate before sampling.

Soil profile nitrate test. This procedure has been used most successfully in the drier parts of the Corn Belt, especially west of the Missouri River. It involves collecting soil samples in 1-foot increments to a depth of 2 or 3 feet in late fall (in drier areas) or early spring for analysis of nitrate N. The amount of N in the soil is then used to lower the amount of fertilizer N to be applied. Results obtained by scientists in both Wisconsin and Michigan have shown this procedure to work well, but research in Iowa showed that the procedure did not accurately predict N needs. With samples collected in early spring when soils are still cool, this test measures mostly N carried over from the previous crop, from manure, or from fertilizer applied before sampling. 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 during the off-season limited loss of N from the soil. Substantial amounts of soil N were found in Illinois fields after corn harvest in the drought year of 2012, but by the next spring, much of this N had moved out of the soil profile. In normal years, amounts of soil N after harvest of properly fertilized corn tend to be relatively low, and wet fall conditions can lower this amount further. Heavy rainfall in the spring or early summer after soil sampling can cause leaching or denitrification, thereby decreasing the amount of measured soil N that will be available for plant uptake.

Pre-sidedress nitrate test (PSNT), also known as the late-spring soil nitrate test (LSNT). Work in several states has shown this test to be useful, including in some cases where N has been provided using sources (manure, established forage legumes) other than fertilizer. Because of the complex effects of soil, weather, and organic source on microbial processes that release N, however, this test has not always been reliable. By sampling after soils have warmed, this test measures the amount of N mineralized up to that point from organic N plus the amount of carryover (upper soil profile or from early-applied fertilizer) N present in the soil as crop uptake begins to increase. If, however, low soil temperatures limit mineralization before sampling and then rise after the test, the test may underestimate the N supply and lead to over-application of fertilizer. Conversely, rainfall after the test can diminish the amount of soil N and lead to under-application of fertilizer. Young plants do need some N as they become established, and applying 20 to 30 lb of N per acre early won't compromise the usefulness of the test, although row-applied N may not end up in the soil samples to be counted. The test is useful only for fields that will receive sidedress N application, and if application conditions are unfavorable, taking samples and then waiting for the test results before sidedressing N can be a challenge, and in some cases might delay application enough to lower yield.

Because nitrogen is not uniformly distributed in the soil, sampling needs to be thorough to assure an accurate nitrate estimate. Collect samples to a depth of 12 inches when corn plants are 6 to 12 inches tall (V4 to V6 development stage), typically in late May or early June. If the previous crop was soybean and MAP or DAP was uniformly applied, or no prior N was applied the previous fall or in the spring, one or two probes per acre in each soil type or zone in the field, with probes mixed to produce one sample, should be enough. If the field has a history of manure application, collect two or three probes per acre and mix them to produce a composite sample for every 5 acres or so, or one sample for each zone of manure application, if that is known. If MAP, DAP, or manure was banded in the past, nitrate distribution in the soil will be non-uniform, so samples should be pulled in roughly equal numbers from each of three zones—2 to 6 inches away from each row and in the middle between rows. If a delay in sample delivery to the lab is likely, freeze the samples or air-dry them with a fan to slow the mineralization process before getting them to the lab. Ask the laboratory to measure only NO_3-nitrogen.

No additional N is needed if PSNT test levels are above 25 parts per million, and the full N rate planned for the field should be applied if NO_3-N levels are less than 10 parts per million. When test levels fall between 10 and 25 ppm:

- Divide the full rate to be used on the field by 15 (25 – 10) to calculate the amount of N to apply to make up the deficit. For example, if the full rate to be applied is 180 lb N per acre, divide by 15 ppm to give 12 lb N per ppm.
- Subtract the PSNT soil N value from 25 to give the N deficit: if the PSNT is 17 ppm, the deficit is 25-17 = 8 ppm
- Multiply this deficit by the lb of N per ppm. In this example, 8 ppm x 12 lb N per ppm means that 96 lb of N should be sidedressed.

Use caution when applying results of the PSNT if they indicate that much more or much less N should be sidedressed than would have been applied had the test not been used. The trials used for the MRTN approach described above include the soil N supply that would have been estimated by the PSNT, so should be a sound basis for suggesting an N rate without the need for the test.

Modeling soil N

In recent years, a number of commercial companies and public research scientists have worked to develop sophisticated models that use soil, weather, and crop data to estimate how much soil inorganic N ($NH_4^+ + NO_3^-$) is present, and to predict how much more fertilizer N might be needed to meet crop needs. These models typically include estimates of N supply (mineralization and N fertilizer applied); N loss (leaching and denitrification); and projected crop uptake needs (based on projected yield) to generate soil N profiles over the season, then use soil N threshold values to predict if the amount of N in the soil will be sufficient throughout the season. While this approach makes logical sense, it has not proven to be very good at predicting actual soil inorganic N levels over time, nor at predicting how much additional fertilizer N the crop will need. One way to deal with such uncertainty is to use more N than is likely to be needed, which leads to both economic and environmental losses. It is theoretically possible to develop adjustments that limit the risk of under-application, for example by using predicted weather to adjust soil inorganic N. But the soil N supply is highly complex, and has proven to be no more predictable than yields early in the season, which in turn are no more predictable than the weather. Interactions between soil N and plant N uptake and use lower the predictability even further.

Monitoring Plant N Status

Although the human eye can often detect the lightening in plant color that signals N deficiency, new technology has made it possible to monitor plant N status over large areas, and to do this often enough to detect when deficiency develops and how severe the deficiency is. Once deficiency develops, a logical next step is to use the measure of deficiency to determine how much additional N should be applied to correct the shortage of N by applying more N where leaf color is lighter, and less (or no) N when leaves are darker green.

While this approach makes sense, it has been difficult to put into practice. A major problem is that N deficiencies do not develop consistently, even when little or no fertilizer N was applied, due to the small amount required to meet plant needs early in the season, and to differences in soil organic matter and mineralization rates. Research has also shown that plants that become deficient in early growth stages (V2 to V5) may already have lost some yield potential that cannot be fully recovered by N applications after the deficiency has been detected. Preventing this by applying 20 to 40 pounds of N near the row delays deficiency symptoms, but also diminishes the ability to use degree of deficiency to set N rates.

Plant tissue testing. Plant tissue analysis can help confirm that plants are deficient in N, but cannot identify the direct cause. Low N in plants early in the season when soils are dry, wet, or cool, or when the weather has been cool and cloudy, may reflect these temporary conditions, and may not reflect the amount of N in the soil or indicate the need for more N. If every field in an area shows the same pale color and samples test low in N, then it's almost certain that this is due to conditions and not to N management. Also, plants growing in warm, moist soils with good sunshine may have good leaf color and normal leaf or plant N levels, even when little or no N has been applied: under good mineralization conditions, plants can reach stage V8 to V10 (2 to 3 ft tall) before they begin to show deficiency. Plants at stage V8 typically contain only about 20 lb of N per acre, and mineralization can supply that amount in most soils, especially when soils are warm and rainfall is moderate. Any N fertilizer applied early will further delay the development of deficiency symptoms. This means that the practical window to apply N may open well in advance of the development of deficiency symptoms.

Corn tissue testing may be done on small plants, with the entire plant harvested and analyzed, or on the ear leaf of plants between tasseling and stage R3. The N concentration needed in tissue to avoid yield loss is called the "critical level," and may be presented as a "sufficiency range" above the critical level based on observed values in well-fertilized crop plants. A major problem is that there is no uniform standard for determining these values. Hybrid, soil, weather, and growth stage may all affect how much N is in the plant, especially in young plants. Some of the published critical values are several decades old, and laboratories that do tissue testing typically choose their own values, sometimes using their own data generated from previous samples. As a result, it is possible to find critical levels for small corn plants (stage V6 or so) ranging from 2.7% to 3.8% (N on a dry weight basis.) Such a wide range, along with unpredictable development of deficiency symptoms early in the season, leads some to question the value of tissue testing for N, especially early in the season. Tissue testing corn before stage V8 or so may not tell us anything that we can't learn by simply looking at the crop.

