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Nitrogen

Richard B. Ferguson
UNL Professor of Agronomy

Nitrogen (N) is one of the most abundant elements on earth, and after carbon (C), hydrogen (H), and oxygen (O), the element living creatures need most. The atmosphere over each square foot of the earth's surface—which is 78% dinitrogen (N_2) gas—contains approximately 6,000 pounds of nitrogen. However, the majority of the earth's nitrogen (98%) is in rock, sediment, and soils. The amount of nitrogen in rocks is about 50 times more than that in the atmosphere, and the amount in the atmosphere is approximately 5,000 times more than that found in soils (Stevenson, 1982).

Biological fixation of nitrogen and atmospheric deposition are the primary means by which nitrogen is added to soil. (Fixation is the conversion of dinitrogen gas—which is chemically unreactive—to nitrogen combined with other elements, such as oxygen or hydrogen, which can readily undergo chemical reactions.) The atmosphere contributes approximately 11.4 pounds of nitrogen per acre to soils annually (Stevenson, 1982). Biological nitrogen fixation accounts for 8.2 of the 11.4 pounds of nitrogen per acre per year. Biological nitrogen fixation occurs symbiotically (dinitrogen-fixing bacteria, such as *Rhizobium*, in conjunction with legumes) and non-symbiotically (free living organisms such as photosynthetic bacteria, blue-green algae, and free-living *Azotobacter* species). The balance, 3.2 pounds of nitrogen per acre per year, consists of various sources of ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-) deposited in precipitation. The amount of nitrogen added each year from atmospheric deposition varies considerably with climate and proximity to industrial sources of atmospheric nitrogen, but generally it is too small to significantly affect crop production.

Forms of Nitrogen in Soil

In addition to nitrogen occurring as atmospheric dinitrogen gas in soil pore spaces, nitrogen occurs in both organic and inorganic forms in the soil.

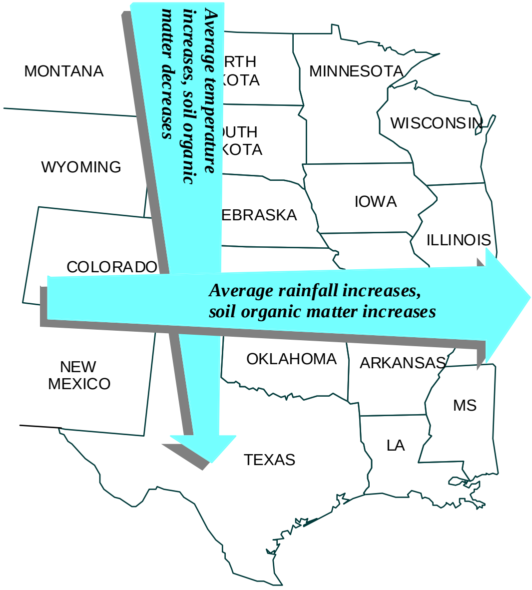
■ *Organic nitrogen*

Several organic compounds (compounds containing carbon), grouped into humic, fulvic, and amino acids, amino sugars, and other proteins, compose the organic fraction of nitrogen in soil. Soil organic matter exists as decomposing plant and animal residues, relatively stable products of decomposition-resistant compounds, and humus. Nitrogen has accumulated in these various organic fractions during soil development.

Organic matter formation and stability is largely related to long-term moisture and temperature trends. With higher average temperatures, soil organic matter decreases. As moisture increases, soil organic matter increases. Higher temperatures lead to more rapid and complete organic matter decomposition to soluble products which can leach from soil. Increasing moisture causes more plant growth, resulting in more organic residue. Trends of moisture, temperature, and organic matter in soils in the Midwest and Great Plains are shown in Figure 1-1.

