FERTILIZER NITROGEN USE EFFICIENCY

Introduction

Nitrogen is both abundant and scarce at the same time: It makes up about 78% of our atmosphere, but this nitrogen is in a form that is not usable by plants or animals. Only after it is converted from the highly stable N_2 form into ammonium (NH_4^+) or nitrate (NO_3^-) is it available for uptake by plants. It is only within the last century that large-scale industrial fixation of nitrogen by the Haber-Bosch process has been available, but it has grown to the point where half of the global food production is attributed to nitrogen fertilizers created through the Haber-Bosch process (Ladha et al., 2005).

With this increase in available N, there are also increased losses of N to the environment. Nitrogen in the wrong place can be harmful to groundwater (nitrate contamination of drinking water), surface water (harmful algae blooms and hypoxia in marine environments), forests (species shifts from increased N supply from atmospheric deposition), air (smog and "white haze" from ammonia combining with car exhaust), and climate (nitrous oxide is one of the "big three" greenhouse gases, along with carbon dioxide and methane).

Plant-available forms of nitrogen are predominantly nitrate (NO_3^-) and ammonium (NH_4^+). This means that the nitrogen must be in these forms for the plant to use the nutrient. Most chemical fertilizers are in these forms (i.e. calcium nitrate, ammonium sulfate, etc.) or are quickly converted into a plant-available form. On the other hand, most organic-based fertilizers (i.e. manures, composts, digestates, etc.) must be converted by soil microbes into a plant-available form first. The NH_4^+ and NO_3^- from both chemical and organic fertilizers are identical to plants or environmental losses (Figure 1). Organic-based fertilizers are often called "slow-release" fertilizers as the conversion from organic-N to plant-available N occurs over time (days, weeks, months, sometimes years).

Sometimes applied nitrogen fertility is lost – this can be due to application exceeding crop needs, soil conditions (i.e. too cold and wet, or too hot and dry), or a number of other environmental and biological conditions. These losses may be down through the soil profile, ultimately leaching into the groundwater, or up into the atmosphere as ammonia or nitrous oxide (a greenhouse gas).

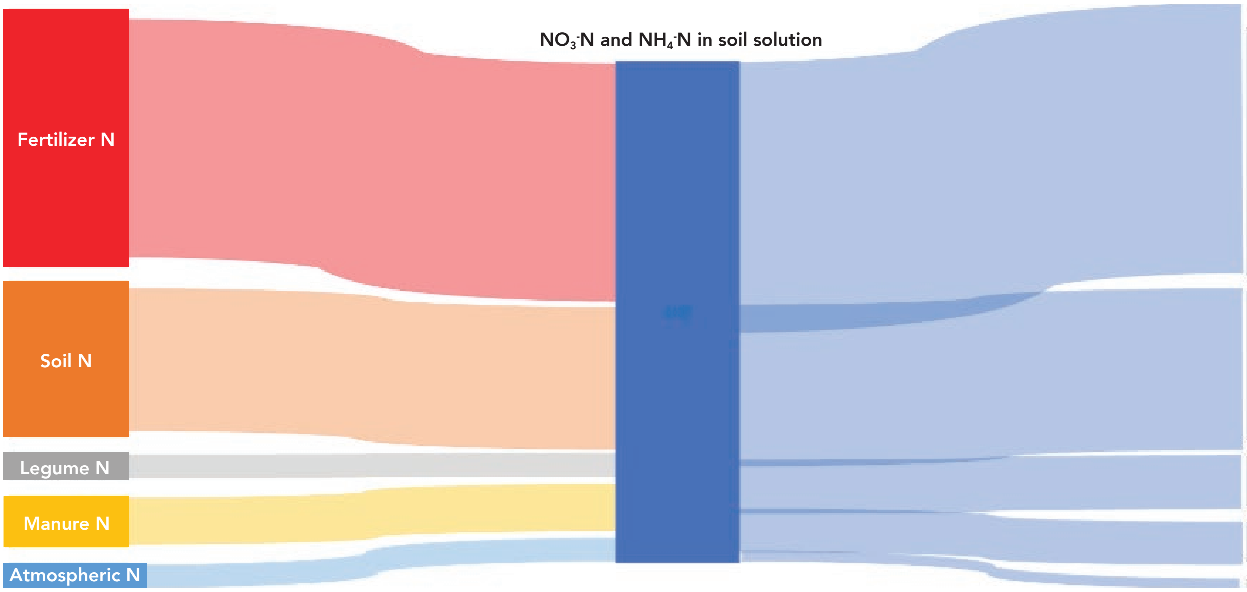

Figure 1. Nitrogen flows in a typical cropping system. Regardless of the source or form of nitrogen added to the soil, it is converted to NH_4-N or NO_3-N before it is taken up by plants or lost to the environment.