Tissue testing becomes more accurate the larger plants get, but the possibility of yield loss due to low tissue test values in larger plants also makes correcting low N more urgent. If normal amounts of fertilizer N has been applied by stage V8 and plant and soil conditions are normal, without standing water, it is very rare for N deficiency symptoms to appear during the period between V8 and pollination. During this period of rapid N uptake, growth of the root system together with N provided by mineralization and fertilization help to assure enough N uptake in almost every field where N had been applied. There is no need to use tissue testing on plants with dark green leaves. During and after pollination, the N content of the ear leaf (the leaf beneath the ear, attached at the same node as the ear) correlates well with final grain yield in N rate trials, as long as the canopy remains healthy during grainfill. Testing for nutrients in addition to N is common in ear leaf samples, but unless soil test values for other nutrients are low, such deficiencies will rarely appear, and applying nutrients that late may not correct them if they do.

SPAD meter. The SPAD meter, also called a chlorophyll meter, is a handheld device developed by Minolta that measures leaf greenness by determining how much light of specific wavelengths passes through a leaf. Greenness is related to N level in the leaf, and in fully developed leaves, the SPAD meter is a fast way to estimate relative levels of leaf N. By comparing chlorophyll meter readings to those in a strip of the same hybrid where a high rate of N has been applied, 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 measure N deficiency improves as plants begin to take up more N during later stages of vegetative growth. Plants at stage V10 (typically about waist-high) may show differences in leaf greenness while there is still enough time to apply supplemental N if it is needed.

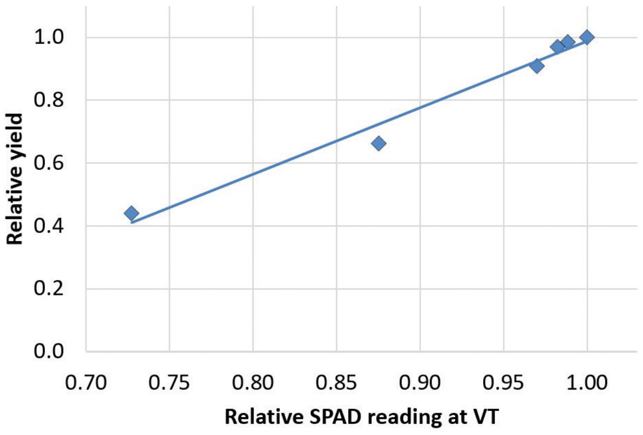


Fig 9.9. SPAD readings at tasseling and relative grain yield—proportion of yield at the highest reading (237 bushels per acre at 250 lb of N per acre)—from a nitrogen rate trial at Urbana, Illinois, in 2016.

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 9.9**. That may, however, be too late for the plant to respond to added N.

While SPAD readings have proven useful in research, measuring enough leaves in a field to determine the degree and consistency of greenness is a daunting task, and whole fields are seldom monitored using only this device. SPAD readings can be useful in calibrating large-area methods such as aerial images, however. SPAD timing studies in N rate trials have shown that readings taken before growth stage V8-V9 are not well correlated with N rate. Before tassels appear, readings are usually taken on the uppermost leaf with a fully visible collar. At or after tasseling, SPAD readings should be taken on the ear leaf. The same leaf of each plant should be measured, and readings are more uniform if taken at about the same position on that leaf—about halfway between the tip and the base and as far from the edge as the instrument allows.

Different hybrids with full N rates can have different SPAD readings, SPAD instruments do not all read the same leaf the same, and different people can get different readings from the same plot. Using a reference strip with 50 to 100 lb more N than in the rest of the field is a good way to eliminate the effects of such variation. The SPAD reading in the reference strip is treated as the maximum value for that hybrid at that stage, and dividing readings in other parts of the field by the reference strip reading converts them to a relative value. In **Figure 9.9**, the highest N rate used (250 lb/acre) was used as the reference strip, and SPAD readings and yields at lower N rates were expressed as proportions of those in the reference strip.

While it seems logical to use such relative values to determine how much more N to apply, it has been difficult to make this work consistently in the field. An early study in Iowa showed that applying 100 lb of N when the relative SPAD was less than 0.88 would restore full yields, and that 30 lb of N would bring yields back to normal with relative SPAD values of 0.95-0.97. More recent research in Iowa has shown less promise from using relative SPAD values to set corrective N rates, however. While SPAD readings stabilize as leaves mature during late vegetative growth, the ability of (N-deficient) plants to respond to additional N declines over this same period. In the study shown in **Figure 9.9**, the 50-lb N rate with a relative SPAD value of 0.88 yielded 77 bushels less than the treatment with 150 lb of N, which had a relative SPAD treading of 0.99. Adding 100 lb of N late to the crop with only 50 lb applied early would have increased yield some, but with some yield potential already lost by then, would not have restored full yield.

Other crop color sensing technology. Optical sensing technologies remain under development for use in measuring the N status (leaf color) of the crop across entire fields. These include "remote" sensing (usually aerial photography) or sensors mounted on applicators, with differences in crop color used to adjust N application rate in different parts of the field. Satellite images are also becoming available with enough resolution to find canopy differences in different parts of a 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: red reflectance indirectly measures chlorophyll and infrared provides some measure of the amount of leaf tissue present. These readings are used to calculate indexes such as the "normalized difference vegetation index" (NDVI). The NDVI ranges up to 1.00, with lower values indicating lower amounts of N in the leaves. Comparing NDVI readings in the field to those in high-N reference strips provides a measure of N deficiency. Such readings can be taken on-the-go by sensors mounted on the applicator, with N rates varied based on these readings. Readings from an aerial photo can also be used to make a map, which can then direct different N rates to different parts of the field. Due to limitations in translating deficiency readings into applied N rates, use of this technology is developing slowly.

As a general rule, if a field has a dark green canopy color, there's little ability (or need) to confirm using imagery that the crop has enough N, at least at that point in time. If only part of the N has been applied, however, good canopy color does not always indicate that there is enough N present to maximize yield. It may be possible to lower the planned amount of N some if imagery taken after stage V11-V12 shows dark green canopy color, but if the amount of applied N is no more than two-thirds of the MRTN rate, the last increment of N (or at least the amount needed to reach the lower end of the MRTN range) should be applied without waiting to see if deficiency begins to show. If leaf color fades only in lower-lying parts of a field after substantial rainfall, this is likely the result of having roots in wet soils, not (initially, at least) because of loss of N. If color begins to fade uniformly across the field (measured against a high-N reference strip), then it's time to apply N, without delay. Nitrogen applied after the appearance of deficiency can be effective, but it is often less effective than early-applied N, especially if dry weather after application delays N uptake.

Using canopy sensing to help manage nitrogen can be effective on irrigated fields where additional N can be applied through the irrigation system at low application costs and without damage to the crop. It can also be useful in rainfed systems where significant N loss has occurred or when the full rate of N has not been applied, although, as mentioned above, waiting until deficiency develops may mean loss of yield even if N is applied quickly. For most Illinois fields that depend on rainfall, it is not clear that N rate adjustment based on crop color is cost effective, nor is it clear how it can best be done.

Nitrogen Fertilizer Materials

Most of the nitrogen fertilizer materials available for use in Illinois provide N in the forms of NH_3, NH_4^+, urea, or NO_3^- or as combinations of these. Regardless of the source, most fertilizer N eventually ends up as NH_4^+ or NO_3^-, which are the two forms that plants take up. In many fields, all fertilizer materials are likely to produce about the same yield, as long as they are applied correctly and remain in the soil and available for plant uptake. So while most forms might be considered as "right" forms of N, understanding how different forms behave in the soil can help us understand how to best use these forms.

Ammonia (NH_3). This source of N is often the least expensive per unit of N and it contains the highest percent N by weight (82%; 82-0-0) of all N fertilizers. Anhydrous (meaning "without water") ammonia is a liquid when kept under pressure, but it turns into gas when not under pressure. The density of NH_3 in its liquid form is 5.9 pounds per gallon; one gallon contains 4.84 lb of N. One of the drawbacks to the use of NH_3 is the danger it poses to living organisms in the event that it escapes into the air and is breathed in, or if it spatters on skin, which it dries out to cause "burns." Its great affinity for water—it will dissolve to a concentration of about 30% by weight at room temperature—helps to keep it in the soil when it's applied, but makes it harmful to life forms. Ammonia is lighter than air, but if released into the air, it lowers the temperature which causes water droplets to form, and it dissolves in these to make a fog that can stay near the ground. It requires equipment that can handle high pressure (rated to withstand 250 pounds per square inch), and its safe transport, handling, and application require expertise, appropriate and well-maintained equipment, and user training. Users of anhydrous ammonia should consult with their ammonia supplier and equipment providers to stay informed on technologies that help ensure safe and uniform application of ammonia.