FIGURE 1-1

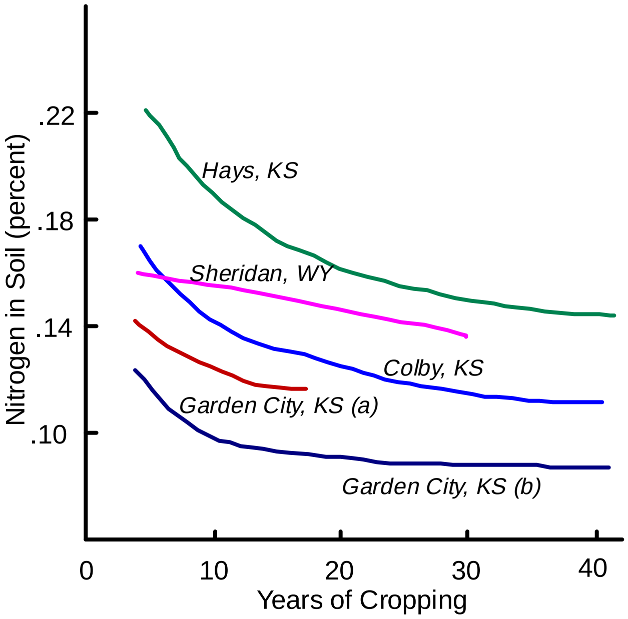
Soil organic matter in relation to temperature and moisture. Soil organic matter decreases with higher average temperatures. It increases as moisture increases.



Through thousands of years of development, soils in the Midwest have accumulated significant quantities of organic matter; yet organic matter levels have declined by cultivating virgin soils, thereby increasing organic matter oxidation and decreasing soil organic matter nitrogen through crop uptake (Figure 1-2). Soils that once contained 4% to 5% organic matter may contain only 1% to 2% after 50 years of cultivation. However, soils under cultivation in the Midwest have, for the most part, reached a new equilibrium of organic matter levels with widespread commercial fertilizer use. Reduced tillage techniques in combination with legume rotations and judicial fertilizer use may increase organic matter levels with time.

FIGURE 1-2

The influence of long-term cropping on organic nitrogen in soils in the Midwest (adapted from W.J. Hase et al., 1957; Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments; Technical bulletin 1167, USDA, Washington D.C.).



The nitrogen cycle

Ammonium and nitrate are the predominate inorganic forms of nitrogen in soils. Ammonium exists as exchangeable and nonexchangeable forms. Nitrite and nitrous oxide (N_2O) are present in soil in lesser quantities. Plants normally use nitrogen in only the ammonium and nitrate forms. Nitrite is actually toxic to plants. The nitrogen cycle (Figure 1-3) shows reactions that various inorganic nitrogen compounds undergo in soil. The nitrogen cycle begins with nitrogen in its simplest stable form, dinitrogen (N_2), and follows it through the processes of fixation, mineralization, nitrification, leaching, plant assimilation, ammonia volatilization, denitrification, and immobilization.

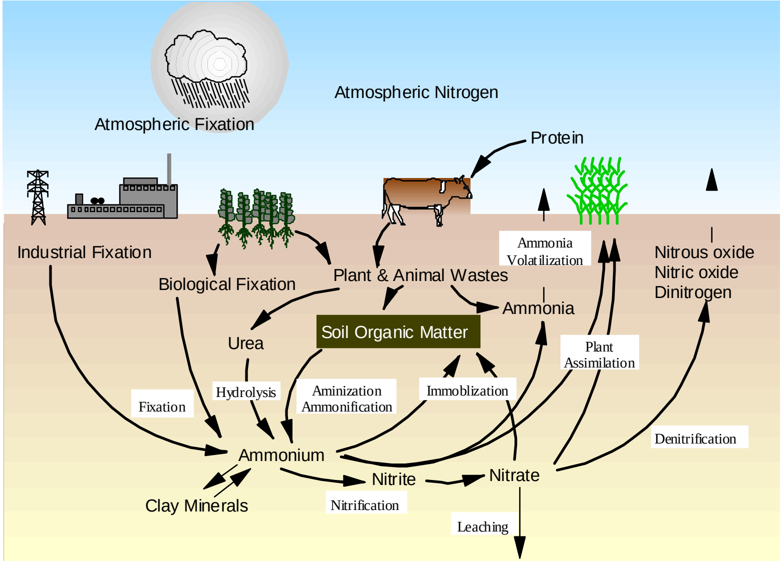


FIGURE 1-3

The nitrogen cycle.