The goal of nitrogen fertilizer management should be to maximize how much of the fertilizer we apply gets into the crop. This will impact the profit from crop production by maximizing the economic return to the fertilizer expense and minimizing the risk of environmental impact. Crop Nutrient Use Efficiency (NUE_{crop}) is a tool to measure both these aspects. It is calculated as the ratio of N recovered in yield to the N applied as fertilizer:

$$NUE_{crop} = \frac{\text{Crop Yield* (\%N in Crop)/100}}{\text{(N applied as (fertilizer+manure+legume))}}$$

This can indicate how well fertilizer applications are being used by the crop. This calculation is simple for crops where the entire biomass of the plant is harvested from the field (i.e., silage corn) but is more complex when harvested crops leave significant residue. For example, after cabbage harvest, approximately 80 lbs N/acre is removed with the crop, and 100-120 lbs N/acre is left in the field in leaves, stems, and roots. This calculation also doesn't take into consideration background soil mineralization rates. Also note that these calculations don't apply to legume crops, which fix their nitrogen out of the air in the nodules on their roots.

NUE can be measured in different ways. The simplest is to divide the N removed in the harvested part of the crop by the amount of fertilizer N that was applied (NUE_{crop}). This is easy to determine but does not account for any N that the soil could have supplied, so can overestimate the efficiency of the system. Research trials often use yield increase rather than the total yield in this calculation ($NUE_{response}$), but this requires a zero N check strip. The numbers calculated for $NUE_{response}$ will be lower than for NUE_{crop}.

A NUE_{crop} ratio of 1 would indicate that the fertilizer-N applied exactly matches the N in the crop harvest, and a number less than 1 indicates that not all N has been recovered and that there is a loss of N. A goal of NUE_{crop} of 1 is unrealistic since some losses and inefficiencies are inevitable, and even a value greater than 0.9 indicates that the N is being mined from soil organic matter (EU Nitrogen Expert Panel (2015)). An N surplus greater than 80 kg/ha, or a NUE_{crop} less than 0.5, indicates excessive N applications and a high risk of N losses. Globally, the efficiency of nitrogen use for cereal production (wheat, corn, rice, barley, sorghum, millet, oats and rye) when expressed as NUE_{crop}, is roughly 66% (Raun & Johnson, 1999). Factors that reduce the amount of N available for plant uptake, such as a residue with a high carbon to nitrogen ratio, or saturated soils, will reduce NUE_{crop}.

Interpreting NUE values for your field:

Values for NUE_{crop} will vary more from field to field or year to year than will long-term regional averages. Tracking the NUE_{crop} for your farm is a good indicator of how well your fertilizer program is performing, both economically and environmentally.

NUE greater than 0.9

On the surface, this looks like a positive situation: you are getting more N in the harvest that has been applied, which is pure profit for you. The reality, however, is that the N you are harvesting must have come from somewhere.

A single year of high NUE is not necessarily a concern. There could be organic-N from previous manure applications or a legume plowdown that was mineralized that year, or perhaps there were ideal growing conditions that allowed vigorous crops to absorb more N from the soil than normal.

Continuous high NUE values indicate chronic under-fertilization, so the N in soil organic matter is being mined to support crop growth. This will not show up immediately since the reserves of organic-N in the soil organic matter are large (soil with 4% organic matter will contain about 4000 lb/ac of organic-N), and we know that a certain proportion of that mineralizes each year and is absorbed by plants. A rough book value is that for every 1% organic matter, you can expect 15-20 lbs N/acre to be mineralized from that organic-N pool and made available to plants. In natural systems such as a forest, this is returned to the soil at the end of the growing season, but arable systems can interrupt this cycle. There are times when our soil management will lead to a net breakdown of organic matter, and the release of mineralized N is the side effect of this process rather than the driving factor. Applying fertilizer N will not reverse this process but will increase the excess N in the soil. A high NUE over 0.9 can be a red flag for soil management.