Besides the issue of safety, there are several concerns with using anhydrous ammonia as fertilizer:

- Damage to corn seedlings: ammonia is harmful to anything living in the soil near or at the point of ammonia release, including roots of new seedlings. If soils are moist after application, ammonia dissolves in soil water, and converts to ammonium, which is not harmful to plants, as soil pH drops. But if soils are dry at application, or if they dry out after application, free ammonia can move to seeds or seedlings to cause damage. Chances of this happening with fall- or early-spring-applied ammonia are small. But in light-textured soils or in the rare case that soil dries out in the spring, there can be damage. This can be avoided by waiting to plant until after rain falls; by applying ammonia deeper (and in soils not as wet) in early spring; and, most effectively, by using RTK (precision) guidance to place ammonia bands away from rows where corn will be planted.

- Anhydrous ammonia kills microorganisms, including beneficial ones, in the soil at the point of injection where ammonia concentration is highest. With normal soil moisture, ammonia moves only a few inches from the point of release out into the soil, and only within the zone closest to the release point—normally 5-8% of the volume of the topsoil—will microbes be affected. This effect is temporary: the N supplied by ammonia will enhance microbial growth once microbes re-establish back into the application zone. So while nitrification has a lag period due to loss of microbes, this process is restored once the microbes regrow, and with more ammonium present, the net effect is to increase microbial populations.
- Ammonia does not adversely affect the physical and chemical properties of the soil. The release of ammonia into the soil causes a temporary increase in pH as the ammonia dissolves. Hydrogen ions (H^+) released during the oxidation of ammonium to nitrate lower pH, regardless of the source of N. There is no basis for the idea that ammonia can "make the soil hard," although applying it with heavy equipment when soils are moist does causes compaction. When ammonia is released from pressurized containment, it takes on energy (heat), which lowers the soil temperature. At normal rates of ammonia, this typically lowers soil temperature by only about 2 °F in the application band, and this effect disappears quickly.

While rarely used in the Corn Belt, the N fertilizer material commonly called "aqua ammonia" is NH_3 dissolved in water to a concentration that is typically 21% N (21-0-0). This product behaves in the soil like anhydrous NH_3, but as a solution, it is easier to distribute uniformly across the application bar. It usually can be applied at a shallower depth than anhydrous ammonia, and because it does not need to move into the soil to reach water in which to dissolve, it forms a narrower band. This is not necessarily advantageous, since shallower placement into warmer soil can speed nitrification, and a narrower band may mean less root access. Aqua ammonia must be stored in sealed tanks to prevent loss of NH_3 from solution, but it generates only about 2 psi of pressure (versus up to 200 psi for anhydrous ammonia) so can be stored in lighter-weight tanks and is safer to apply. It requires a pump for application, though, and because it weighs nearly four times as much as anhydrous ammonia per unit of N, it is more costly to ship and it takes up more storage volume.

Ammonium nitrate (NH_4NO_3), or AN. This fertilizer material is 34% N (34-0-0), with half of the N in the NH_4^+ form and half in the NO_3^- form. Ammonium nitrate is highly soluble in water. With 50% of its N is present as nitrate, AN is more susceptible than many N fertilizers to loss from both leaching and denitrification. For this reason, it should not be applied to sandy soils because of the likelihood of leaching. It should be applied just as the crop is beginning to take up N, in order to lessen the opportunity for possible loss through leaching or 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 for corn in the U.S.

Urea ($CO[NH_2]_2$). This source is 46% N (46-0-0), with all of the N in the urea form. Urea is very soluble, and it can move freely down with soil water, and move back up as the soil surface dries out. After application, urea reacts with water to release CO_2 and NH_2, which changes to NH_3 either chemically or with the aid of the enzyme urease; NH_3 then converts to NH_4^+. The speed with which this conversion occurs depends largely on temperature, with fairly rapid conversion at temperatures of 55 °F or higher.

If the conversion of urea to NH_3 and CO_2 occurs on the soil surface or on the surface of crop residue or leaves, some of the ammonia will be lost as a gas to the atmosphere before it can convert to ammonium. 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 losses can be substantial if the materials remain on the surface of the soil for more than a week or two.
- Urea is left on the soil surface without incorporation.
- Considerable crop residue remains on the soil surface.
- Application rates are greater than 100 pounds of N (217 pounds of urea) per acre.
- The soil surface is moist but drying rapidly (under high temperatures) after application.
- Soils have a low cation-exchange capacity (light texture and low organic matter.)
- Soils are neutral or alkaline (pH>7) in reaction.

In the past, the manufacture of urea generated considerable amounts of biuret, a byproduct of urea formation that is harmful to plants. Modern manufacturing processes have lowered the amount of biuret produced, and along with it, the concern about toxicity.

Ammonium sulfate ($[NH_4]_2SO_4$), or AS. This source is 21% N (21-0-0-24[S]) and all of its N is in the NH_4^+ form. This provides some advantage over products that have a portion of their N as NO_3^-, because NH_4^+ is not susceptible to leaching or denitrification. This advantage is usually short-lived, however, since NH_4^+ quickly converts to NO_3^- once soil temperatures are favorable (above 50 °F) for activity of soil organisms that carry out this conversion.

Ammonium sulfate doesn't hydrolyze to produce free ammonia, so there is little risk of loss of the NH_4^+ in AS through volatilization. This makes it 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 of AS when soils remain too dry for roots to be active 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. Dry soils restrict root growth and slow nitrification, which keeps ammonium N from moving down to the roots.

Ammonium sulfate is a good material for use on soils that may be deficient in both N and sulfur. The crop needs less S than N, so applying AS at a rate sufficient to meet the N need provides more S than the crop needs. The S is in sulfate form (a negatively charged ion) and so can move readily through the soil with water. While sulfate-S in water supplies or in the environment is not considered harmful, the N in AS often costs more than N in other N fertilizers, and depending on the need for S, using AS may not always be cost-effective as an N source. As a source of S, however, its rate can be set to meet the S needs, with other sources of N used to supply the rest of the N.

Most ammonium sulfate sold as fertilizer is a byproduct of the steel, textile, and lysine industries, and is marketed as either a dry granulated material, a slurry (fine-ground AS in suspension), or a solution. Ammonium sulfate is more acidifying—it lowers soil pH more—than most other N sources. About 5 pounds of lime are needed to neutralize 1 pound of N from AS, compared to 2 pounds of lime per pound of N from ammonia or urea. This can be managed by monitoring soil pH and applying lime to correct it every 4 years or so. This need for more lime lowers slightly the cost-effectiveness of AS used as an N source.

In soils and regions where fall NH_3 application is acceptable, it is possible to apply ammonium sulfate in late fall. Both the ammonium and the sulfate can, however, dissolve and move off the field if it rains before they move into the soil. For this reason, application on frozen ground is discouraged: large amounts of ammonium and sulfate have been recovered from streams after AS was applied on frozen, sloping soils followed by heavy rainfall.

Nitrogen solutions. The most common nitrogen solution used as fertilizer contains both NH_4NO_3 and urea. Such solutions are commonly called "UAN" for urea-ammonium nitrate. The most common UAN products are 28% N (28-0-0) of which a gallon weighs 10.7 pounds and supplies 3.0 pounds of N; and 32% N (32-0-0) of which a gallon weighs 11.05 pounds and supplies 3.5 pounds of N. With equal amounts of ammonium nitrate and urea, half of the N in UAN solution is urea (the N in urea is called an amide in solution), one-fourth is ammonium, and one-fourth is nitrate.

The constituents of these solutions will undergo the same reactions as described for the constituents alone, although application as a liquid distributes them more uniformly, and may result in more contact with urease. Urea-containing solutions can be dribbled or sprayed on the soil surface or injected to prevent urea volatilization. Another N solution, but one that is little used today, is UAN with NH_3 added to raise the analysis to 39-41% N.