Fixation

As described earlier, fixation is the process of converting dinitrogen gas to chemically reactive forms—where nitrogen combines with other elements such as oxygen, hydrogen and carbon. Energy is required to convert dinitrogen to ammonia or other forms of fixed nitrogen. Lightening fixes nitrogen into various oxides that rain and snow deposit, typically less than 10 pounds of total nitrogen per acre per year. Bacteria can convert nitrogen to organic forms through fixation. Fixation can occur either in free-living organisms or symbiotically in association with legumes. Nitrogen is also fixed industrially through several processes using fossil fuel as an energy source.

Mineralization

Once nitrogen is fixed, it is subject to several chemical reactions which can convert it to different organic or inorganic forms. Mineralization occurs in soil as microorganisms convert organic nitrogen to inorganic forms. The first step of mineralization is called aminization, in which microorganisms (primarily heterotrophs) break down complex proteins to simpler amino acids, amides, and amines. *Heterotrophic* microorganisms require preformed organic compounds as sources of carbon and energy. *Autotrophic* microorganisms can derive energy from the oxidation of inorganic elements or compounds such as iron (Fe), sulfur (S), ammonium, nitrite, or from radiant energy; they derive their carbon from carbon dioxide (CO_2). For example, urea is an amide added directly to soil either in animal urine or as commercial fertilizer.

EQUATIONS 1-1 AND 1-2

Mineralization.

Aminization: $Proteins \rightarrow R^{*}\text{-}NH_2 + CO_2$

(*R designates a carbon chain of indefinite length.)

Ammonification is the second step of mineralization in which amino (NH_2) groups are converted to ammonium. Again, microorganisms (primarily autotrophic) accomplish this action.

Ammonification: $R\text{-}NH_2 + H_2O \rightarrow NH_3 + R\text{-}OH$

Nitrification

Microbial activity is also responsible for the two steps of nitrification. *Nitrosomonas* (obligate autotrophic bacteria) convert ammonium to nitrite. Nitrification inhibitors, such as nitrapyrin (N-Serve®) or dicyandiamide (DCD) interfere with the function of these bacteria, blocking ammonium conversion to leachable nitrate. The second step of nitrification occurs through *Nitrobacter* species, which convert nitrite to nitrate. This step rapidly follows ammonium conversion to nitrite, and consequently nitrite concentrations are normally low in soils.

EQUATIONS 1-3 AND 1-4

Nitrification.

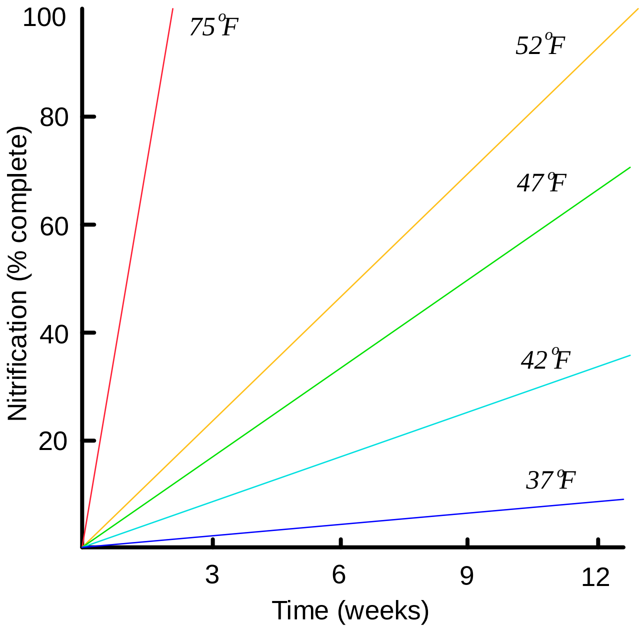
$$2NH_4^{+} + 3O_2 \rightarrow 2NO_2^{-} + 2H_2O + 4H^{+}$$