NUE between 0.5 and 0.9

Within this range, crops are generally using fertilizer-N efficiently, so losses to the environment will be moderate. From an economic perspective, keeping the NUE as close to the top of this range as possible will make a huge difference to the bottom line. If you are applying 200 lbs N/acre in fertilizer to your potato crop and have an NUE of 0.5, this means 100 lbs of the applied N is not being used by the crop and is kind of like burning money. If you are applying 200 lbs N/acre in fertilizer to your potato crop and have an NUE of 0.9, that means that you are only losing 20 lbs N/acre. In a year when you are paying $1400/ton urea, that increase in efficiency is like saving more than $110/acre. It is within this range that the tools of 4R Nutrient Stewardship will be likely to show a benefit for improved NUE and profitability.

NUE less than 0.5

In this range, more than two pounds of N have been applied for every pound of N in harvested yield. Numbers in this range can show up occasionally on even the best farm, but only when there is a crop failure due to drought, frost or some other natural disaster. In this situation, the best we can do is recognize that there will be more N than usual left in the soil and try to manage it by planting cover crops to soak it up.

Consistent numbers in this range indicate that fertilizer applications are much higher than needed. There could be unrealistic yield expectations or applications at times when losses of N are high, so the applied N is not getting to the crop. Low NUE can occur on livestock farms where the N from manure applications is not properly credited or where manure applications are not managed to optimize N supply to the crop.

Fine-tuning of N management will have little effect if NUE is this low. It is time to look seriously at N application rates.

N uptake by crops

Understanding how N gets to the crop and how it can be lost is important so that producers can optimize fertilizer use (Figure 2). Modern fertilizer technologies have been developed to target reductions in specific N-loss pathways and to increase the amount of N that remains available to the crop.

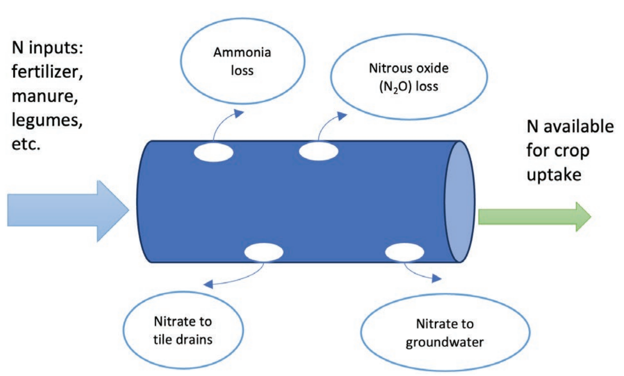

Figure 2. The "leaky pipe" model of N use efficiency. Some leaks are inevitable, but the goal is to minimize them.

Nitrogen is carried to plant roots with soil water; either ammonium (NH_4^+) or nitrate (NO_3^-) can be used by the plant, but since NO_3^- moves more easily with water, it is the dominant form absorbed. Plants can also absorb N through the leaves, but it is impractical to apply large amounts of N this way since it could cause leaf burn. In a corn or grain system, plants will happily absorb as much N as the soil supplies, but what is not needed for grain will accumulate in the vegetative parts of the plant. This excess will be returned to the soil in the crop residue, but it can create feed quality problems for corn silage or forages where the whole plant is harvested.

Maximum N uptake by crops coincides with the time of maximum vegetative growth. High levels of N in the soil outside of this time do not provide any benefit for the crop and are at risk of loss.

Nitrogen is used within the plant to produce proteins and enzymes, including chlorophyll, so adequate N is needed to support high-yield potential. Approximately half of the N absorbed by the plant goes to support the structure of the plant (roots, stalks, leaves), with the other half in the grain. In most cases, the N in the stover has come from the soil and will be recycled back into the soil at the end of the growing season.

Nitrogen Transformations and Pathways

Nitrogen in the soil is constantly on the move between different pools (Figure 3) – each of which behaves differently. This creates lots of challenges for N management, but also opportunities. The biggest pool of soil-N is in the soil organic matter, where it is bound up in stable molecules and microbial life that cannot be used directly by plants. Some of this organic-N is mineralized each year by microbial activity, where the stable molecules are broken down to release ammonium (NH_4^+) ions and nitrate ions (NO_3^-), which are plant available.