Ammoniated phosphates. Mono-ammonium phosphate $(NH_4)H_2PO_4$ (MAP; usually 11% N, 11-51-0) and diammonium phosphate $(NH_4)_2HPO_4$ (DAP; 18% N, 18-46-0) are considered primarily phosphorus (P) fertilizers, but they are used widely and so provide an appreciable amount of N to the crop. These sources have a high acidifying potential—about 7 pounds of lime are needed to neutralize the effect of each pound of N supplied. Under warm soil conditions, the NH_4^+ from both products transforms quickly to NO_3^- and is subject to leaching or denitrification; waiting to apply MAP or DAP in the fall until soil temperatures fall to 50 degrees or less, or waiting until spring to apply, will help to preserve the N for the following crop. Another fertilizer material that provides both N and P is ammonium polyphosphate, applied mostly as a solution (10-34-0) near the row at planting, but also as a dry product, with 15% N. Like MAP and DAP, polyphosphate is considered primarily a P source, but N applied this way should be considered part of the N supply. UAN may be added to 10-34-0 to increase the amount of N applied in this way.

Organic-N materials. Manure, poultry litter, and other organic-N materials 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 manufactured fertilizers. They should be injected or incorporated to avoid N loss by volatilization or runoff. Much of the N in these materials is in the form of urea, uric acid, proteins, and amino acids, all of which eventually release ammonium when broken down by microbes and microbial enzymes in the soil. Most manures also contain some NH_3 and NH_4^+. Manures with straw bedding may have most of their N in organic form, but in some liquid manures including liquid swine manure, most of the N is present as ammonium. Most of the N present as ammonium is quickly available to the crop after application, while that present in organic form needs to be broken down by microbes first, and only about half of it might become available the first year after application. Organic-N conversion to ammonium increases as soils warm, as does NH_4^+ conversion to NO_3^-, which is subject to loss. Applications should be done as far as possible from environmentally sensitive areas such as on steep slopes and near bodies of water.

Before application, organic-N sources should be analyzed for nutrient content. Some manures have a high P content, and if applied at rates needed to meet the N needs of the crop, may provide more P than the crop requires. This has led to buildups of soil P to the point where P runoff becomes an environmental problem. More recently, techniques such as feeding low-P corn grain and adding phytase enzyme to animal diets have substantially lowered the amount of P in manures, and this problem has decreased. Where lower-P manure is not available, application rates should be based on meeting the P requirements rather than the N requirements of the crop, with additional N supplied by fertilizer. Managing manure successfully requires knowledge of the soil P level, crop removal rates, and nutrient contents of these organic-N materials.

The use of manufactured fertilizers is prohibited in the production of certified organic corn, so organic producers usually rely on organic-N materials, including manure, composted manure, or previous crop to provide N. Corn that follows an established stand (harvested for one or more years) of a forage legume such as alfalfa in rotation can get most or all of its N from residual soil N and residue. Poultry litter is an excellent source of both N and P where it is available, and is often used as a source of nutrients for organic corn. Other sources include various types of manure, either raw or composted, and feather meal, produced from poultry feathers. Those who produce certified organic corn are required to follow strict rules regarding manure source, use and composting.

Nitrogen Fertilizer Additives

The critical need to supply adequate but not excessive N to crops, high N fertilizer prices, and variable conditions that affect the supply of N have resulted in the development of products designed to make the use of N fertilizers more efficient. Most of these products are designed to affect biological reactions in order to slow the conversion of ammonium to nitrate, or to slow the release of ammonia from urea. Because such conversions are primarily carried out by soil microbes or enzymes, many of these amendments are designed to decrease microbial growth and activity. Such additives would usually be considered as belonging to the “source” category on the 4R list.

Nitrification inhibitors (NIs). As **Figure 9.1** shows, once NH_4^+ is nitrified to nitrate (NO_3^-), the N is susceptible to loss by denitrification or leaching. Nitrification inhibitors such as dicyandiamide (DCD), nitrapyrin (N-Serve®), and pronitridine (CENTURO®) are designed to slow this conversion, reducing loss potential. When properly applied, inhibitors can significantly affect crop yields. In one experiment, 42% of N applied as 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 bushels per acre or more are possible by using an inhibitor in years with high spring rainfall at certain times, but there may be no advantage when soil conditions are not conducive to leaching or denitrification, or when the inhibitor itself breaks down before N uptake begins.

Nitrification inhibitors (NIs) are most often used with fall NH_3 applications to help slow nitrification to help protect against N loss during the six months or more between application and crop uptake. NIs are not fully effective at “locking in” N in ammonium form: any period with soil temperatures above 40 degrees will result in some nitrification, even with NI at normal use rates. Soil temperatures typically reach these levels in March, but soils can warm to 50 degrees or higher even during the winter. Even without an extended period of nitrification (warm soils) before crop N uptake begins in May, any nitrate present during periods of rainfall is subject to loss. Loss rates are higher in poorly-drained and in light-textured soils. Using NIs can significantly improve the efficiency of fall-applied N on loam, silt loam, and silty clay loam soils of central and northern Illinois in years when the soil is very wet in the spring, especially in fields that frequently experience periods of three or more days of flooding in the spring. 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 crop. The lower organic matter content and the warmer temperatures of southern Illinois soils, both in late fall and early spring, result in more rapid degradation of the inhibitor as well as higher rates of nitrification.

The longer the period between N application and the beginning of N uptake 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 is affected by soil temperature. In one study on a Drummer silty clay loam soil, an NH_3+NI application when soil temperature was 55 °F kept 50% of the applied ammonia in NH_4^+ form for about 5 months, but at a soil temperature of 70 °F, only for about 2 months. Application of inhibitors is not recommended for sidedress NH_3 applications, mostly because of the short time between application and plant uptake, and also because keeping N as NH_4^+ in the upper layer of soil can keep it from reaching the roots. Even in wet soils, the process of converting sidedressed ammonia to ammonium and then to nitrate takes enough time that there is little benefit to slowing this process with an NI.

The question whether to use nitrification inhibitors for spring N applications is more difficult to answer, although it is clear that NIs show much less effect as soils begin to warm. Here are some points to consider:

- If it’s March or early April and soil temperatures are at or above 50 degrees (more likely in southern Illinois) and likely to stay there, using an NI with ammonia might be profitable.
- If soils dry and planting begins early, an NI may not be necessary, especially if planting can proceed quickly, and N can be applied just before or soon after planting.
- Using NI with UAN or urea is typically not necessary, if these materials are applied around the time of planting or later. One-fourth of the N in UAN is already nitrate, unaffected by NI.

Nitrification inhibitors should be viewed as management tools designed to lower N loss. Whether or not lowering N loss increases yield depends on how much N was applied: if rates around the MRTN rate are used and conditions after N application are conducive to N loss (warm and wet soils, with rapid nitrification), the inhibitor may act to keep more N in the soil and increase yields. If N rates are high, losing that same amount of N under these same conditions may not lower the amount in the soil by enough to lower yields. On the other hand, 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.

Urease inhibitors (UIs). The chemical compound N-(n-butyl) thiophosphoric triamide, commonly referred to as NBPT and sold under a number of trade names, has been shown to inhibit the urease enzyme that converts urea to ammonia. Added to UAN solutions or to urea, UIs lower the potential for volatilization (loss of NH_3 as a gas) when these urea-containing products are surface-applied. A set of results collected around the Corn Belt showed that applying UI with urea increased yield by 4.3 bushels per acre, and by 1.6 bushels per acre when applied with UAN solution. Under conditions conducive to loss of N from urea (that is, when N treatments without urea produced higher yield than urea alone), adding UI 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 added to urea resulted in yield increases as high as 20 bushels per acre compared to urea alone. These results show the value of using UIs in years when it stays dry after surface application of urea as granules or in solution.

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 increased 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, by injection, or by adequate rainfall (at least 1/2 inch), the potential benefit from adding a UI is low.

One current question is whether or not to use a UI when urea-based materials are surface-applied at sidedress time. Broadcast urea or UAN sprayed on the soil surface (not normally recommended on warm soils) could benefit from a UI, especially if application is during a dry period with little rain in the forecast. If UAN is surface-dribbled near the row (for example, using “Y-Drop” attachments) the question gets more complicated. Dribbling allows some of the UAN to move into the soil, but not very much: applying 15 gallons of 32% UAN (52 lb N) per acre is only about a teaspoon of solution per foot of row, or a half-teaspoon from each tube. That’s little more than enough to wet the soil surface, and volatilization is likely to start quickly in such bands. Protection from adding a UI could be helpful, but may not always last until it rains.