$$2NO_2^{-} + O_2 \rightarrow 2NO_3^{-}$$

Mineralization and nitrification are influenced by environmental factors that affect biological activity such as temperature, moisture, aeration and pH. Nitrification, for example, occurs very slowly at cold temperatures and ceases once the temperature declines below freezing (Figure 1-4). The rate increases with increasing temperature until the point at which bacterial viability is reduced, (around 95^{o} F to 100^{o} F) and then nitrification begins to decline with increasing temperature. Moisture is necessary for microbial function in both the mineralization and nitrification processes. Excessive moisture limits oxygen availability, reducing mineralization and nitrification rates, which, perhaps, lead to anaerobic conditions in the soil. Rates of mineralization and nitrification proceed most rapidly at pH levels near 7, and decline as soils become either excessively acid or alkaline.

FIGURE 1-4

Reductions in nitrification based on temperature.



Denitrification

Denitrification—the conversion of nitrate to various gaseous forms of nitrogen which can be lost to the atmosphere (nitric oxide, nitrous oxide, dinitrogen)—occurs under oxygen-limiting conditions when anaerobic bacteria use nitrate in respiration in the presence of a carbon source such as organic matter.

Low areas of fields that are subject to ponded water for sustained periods during the irrigation season often exhibit nitrogen deficiencies related to denitrification losses.

EQUATION 1-5

Denitrification.

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Denitrification losses from saturated soil will vary with temperature and the amount of carbon (organic matter) available. Table 1-1 illustrates the effect that time and temperature can have on potential nitrogen losses from denitrification.

TABLE 1-1

Denitrification rates from saturated soil*.

Time	**Temperature**	**N loss**
days	*degrees F*	*percent*
5	55 - 60	10
10	55 - 60	25
3	75 - 80	60

*Denitrifcation loss will be less with soils having less than 1% organic matter.

Ammonia Volatilization

Ammonia (NH_3) loss to the atmosphere is called ammonia volatilization. Technically, ammonia volatilization is different from gaseous loss of applied anhydrous ammonia, which is not retained in the soil. Instead, ammonia volatilization occurs when ammonium in the soil, because of pH, is converted to ammonia, which can be lost as a gas. Ammonia volatilization is normally only a problem in Nebraska with fertilizers containing urea, such as urea or urea ammonium nitrate (UAN) solution. Urea in soil is decomposed, or hydrolyzed, enzymatically by the enzyme urease to ammonium.

EQUATION 1-6

Ammonia volatilization.

$$CO(NH_2)_2 + H^+ + 2H_2O \xrightarrow{\text{urease}} 2NH_4^+ + HCO_3^-$$
$$+ H^+ \leftrightarrow CO_2\uparrow + H_2O + NH_4 \leftrightarrow NH_3\uparrow + H^+$$