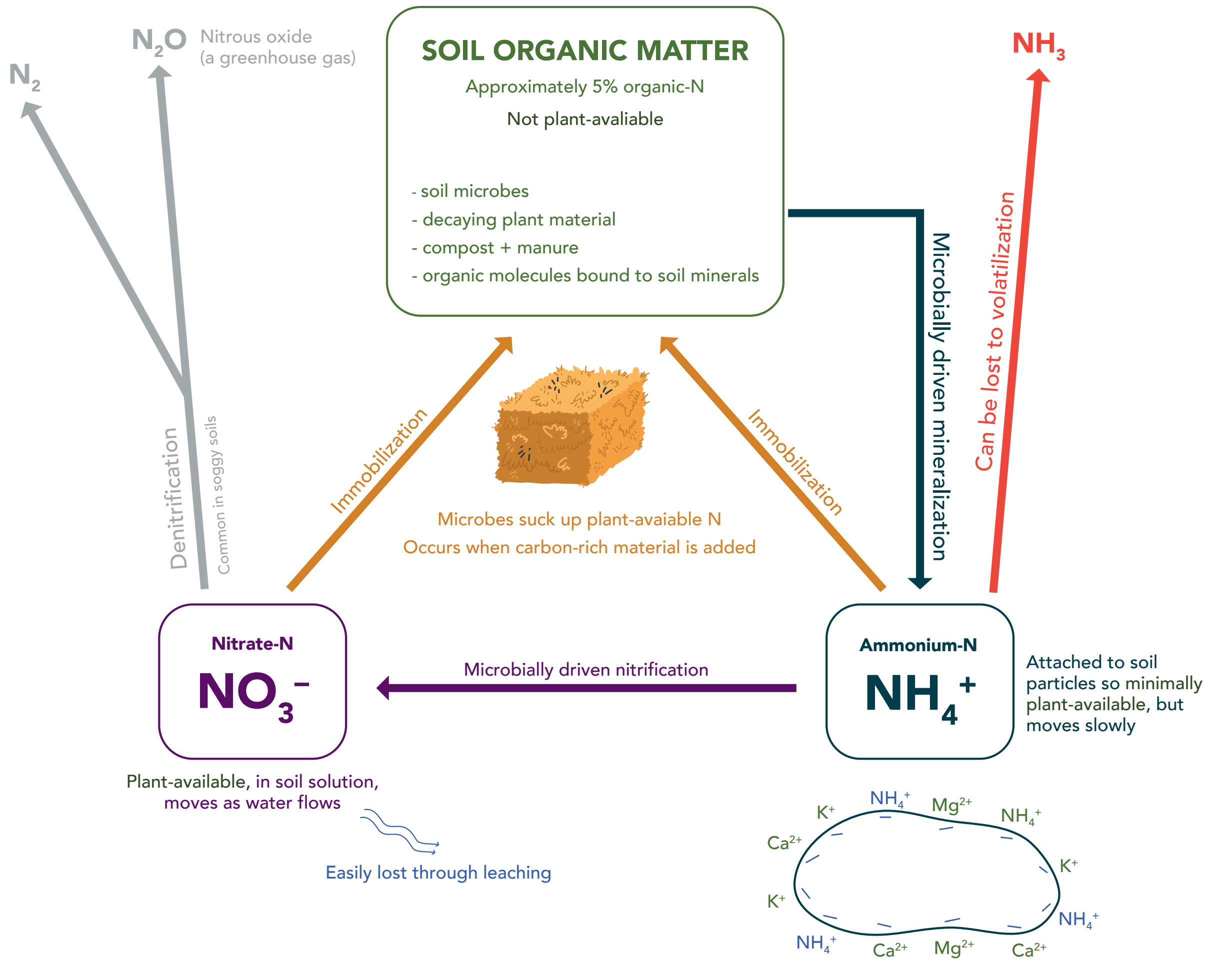

Figure 3. Soil nitrogen pools and pathways.