NI + UI: There are currently on the market several urea-based fertilizer products that contain both nitrification and urease inhibitors. Adding both increases the cost per pound of N substantially, and although we have had some good results from using such inhibitor combinations, it is not yet clear whether the benefit over a range of conditions is sufficient to pay the extra cost.

Coatings and ureaform. Urea is available in forms that provide physical or chemical protection against volatilization loss. Physical barriers can include polymer and sulfur coatings, both of which release urea into the soil once the coating has weathered sufficiently. Different thicknesses can provide a range of release timings, and such products may be mixed with uncoated urea to initially provide some plant-available N and avoid early season deficiency. One drawback to coated urea is that intact granules may float, and move with water running down slopes. Chemical barriers can include the use of formaldehyde (the “form” of “ureaform”) 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.

Other “inhibitors:” Spurred in part by emphasis on the 4R approach, a number of products called “inhibitors” have appeared on the market in recent years. Most of these do not fit clearly into one of the categories mentioned above, and it is difficult to know what they actually "inhibit." Laboratory tests for nitrification and urease inhibitors are fairly straightforward and accurate, and some of these products have been shown to inhibit neither nitrification nor urease. Products that do not contain recognized inhibitor ingredients or that contain substantially less inhibitor than recommended may have lower cost, but may not provide the expected protection that comes with recognized, labeled products.

Time of Nitrogen Application

The timing of N fertilizer application is one of the most complex of the 4Rs: each source has a different response to timing, additives such as inhibitors affect "best" timing, and timing can differ by cropping and tillage system. Sound timing decisions can also be undone by unpredictable weather.

Fall NH_3 applications. The ammonium that forms from ammonia in the soil can remain in cold soils for months; this makes ammonia the main N source that can be applied in the fall with relative safety from loss. Ammonium is the first product of urea hydrolysis as well, and the ammonium in ammoniated phosphates (MAP and DAP) can remain in cold soils, although as surface-applied materials, this N is less safe from loss by runoff with fall rains. Ammonia should be applied only in soils and in regions with low N-loss potential. Fall N applications should not be done in soils that are sandy, organic (with low mineral content), very poorly drained, excessively well-drained, or in regions where soil temperatures decline very slowly from 50 °F to freezing, then begin to warm up by late winter. In practical terms, this means that ammonia can be fall-applied once soil temperatures are low enough in most silt loam and silty clay loam soils in central and northern Illinois, bounded on the south by the southern terminus of the last glacier, which roughly follows IL Route 16, from Paris on the east through Jerseyville. This is not a hard line: fall ammonia may work on prairie-derived soils with higher organic matter south of Rt. 16, and may not be appropriate for lower organic matter, lighter-textured soils north of Rt. 16. When in doubt, it's better to wait until spring to apply N.

Ammonia is a versatile and low-cost N source, and has been fall-applied in Illinois for decades. Soils are often in better condition (drier) in the fall than in the spring, so experience less compaction during fall application; fall application moves a major field operation to the period following harvest rather than the spring; and the ammonia price has historically (although not consistently) been lower in the fall than in the spring. Some fertilizer retailers no longer carry ammonia, while others custom-apply ammonia. Despite the advantages, N from fall-applied NH_3 needs to stay in the soil for six to seven months before plant uptake begins, and this increases the risk of nitrification, and so increases the risk of denitrification or leaching losses. Warm spells can reactivate nitrification during the winter and spring; heavy rainfall can move nitrate through the soil to tile lines (highest tile nitrate loads often occur in March through May); and delays in planting can result in weeks in the spring with high N-loss conditions before the crop takes up much N.

Figure 9.10 shows N responses over 18 on-farm trials in central Illinois (corn following soybean) where rates of fall-applied (into cool soils) and spring-applied NH_3 were placed side-by-side. The two curves look very similar: fall- and spring-applied NH_3 produced optimum yields that were identical, at 238 bushels per acre. The amount of N needed to reach this yield, however, was 211 lb per acre for N applied in the fall, but only 194 lb per acre for N applied in the spring. This difference (17 lb N) is on the

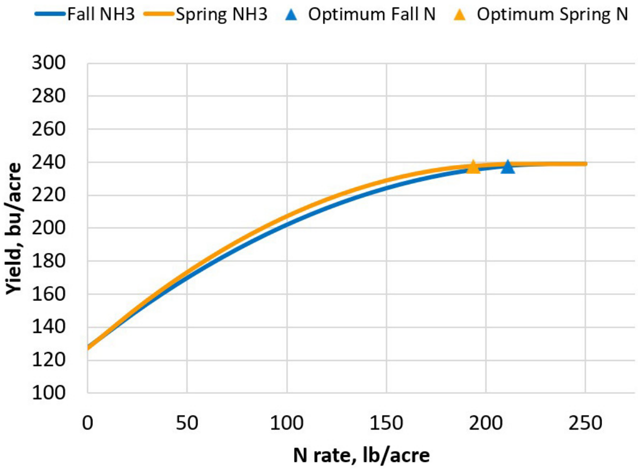


Fig 9.10. Side-by-side comparison of N responses from fall- and spring-applied NH_3. Data are from 18 on-farm N rate trials with corn following soybean, 2015-2020.

same scale as the amount of N loss through tile drainage water measured when N is applied in the fall versus in the spring. While 17 pounds of N per acre may not seem like very much, moving N application from fall to spring on many acres could keep a large amount of purchased N in the soil and available to the crop.

Keeping fall NH_3 application as an option in Illinois requires that it be done carefully. Safety has to be a first priority; handling equipment needs to be maintained, and those who transport and apply NH_3 need to follow rules for safe handling. Fall NH_3 applications should be done only after bare soil temperature at 4 inches (at 10 AM) is below 50 °F, and is forecast to keep dropping. While this temperature is typically reached by about November 1 in northern and central Illinois, the decline in soil temperatures needs to be tracked each year to account for year-to-year variability. Current soil temperatures for different regions of Illinois are available at https://www.isws.illinois.edu/warm/soil/. If soil temperature drops below 50 °F before the end of October, apply if the forecast is for the weather to stay cool.

While the rate of nitrification is significantly reduced as temperatures drop below the recommended 50 °F threshold, nitrification does not stop completely until temperatures reach 32 °F. As shown in **Figure 9.11**, the nitrification rate at 50 °F is about 20% of the maximum rate, and that can mean conversion of as much as 7 or 8% of soil ammonium to nitrate per week. So while the 50 °F temperature for fall application is a reasonable guideline, reaching that temperature does not guarantee that there will be no nitrification. Waiting until later risks wet or frozen fields that may prevent application. Moving application to the spring is usually preferable to risking substantial losses by applying when fall conditions are not favorable.

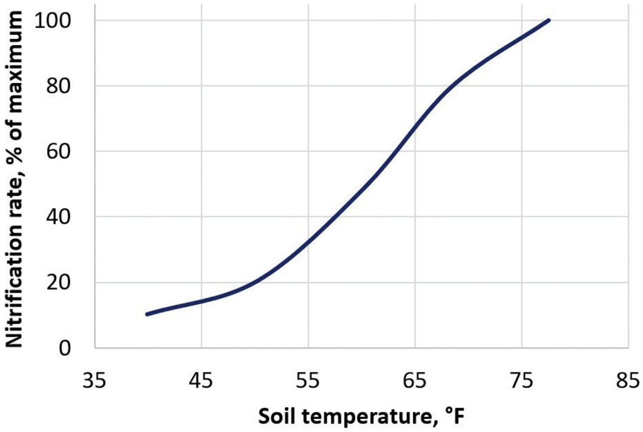


Fig 9.11. Effect of soil temperature on relative rate of nitrate formation (nitrification) in soil. Redrawn from Frederick & Broadbent, 1966.

In Illinois, most of the N applied in late fall is converted to NO_3^- by corn planting time because of nitrification during periods when soil temperatures are above 50 degrees. In years when soils freeze in December and stay frozen until late February, the difference in susceptibility to loss between late fall and early spring (March or April) applications of NH_4^+ sources is typically small. Both are, however, more susceptible to loss than is N applied at or near 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, including N application, 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's needed. 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 that applying liquid or dry N in the fall fails to increase microbial decomposition of corn residue, or to improve N availability for the next crop. Typically, low temperature or dry conditions, not lack of N, limit rates of microbial decomposition of residue in the fall and early spring.