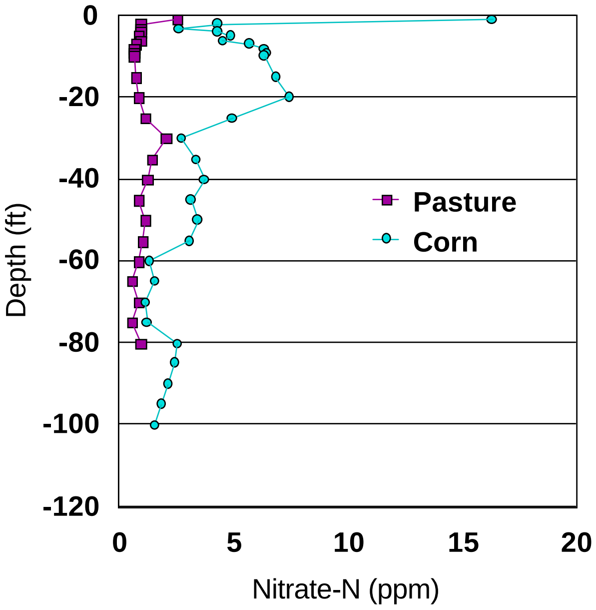
Ammonia loss can be significant where the producer surface-applies fertilizers containing urea without incorporation, particularly if significant amounts of residue are present and conditions are warm and moist. The amount of total nitrogen loss from fertilizers containing urea due to ammonia volatilization can vary considerably, from no loss to 50% or more of the applied nitrogen. Typical losses from urea broadcast to a silt loam soil in the spring, without rain for at least a week following application, may be in the range of 10% to 20% of the applied nitrogen. The potential for ammonia volatilization is influenced by soil moisture, temperature, soil pH, soil buffering capacity, urease activity, residue cover, precipitation, wind and other factors. Warm, moist soil with heavy residue and urea broadcast to the surface are ideal conditions for ammonia loss. Precipitation or irrigation of ½ inch or more is adequate to move urea far enough into the soil to minimize volatilization loss potential.

FIGURE 1-5

Urea granules on corn residue.

FIGURE 1-6

The effect of nitrogen fertilization and irrigation on vadose zone nitrate levels (Upper Big Blue Natural Resources District - Mid-Nebraska Water Quality Demonstration Project).



Leaching

In order for leaching to occur, nitrogen must be in a water soluble, mobile form and abundant enough to transport nitrogen through the soil. Although urea and nitrite are mobile, neither exists in significant concentrations in soil. Nitrate is the form of nitrogen most susceptible to leaching loss. Nitrate leached below the root zone (four to six feet) of most agronomic crops will eventually leach downward until it reaches a saturated zone, either an aquifer or aquitard. Nitrate leached below four to six feet is generally unrecoverable by most crops except deep rooted species such as alfalfa. The rate of nitrate movement downward depends on a variety of factors, including soil texture, precipitation and irrigation amounts, crop uptake of water and nitrate, and so on. Nitrate leaching from relatively sandy soils overlying coarse-textured vadose zones and shallow aquifers (such as in the Central Platte Valley) can leave the root zone and enter the aquifer in a matter of months, while nitrate leaching from upland, silt loam soils overlying aquifers 100 feet or more below the surface can take 25 to 30 years to reach the aquifer.

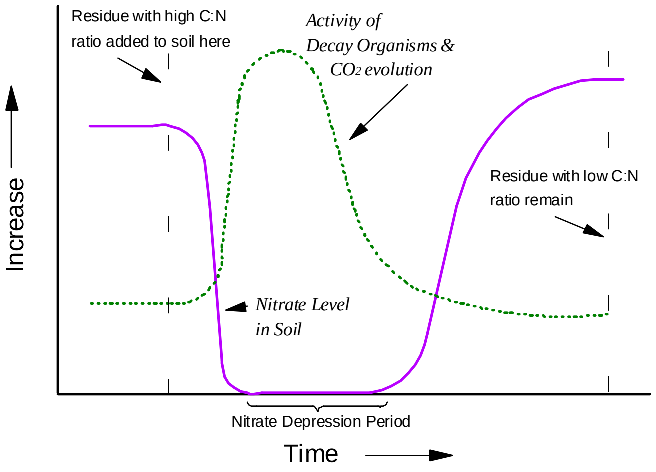
Figure 1-6 shows the nitrate levels in the vadose zone of a 35-year continuous irrigated corn field and a native grass pasture. In this example from Seward County, the native grass pasture contains 307 pounds of nitrate-nitrogen per acre to a depth of 80 feet, while the continuous corn field contains 1,224 pounds of nitrate-nitrogen per acre to a depth of 100 feet.