Winter applications. The risk of N loss through volatilization or movement of urea off the field following winter application of urea on frozen soils is too great to consider this a safe practice. 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. Dilute by-product ammonium sulfate solution generated by microbial fermentation processes should also not be applied to frozen soils, due to risk of rain moving the ammonium (and sulfate) off the soil surface. 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 can result in substantial N and P loss, creating environmental problems.

Table 9.1. Yield of corn following soybean with different N forms and application timings. Trials were conducted at six or seven locations in central Illinois each year. Fall NH_3+ N-Serve and spring NH_3 (without N-Serve) were applied at 200 lb N/acre. The Fa-100+P-50+SD-50 treatment was 100 lb N as NH_3 with N-Serve in the fall, 50 lb N as injected UAN at planting, and 50 lb N as injected UAN at sidedress (V6). The 50-P+SD-150 treatment had 50 lb N as injected UAN at planting and 150 lb N as injected UAN at sidedress. Within columns, yields followed by the same letter were not statistically different at p=0.1.

Treatment	2015	2016	2017-18	Average
	- Yield, bu/acre -			
Fall NH_3-200+ N-Serve	234 b	233 a	247 a	241 a
Fa-100+ P-50+SD-50	234 b	233 a	243 a	238 a
Spring NH_3-200	229 b	234 a	246 a	239 a
P-50+SD-150	242 a	235 a	234 b	236 a

Spring (preplant) applications. Relative to fall applications, applying N in the spring decreases the time for nitrification (and potential N loss) before crop uptake. Applying ammonia some weeks before planting lowers the risk of ammonia damage to plants. There are some drawbacks to spring N application: soils in the spring tend to be wet; additional wheel traffic to apply N can result in soil compaction; application can delay planting; and there is a small chance that NH_3 might, if soils dry out after application, cause seedling root damage. Because planting date is so important, it is not advisable to delay planting to apply N, although it is important to apply N in a way that makes it available to corn seedlings soon after emergence. If anhydrous ammonia is applied within a week or two before planting, keeping it away from the planted rows by applying parallel to the rows using GPS should prevent seedling injury.

Sidedress applications. Using sidedressing to apply N fertilizer close to the time of crop uptake lowers the chances of N loss. It also allows late adjustments in rate or source of N, and can save the cost of some N if corn needs to be replaced with another crop. Potential drawbacks of sidedressing include not being able to apply N on time due to prolonged wet periods, not receiving sufficient rain to move surface-applied N into the root zone, and, in some cases, the added cost if high-clearance equipment or aerial application is needed due to delays from wet weather. Sidedressing also increases production costs.

While sidedressing is an appropriate way to apply some of the fertilizer N for corn, the benefits from sidedressing are in terms of operations rather than in lowering N rate or increasing yield. **Table 9.1** shows yields from a study conducted over 27 site-years in highly productive soils in central Illinois from 2015-2018. Yields across all site-years were not affected by time of application, but yields from the "split-sidedress" treatment, with 50 lb N at planting and 150 lb N as sidedressed UAN, showed more variability than the other treatments, and on average did not pay its additional cost. In 2015, with a very wet June, split-sidedress increased yield by 10 bushels per acre compared to the average of the other three treatments. All four treatments produced the same yields in 2016, when the spring was relatively dry. But averaged over 2017 and 2018, split-sidedress N yielded significantly less (12 bushels) than the average of the other three treatments. We think this was because the young plants did not have enough N near the row after emergence, and that N injected between the rows at sidedress did not reach the plant until some yield had been lost. We also saw no advantage from splitting N into three applications (fall/planting time/sidedress); this treatment consistently yielded the same as the two one-time ammonia applications, and would not have paid its additional costs.

Results from another experiment conducted at four locations in central and northern Illinois over 18 site-years are shown in **Figure 9.12**. Compared to applying

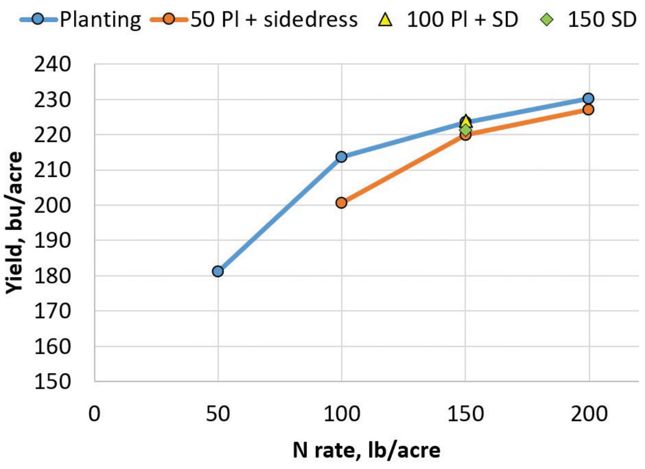


Fig 9.12. Yields by N rate and timing, averaged across 18 site-years, 2014-2018, at four Illinois sites. All N was applied as injected UAN. N rates (50 to 200 lb) were applied at planting; 50 lb at planting + 50, 100 or 150 lb at SD; 100 lb at planting + 50 at SD; and 150 lb N all at SD.

all of the N at planting, splitting N between planting-time and sidedress applications produced lower yields at low N rates, and never produced higher yields at higher N rates. This supports the importance of having some N near the row during early stages of seedling growth, which allows nodal roots to take up N as soon as they emerge, at about growth stage V3. The results also show that sidedressing should not be expected to yield more than the same total amount of N applied early. If the N is placed near the row, 20 to 30 pounds may be enough, but if N is broadcast, more N may be needed to assure having enough close to the row. If N is managed in a way that results in the appearance of N deficiency symptoms during early vegetative growth, yield may be lost that cannot be recovered by subsequent sidedress N applications. Such deficiency may develop earlier in soils with lower organic matter than the soils used in this and other studies.

We have also looked at how timing of a split N application affects yield. In one study, we applied N rates ranging from 0 to 250 lb N/acre at planting in one set of treatments, and in the other set, we applied the same rates but split, with 50 lb subtracted from each rate at planting then added back by dribbling UAN near the row at tasseling. Across eight trials with corn following soybean and four trials with corn following corn, we found no benefit—higher yield or lower N rate to produce the same yield—from keeping back 50 lb of the N to apply late, at tasseling. While late application can be helpful if there is a clear need to apply more N, it is not profitable to plan to apply the last amount of N in this way. Nitrogen uptake rates drop following pollination, and mineralized N can provide most of the crop's N requirement during grainfill. Unless dry soils decrease mineralization and the movement of N (with water) to the roots, corn that has good canopy color at pollination almost never responds to fertilizer N added that late.

In a three-year study at Urbana, Illinois, we either split N application, with 100 lb N/acre applied at planting and the other 100 lb applied at one of eight stages ranging from V3 to R3 (roasting-ear stage); or we applied all 200 lb N at once, at these same stages. Treatments were applied to both corn following soybean and corn following corn. Results in **Figure 9.13** show that, if half the N was applied early, the rest could be delayed to pollination with no loss in yield, and with little loss in yield even when the remaining N was applied after pollination. If no N was applied early, however, yield began to drop once application was delayed to stage V6 or V9. Yield loss accelerated as application was delayed past V9, reaching about 20% by VT and more than 30% R3, with slightly greater losses in corn following corn. We tracked the development of N deficiency in this study using a SPAD meter, and found that SPAD readings (leaf greenness) increased quickly after N applications made as late as R1 or R2, but by then, N deficiency was so pronounced that leaves couldn't recover fully in time to produce full yields. We also found that dry weather following delayed N application postponed recovery, and resulted in more yield loss. Surprisingly, N-deficient plants developed enough kernels for good yields even with N delayed to pollination. That would be less likely in soils with less organic matter or where dry or very wet soil conditions limited N uptake and crop growth.