Immobilization

Immobilization, or the temporary tying up of inorganic nitrogen by soil microorganisms decomposing plant residues, is a recycling process. Immobilized nitrogen will be unavailable to plants for a time, but will eventually become available again as residue decomposition proceeds and populations of microorganisms decline (Figure 1-7). Fertilizer nitrogen immobilization can be reduced by placing fertilizers below crop residues, instead of incorporating fertilizer into the soil with residue. The producer can accomplish this most directly by knifing in anhydrous ammonia or solutions.

FIGURE 1-7

Levels of nitrogen available to plants based on microbial decomposition.



The duration of the nitrate depression period during immobilization is dependent on environmental factors such as moisture and temperature and the carbon-to-nitrogen (C:N) ratio of the residue. Soil organic matter contains an average of approximately 50% carbon and 5% nitrogen. This ratio (10:1) is relatively constant for organic matter. The C:N ratio of plant residue ranges from 10:1 for young leguminous plant tissue to as high as 200:1 for straw of some grains. Plant tissues low in nitrogen generally are more resistant to decomposition and require a longer time before the nitrogen is available to plants.

TABLE 1-2

Typical carbon-to-nitrogen ratios for selected organic materials.

Source	C:N ratio
Organic matter in undisturbed top soil	10:1
Alfalfa	13:1
Cattle manure	20:1
Corn stalks	60:1
Wheat straw	80:1
Coal and shale oil	124:1
Oak	200:1

FIGURE 1-8

Field example of immobilized urea (chlorotic area where urea was incorporated with crop residue) next to NH_3-injected field (darker green area).

When a high C:N ratio plant residue is incorporated into the soil, microbial decomposition of the residue starts. Microorganism populations increase rapidly, evidenced by increased release of CO_2 leaving the soil through respiration. The microorganisms take nitrogen from the soil for synthesis. Consequently, for a period of time the concentration of inorganic nitrogen in the soil declines and may be deficient for plant growth. As residue decomposes, the C:N ratio becomes narrower. At a ratio of approximately 17:1, nitrogen becomes available for plant use. Decomposition continues until the ratio is approximately 10:1 to 15:1.

Plant Assimilation

Plants use nitrogen in primarily the nitrate or ammonium forms. If any preference exists, it is usually for ammonium early and nitrate late in the growing season. Research has shown that growth is optimized with a mixture of both ammonia and nitrate, with ammonium used preferentially for synthesis of amino acids and proteins. Some plants can also directly use urea (Harper, 1984), although in most cases urea-nitrogen will hydrolyze to ammonium-nitrogen prior to uptake. In order to take up nitrate-nitrogen, plants require that nitrogen move with water toward the root—a process called mass flow. Consequently, nitrate-nitrogen that has moved below the root zone has potential to move up into the root zone, as surface horizons of soil dry out and crops use water deeper in the profile. Conversely, plants may exhibit symptoms of nitrogen deficiency even though the soil contains adequate amounts of nitrogen, if moisture and consequently mass flow of nitrogen, is limited.