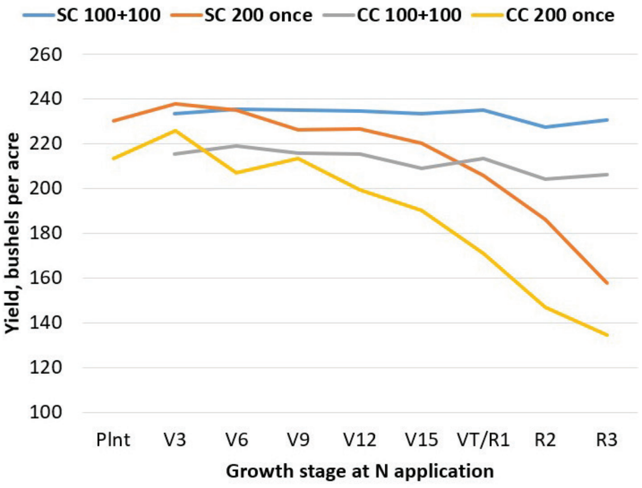


Fig 9.13. Response of corn following soybean (SC) and corn following corn (CC) to timing of N application. N was split, with 100 lb N/acre at planting followed by 100 lb N delayed (100+100); or 200 lb/acre of N was applied at once, at the stage indicated. Data from Nafziger, Yoder, Mathesius, & Carter, Agronomy Journal 113:3665-3674, 2021.

These and other results indicate that the size of the "window" for getting sidedressed N applied can be wide, but it can also be shortened by crop, weather, and soil conditions. Here are some considerations when applying sidedressed N:

- Apply enough N early—at or before planting—so that the crop has adequate N as it begins to determine yield potential in the weeks after emergence. The amount applied early can be as low as 10 to 15% of the total N if it is applied near the row. This should be increased to 20 to 25% of the total if N is broadcast on the surface.

- If soils are relatively warm and rainfall is moderate, mineralization will add to the N supply and lengthen the time to apply sidedress N without yield loss.
- Attempting to "spoon-feed" the crop by repeated applications during the period of rapid N uptake (V7-8 through pollination) is unlikely to be profitable. N in the soil is more readily available than surface-applied N, and dry weather can mean more loss of surface-applied N and delays in uptake of sidedressed N, while periods of wet weather can prevent timely application and can limit the ability of roots to take up N.
- Sidedressing N into tall corn near the time of pollination using high-clearance equipment should be done only when there's reason to expect deficiency following a wet period during vegetative growth. Even then, if the deficiency is due to root uptake problems related to dry or wet soils, adding more N may not boost yield.
- Applying N as late as tasseling in severely N-deficient fields may increase yields (**Figure 9.13**), but the later the application, the more yield will be lost. If the roots have been compromised by standing water, if pollination has already failed, or if the soil is dry, there may be little or no yield response to late application of N.

Nitrogen Fertilizer Placement

Subsurface applications. Nitrogen materials that contain free ammonia (NH_3), such as anhydrous ammonia and aqua ammonia, must be injected into the soil to avoid loss of ammonia in gaseous form. When released into the soil, ammonia dissolves as soon as it reaches water, so it moves farther in dry soil than in wet soil, and farther in coarse-textured soil than in fine-textured soil. On silt loams or finer-textured soils at soil water content suitable for application, ammonia moves 3 to 4 inches away from the point of release, but concentration is far higher near the release point, and is low at the outer part of the zone. For example, if one-third of applied NH_3 stays in the center 1-inch radius cylinder around the release point, one-third moves to the second (1-2") ring, and one-third to the third (2-3") ring, the N concentration in the center cylinder will be three times that in the 1-2" ring and five times that in the 2-3" ring. In sandy loam, ammonia may move 5 to 6 inches from the point of injection. If the depth of application is shallower than the distance the ammonia moves, some ammonia may escape as a gas. This may occur over several days if there is no rain. To minimize this, anhydrous ammonia applied using conventional knives should be placed 8 to 10 inches deep in light-textured soils and 6 to 8 inches deep in heavier-textured soils.

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 not uncommon to see white puffs (water condensed into droplets as the release of ammonia lowers the air temperature) during application, 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 more serious. The ammonia odor indicates the presence of free ammonia, and so tilling will release even more of the ammonia. The only solution is to get enough water (rainfall or irrigation) to dissolve the ammonia in the soil.

Except for soils with very coarse texture, soil can hold large amounts of ammonia, and there is no concern about the capacity of the soil to hold ammonia when typical rates are applied at appropriate soil depths. One "rule" that has been suggested is to apply no more than "CEC times 10" (pounds) of ammonia. In fact, one unit of CEC (of the 10 to 20 units typically measured in silt loam and silty clay loam soils) occupied by ammonium ions is about 280 pounds of N per acre. CEC is increased by clay and organic matter, so is roughly related to how much water—and so ammonia—the soil can hold. But only cations, including ammonium ions that form from ammonia, are held on soil exchange sites measured by CEC. There is no evidence that ammonium ions at normal concentrations have difficulty finding a "home" on these sites.

Equipment companies have recently developed equipment for "high-speed" anhydrous ammonia application. High-speed applicators typically have coulters in front of the knives, they place ammonia only 4 to 5 inches deep, and have an aggressive covering mechanism to improve sealing to limit loss. Combining shallow tillage (field cultivation, disking) 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. In cases where soils following harvest are dry and hard, some have used tillage before ammonia application to loosen the soil to allow deeper application. This may produce more loose soil on the surface, but if that soil is very dry, it may not act as an effective seal on the NH_3. Tillage may also produce clods that cause less uniformity of placement and dispersion of the ammonia in the soil. Fall tillage, especially of soybean stubble, leaves very little surface residue, and greatly increases the chances of wind and water erosion.

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, resulting in “sidewall smearing” that lowers the ability of the soil (after the surface dries out) to trap any ammonia that moves up from the point of release. Ammonia applied in wet soils moves only a short distance from the release point, and so is at a high concentration in the soil, as well as being often distributed more vertically (and so nearer the surface) than laterally. 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. Rainfall after application and before planting usually prevents seedling damage, but corn planted even several weeks after application can be damaged if the soil—especially lighter-textured soils—stays dry. Fall application on wet soils can, if followed by dry winter and spring weather, result in seedling damage, although this is rare, especially in heavier-textured soils common in central and northern Illinois where fall NH_3 application is appropriate. Fall applications are often done at a slight angle to the row direction, which helps keep planting units from dropping into applicator knife tracks, thereby increasing uniformity of depth of seed placement.

One way to avoid potential for ammonia damage to seedlings and to increase uniformity with respect to distance from the row is to apply ammonia between rows, either before or after planting. Every-other-row injection supplies N on only one side of each row, and has been shown to result in yields similar to those from injection between all rows. This decreases the power requirement for a given applicator width, and avoids placing injector knives in wheel tracks, where N losses can be higher due to compaction. A plugged applicator knife leaves two rows without N in this system, so using flow monitors is helpful. With the N rate per unit of travel doubled in this system, injection should be midway between the rows to prevent root damage from high N concentration in the band, and to give each row equal access to the N. To avoid problems of back-pressure that might be created when applying high rates 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 GPS (RTK) and autosteer to both apply ammonia and to plant corn allows ammonia to be applied safely before or immediately after planting.

Subsurface placement of forms of N that do not contain free ammonia is less important for plant safety, but can help minimize the potential for N loss and improve plant availability. Urea–ammonium nitrate (UAN) solutions can be applied on the soil surface, but research has shown that injecting UAN below the surface to avoid contact with crop residue (where urease enzyme is abundant) is superior to broadcast and surface-dribble applications. If UAN is applied as injected sidedress, it is recommended that it be applied 4 inches beneath 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 is usually incorporated with tillage. There has also been some interest in subsurface banding of urea; this practice has been found to be at least as effective as broadcast followed by tillage for incorporation. Subsurface bands should not be placed directly beneath the row, as this can result in yield loss. This is likely the result of urea hydrolysis, which increases initial pH and produces ammonia, which can damage roots growing into the fertilizer band.

One way to assure that corn plants will have N in the soil near the roots during early growth is to apply N in bands near the seed with the planter. This can also be accomplished using early sidedress applications, either injected or surface-banded, although that may mean some weather risk. When planting is into warm soils with N applied before or at the time of planting as broadcast UAN (often with herbicide), there may be little response to planter-placed N. But in soils with low fertility, or when soils are cool and wet before planting or cool at the time of planting, crop growth can be boosted by a nearby supply of nutrients (mostly N, but in some cases P, and perhaps other nutrients.) We can think of early fertilizer N as providing enough nutrients, especially under growth-limiting soil conditions, to get the plant to the point where soils are warmer and root systems large enough to supply the plant's nutrient needs.