Nitrogen Fertilizer Management

Nitrogen is a nutrient easily lost from soil through several pathways, as already discussed. Consequently, plants use nitrogen most efficiently if the producer applies it as close as possible to the time of crop uptake. Ideally, this might include multiple applications of nitrogen during a growing season. Center pivot irrigation systems equipped for fertigation and high clearance applicators are two methods to accomplish multiple nitrogen applications. The use of center pivot irrigation systems for fertigation also facilitates the use of a chlorophyll meter to detect nitrogen deficiency and apply nitrogen according to crop demand. Sidedress nitrogen application also allows for more efficient fertilizer use since the producer applies nitrogen close to the period of maximum nitrogen uptake for corn and sorghum. Nitrogen application prior to or at planting is still more efficient than fall application for row crops such as corn and grain sorghum. Fall application may still be a viable option on some soils for row crops. In that case, the producer should only apply anhydrous ammonia in the fall (because it initially is not leachable), if soils are fine-textured and when the soil temperature is 50° F, on average, for a week or longer. With either fall or spring preplant application, nitrification inhibitors, such as N-Serve® or DCD, help reduce the potential for leaching or denitrification losses of nitrogen. For nitrogen application to winter wheat, late winter or early spring topdress application allows the producer to assess moisture status and crop condition before deciding on the appropriate nitrogen rate.

FIGURES 1-9 AND 1-10

Nitrogen fertilizer application timings: preplant (top) and at planting (bottom).

FIGURES 1-11 AND 1-12

Nitrogen fertilizer application methods: sidedress (top) and broadcast (bottom).

Crops use nitrogen more efficiently when it is placed beneath the soil surface. Broadcasting nitrogen on the soil surface increases the likelihood that some nitrogen will be lost due to ammonia volatilization or runoff. This is one reason why anhydrous ammonia, which must be injected, sometimes appears to be a better nitrogen source than urea or UAN solution, which can be applied on the soil surface. In general, as long as nitrogen fertilizers are correctly applied, all are agronomically equal. If the farmer must apply nitrogen fertilizers to the soil surface, he can increase efficiency by banding, which concentrates the fertilizer and reduces soil/ fertilizer contact. Sprinkler irrigation water application is another efficient method, as long as application rates are not excessive.

The primary nitrogen fertilizers available in Nebraska are anhydrous ammonia (82% nitrogen), urea (44% to 46% nitrogen), UAN solution (28% to 32% nitrogen), ammonium nitrate (33% to 35% nitrogen), and ammonium sulfate (21% nitrogen). Other fertilizers can contain significant amounts of nitrogen, but they are used primarily as sources of nutrients other than nitrogen. All of the above are effective fertilizers when properly applied. Anhydrous ammonia is historically the least expensive nitrogen fertilizer, but it requires injection into the soil, which is a more expensive application method than broadcasting or surface banding. Tillage, irrigation and rainfall soon after application reduces the potential for significant ammonia loss from urea fertilizers. A recent management option for urea fertilizers is the urease inhibitor Agrotain®. This material contains the active ingredient N-(n-butyl) thiophosphoric triamide (NBPT), which inhibits the function of the urease enzyme (responsible for breaking urea down into ammonium and potentially ammonia) for up to several weeks, depending on temperature. This delay in decomposition of urea can increase the chances of rain or tillage moving the urea into the soil where it is protected from volatile loss. Using a urease inhibitor reduces the risk of applying urea fertilizers on the surface in minimum-tillage, high residue conditions which otherwise have considerable potential for ammonia loss. Urease inhibitors, like nitrification inhibitors, will not guarantee a yield increase every year, but they can protect against yield reductions in years when climatic conditions are conducive to nitrogen loss.