There has been some renewal of interest in planter-applied fertilizer in recent years. Equipment to do this is an option on many planters, along with large tanks to minimize refilling delays during planting. Placing fertilizer "in-furrow"—in the same trench as seed is planted—is an option, but the amount of N that can be safely placed with the seed is limited: in-furrow N should not exceed 10-15 pounds per acre, and less if other cations such as potassium are included in the fertilizer. Urea should not be applied in-furrow. Applying more than 10 to 15 lb of N at planting requires moving the application zone away from the seed. This is usually done using separate disk-openers that place fertilizer "2×2" (2 inches to one side and 2 inches deeper than the seed row.) This adds substantial weight to planters and requires a pump and distribution system. Another option uses small knives without disk openers to place liquid fertilizer off to one or both sides of the seed in the furrow, or a device that runs in the bottom of the seed furrow that dribbles fertilizer underneath or to the sides of the seed.

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 if surface application is followed by an extended period without rain, yields are likely to be lower than with injected UAN or ammonia. Rainfall is necessary to move N to the roots, and urease inhibitor can also begin to degrade on the surface of dry soils.

Dribble application of UAN solutions in concentrated bands on the soil surface can lower the potential for N loss compared with an unincorporated broadcast application, by increasing the amount of liquid per unit of application area. This allows more of the solution to enter the soil, and lowers the exposure to urease. Such advantages are small and inconsistent, however, and dribble applications can still 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 of UAN up to tasseling by using high-clearance sprayers with drop nozzles. It is important to keep the UAN off the plants—especially the green, active leaves above the third or fourth leaf below the ear leaf—in order to avoid leaf damage that can reduce yield. A more common method of surface-applying sidedressed UAN in recent years has been surface-dribbling it near the rows using devices that stream or dribble rather than spray UAN. Placement near the rows means that the UAN on the surface is shaded, rain or dew that runs down the stalks can help move it into the soil, and roots are shallower near the row, so the N has a shorter distance to travel to the roots.

In fields that have not received the full amount of N or where there may be insufficient N left after heavy rainfall, aerial application of dry urea can increase yield. Due to its expense, aerial application should be considered an emergency treatment in situations where the crop is tall and soils are too wet to allow application using high-clearance equipment. Urea that falls into the whorl can cause some visual symptoms (typically a thin band of dead tissue on leaf edges), but is generally considered safe at rates less than 125 pounds of N (about 275 pounds of urea.) Using an extended-release form of urea such as ESN increases the cost and, more importantly, may delay the release of some of the N until after the plant no longer has need for it. Aerial application of foliar forms of N fertilizer such as urea-formaldehyde or urea solution is safe, but is costly and typically provides less than 10 lb of N, so may not meet the crop's need.

Developing a Nitrogen Management System

Given the complexities in choosing N rate, source, timing, placement, and additives, it's no surprise that there are almost as many N management systems in use in Illinois as there are corn producers. These systems have evolved over time, in response to changes in prices, equipment, hybrids, products, and to the need to lower the amount of N released into the environment. Following is a series of points to consider when evaluating an existing N management system, and when considering how to develop or modify a system. This is based on the "4Rs" with some refinements. (See below)

In designing or evaluating an N management program, keep in mind that the practices that are on the 4R list based on principals discussed in this chapter often can be "right" in principal but may still not always work well in practice. How well a practice works in the field is dependent on soils and weather, and may also depend on how "right" other factors such as tillage, hybrid, planting, and weeds are managed in that field that season. In other words, there is some slippage between what makes the list as "right" practices in N management and what might be successful or profitable practices in a given field in a given season. As an example, NH_3 with a nitrification inhibitor is certainly the "right" form of N to apply in the fall, in fields that meet criteria (texture, temperature, and climate) for fall application. But under ideal conditions of persistently cold soils through the winter and limited spring rainfall, the inhibitor may not be needed, and may not pay for itself. The same may be true for "right" combinations of forms of N and how and when they are applied. Nitrogen rate (MRTN) is perhaps the most "solid" of the 4Rs, given that it is based on many trials done in different fields and in different seasons. Even so, it is hardly ever the exact N rate needed for a given field. That doesn't make it "wrong," though; any practice based on solid principles and adequate research can be considered "right" no matter how it happens to perform in a given field and growing season.

Decision	Importance		Considerations
	Economic	**Environmental**	
N rate	high	high	• Basing N rates on yield goal as we did in Illinois into the early 2000s no longer works: research shows that corn grown in soils with moderate to high organic matter requires much less fertilizer N than this approach suggests. • The MRTN approach is a rational system based on N response data from trials in Illinois. • Using N rates high enough to eliminate the chance of not having enough N would result in large economic and environmental losses nearly every year.
N source	moderate	moderate	• Almost any N source can be used to provide N to the corn crop. Sources other than organic sources are based on ammonia produced via the Haber-Bosch process, with cost tied to the price of natural gas. • Prices and price differentials among commercial fertilizer sources are fluid: NH_3 is usually the lowest-cost per pound of N, but other sources (urea, UAN) may compete depending on world supply and demand. • Costs for storage and application, as well as safety concerns with anhydrous ammonia, has led some fertilizer retailers and producers to use other fertilizers, most often UAN solutions.
N fertilizer additives	moderate	low-moderate	• Urease inhibitors slow, but do not eliminate, the release of NH_3 from urea, and so lower the volatilization (loss) of N from urea on the soil surface; subsurface placement of urea or UAN eliminates the need for a urease inhibitor. • Nitrification inhibitors (nitrapyrin, pronitridine) inhibit the bacteria that convert ammonium (NH_4^+) to nitrate (NO_3^-); NH_4^+ is held on soil exchange surfaces, and NO_3^- is not, so slowing this process lowers the susceptibility to N losses. • Nitrate in fertilizer is subject to immediate movement in the soil and so to loss, regardless of whether or a nitrification inhibitor is used. • Inhibitors need to stay with the fertilizer materials and to stay active in the soil; neither of these is guaranteed. • There are other "inhibitors" on the market, most without defined activity

N timing	moderate	moderate	• The first consideration in timing is to assure that small plants have access to some N during the period following seedling emergence, as yield potential is being formed. • The second consideration is to have enough N available (in the soil where the roots are growing) during the period of rapid N uptake, from about V7 to pollination. • Fall ammonia application produces yields similar to spring application, but may need more N to reach that yield. Applying only part of the N in the fall is an option that lowers loss potential, but usually at increased cost. • Splitting spring-applied N into early and sidedress applications may be logistically sound, but has not been shown to lower needed N rates or to increase yields compared to applying all of the N early. Making several N applications during vegetative growth is likely to add costs without adding yield. • Nitrogen can safely be applied to tall corn, but doing this after purposely lowering the rate of early N provides little benefit; it should be reserved for emergencies such as failure to get N applied earlier or adverse environmental conditions.
N placement	low-moderate	low-moderate	• Products with free ammonia (NH_3 or aqua ammonia) must be injected into the soil to prevent loss. • Urea and UAN solution are susceptible to loss from urea hydrolysis if they remain on the soil surface without rainfall to move them into the soil. • Equipping planters to apply some N near the seed row helps to assure early access to N that seedlings need, but may not consistently increase yield. • For sidedressed UAN, injection is the safest way to prevent loss, but surface-banding near the row may improve plant access.
Risk management	low-high	low-high	• The risk of yield loss from "lost" N or unusually high N requirements is much lower than many people believe; the largest source of yield loss in saturated soils is usually root damage. • Corn without fertilizer N typically yields 40 to 60% as much as fully-fertilized corn; although the crop needs fertilizer, it does not depend on fertilizer for all of its N. • Crop insurance is often more economically (and always more environmentally) effective as a way to deal with rare instances of yield loss due to insufficient N than is adding more N than is adding more N fertilizer.
Hybrid choice	moderate	low	• Current hybrids vary in yield potential, and so differ in the amount of N they take up, but these differences are not very consistent among fields and years. • Hybrids vary in response to N, but these differences do not appear to be consistent enough to warrant different N management programs for different hybrids.
Tillage	moderate	moderate	• Tillage can help lower the amount of compaction and increase root access to soil water and N, but tillage before planting can also accelerate loss of soil water, which under dry conditions might restrict access to water and N. • Tillage helps soils to warm earlier, which raises the early N mineralization rate. • No-till can work well for corn, but if no-till soils dry out, root access to surface-placed N might be restricted.