Nitrogen Accounting and Credits

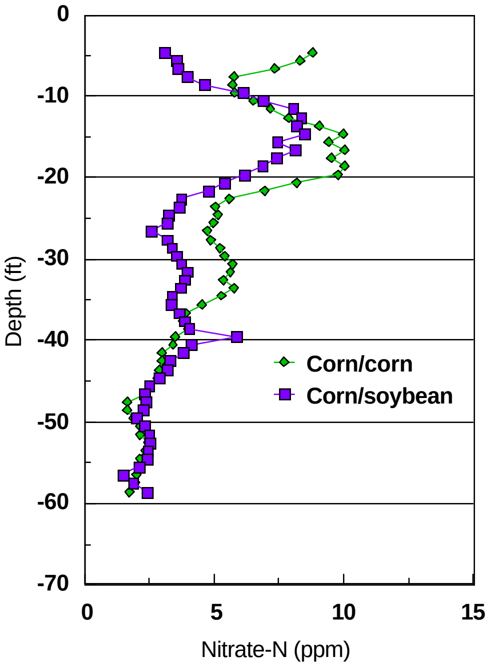
Efficient nitrogen fertilizer use requires that the producer gives proper credit for sources of nitrogen other than the fertilizer before selecting the appropriate nitrogen rate. Significant sources of nitrogen include soil residual nitrate (determined by deep soil sampling), manure and organic materials (determined by analyzing a sample of the material), legumes (determined according to the previous crop), and irrigation water (determined by irrigation water sampling). Actual nitrogen credits from these sources can vary widely, but in many cases the nitrogen fertilizer rate can be reduced significantly after accounting for these credits. More information on nitrogen accounting is available in the resources listed at the end of this chapter.

Crop Rotations

Whenever possible, the farmer should practice rotating crops such as corn and grain sorghum with crops that intensively use nitrogen such as soybeans, alfalfa and clover. Aside from reducing fertilizer nitrogen requirements, crop rotations provide other proven benefits in terms of reduced insect and weed infestation levels and disease pressure. The nitrogen credit to corn following soybeans is not only because of the additional nitrogen in the soil from the soybeans, but also because the low C:N ratio of soybean residue immobilizes less soil nitrogen, and mineralizes nitrogen from residue sooner the following season; this allows more soil nitrogen to be available to the subsequent crop. Legumes such as alfalfa or clover that are tilled in prior to planting corn do increase the level of available nitrogen in the soil as the legume residue mineralizes. Legumes are efficient scavengers of soil nitrate, and can substantially reduce soil nitrate levels following corn. Figure 1-13 illustrates the effect of an annual corn-soybean rotation on the amount of nitrate in the vadose zone. This example, from vadose zone soil cores taken in 1992 from the Long-Term Tillage Study at the University of Nebraska South Central Research and Extension Center Farm, shows the effect of implementing a corn-soybean rotation in 1984.

FIGURE 1-13

The effect of an annual corn/soybean rotation on the amount of nitrate found in the vadose zone (A. Katupitiya, 1995; Long-term tillage effects on nitrate accumulation and movement and denitrification in the root and intermediate vadose zones; Ph.D. dissertation, University of Nebraska).



Monitoring Crops for Nitrogen Deficiency

Nitrogen deficiency in plants is fairly easy to diagnose because of the unique symptoms expressed in plants: initial yellowing of lower leaves with the leaf tip and margin affected first. However, by the time such deficiency symptoms become evident, yield reduction may have occurred, depending on the stage of growth. The chlorophyll meter is a relatively new tool for nitrogen management which can detect developing nitrogen deficiencies before they are visible, and before they can significantly reduce yield. Other recent methods for detecting nitrogen stress are the lower stalk nitrate test (which indicates after the season if the nitrogen supply to the crop has been adequate or limiting), and remotely sensed imaging (which can detect developing nitrogen stress similar to the chlorophyll meter). The producer may be able to use a chlorophyll meter or remote sensing to detect nitrogen stress in time to correct a deficiency during a growing season, and then apply necessary nitrogen through high clearance applicators or via fertigation through center pivot irrigation systems.

Figures 1-14 and 1-15

Nitrogen deficiency symptoms in corn.

Summary

Nitrogen is usually the nutrient most limiting to cereal crop production in Nebraska. It is subject to a variety of transformations in the soil. Some of these transformations are necessary to convert nitrogen into forms which plants can use. Other transformation or transport processes limit the availability of nitrogen to plants by converting nitrogen into forms which plants cannot use, or moving nitrogen away from the root zone.

Management factors, such as choice of nitrogen source, nitrogen placement method, irrigation management, tillage and residue management all can affect how efficiently crops use nitrogen.

Resources

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