Soil microbes can also immobilize plant-available N (NO_3^- and NH_4^+) into organic-N, making it unavailable to plants. This happens by soil microbes sucking up the plant-available N into their bodies and often happens when carbon-rich material with a high C:N ratio is added to soil, such as straw or paper mill biosolids. Soil microbes are abundant enough that they use up plant-available N faster than crop roots can get to it. This N does not stay in the organic pool forever; it is released as microbes excrete the N or die, but this can be at a time that is less ideal for crop uptake.

Ammonium-N

Ammonium in the soil solution may have been mineralized from organic matter or added directly as fertilizer (e.g., anhydrous ammonia, ammonium sulfate or urea). Because the ammonium ion (NH_4^+) is positively charged, it will stick to negatively charged clay and organic matter in the soil, similar to other cations like calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+). This protects it from leaching since it cannot move easily with soil water. At the surface of the soil, however, some of this ammonium can be converted to ammonia gas, which can vaporize into the atmosphere. Under acidic or neutral pH conditions, most will remain as ammonium, but there will be a higher proportion of ammonia (and a greater chance of loss) under alkaline soil pH. Incorporating or subsurface banding of any ammonium-containing fertilizer will virtually eliminate the volatile losses, regardless of soil type.

The unique case of urea:

Urea fertilizer ($CO(NH_2)_2$) dissolves in soil water, and then is hydrolyzed by the urease enzyme to release ammonium. This process makes the zone around the fertilizer granule extremely alkaline, which pushes ammonium towards the volatile ammonia phase (it stays as ammonium if conditions are acidic). Surface applied urea can lose considerable N to the air as ammonia, even though the soil immediately below is acidic.

Ammonium is readily absorbed by plant roots and used by plants. However, the movement of ammonium to the roots is slowed because it binds to the soil, so the amount taken up by the plant is limited.

Most mineral fertilizers are compounds of ammonium with an anion like sulfate or nitrate, or in the molecule urea. UAN solutions are an equal mix of N from urea and ammonium nitrate, so 75% of the N is present as ammonium. The mineral N portion of livestock manure is also predominantly ammonium; in liquid manures, this can make up >90% of the total N.

Ammonium-N can be used by certain soil microbes for energy (ammonium oxidizers), converting ammonium to nitrate in the process called nitrification. This process is quick enough that most ammonium gets nitrified, and the majority of mineral N in the soil is in the nitrate form.

Nitrate-N

Unlike ammonium, the nitrate ion (NO_3^-) is negatively charged, so it is not attracted to soil particles. This means it will stay in the soil solution and is free to move wherever the soil water flows. During times of active plant growth, this is an advantage, as the water pulled into the roots carries the nitrate along with it. Unfortunately, it also makes nitrate prone to leaching in geographic areas like Atlantic Canada that receive significant rainfall. This can result in N moving into lower soil profiles that are inaccessible to roots or into groundwater, causing water pollution. Tile drains can also move excess nitrate directly into streams and rivers. Most of this leaching will happen outside of the growing season, so managing to minimize leftover soil-N after harvest reduces the risk of leaching losses.

Nitrate-N can also be lost to the atmosphere in a process called denitrification. When oxygen supply is limited in the soil, usually because the soil is waterlogged, some bacteria will turn to the next easiest source of oxygen to support their respiration, which is nitrate (NO_3^-). Denitrification is a multi-step process where multiple gaseous N forms are produced, which all contribute to atmospheric losses. Complete denitrification converts nitrate into nitrogen gas (N_2), but a part can also be lost in the form of nitrous oxide (N_2O), a potent greenhouse gas. **In Canada, nitrous oxide accounts for approximately half of the greenhouse gas emissions from agriculture.**

Denitrification is not a process that occurs evenly in time or space. Instead, there are sudden spikes of N_2O emissions when the right combination of nitrate supply, low soil oxygen and high microbial activity coincide. A "worst case" scenario would be heavy rainfall that completely saturates the soil a week after fertilizer application and planting in the spring; much of the fertilizer N that had nitrified would be lost to the air as N_2 or N_2O. A slower process, but one with similar outcomes, would be high levels of nitrate left in the soil after crop harvest in the fall; microbial activity would be slower as the soil cools down, but without any crop uptake, the nitrate would remain available for any time that soil oxygen is low over the winter. We know we cannot control the weather, but we can control when and how much N is applied. Minimizing the time between N application and crop uptake and minimizing the amount applied over crop removal, so there is little residual N after harvest will reduce the chances of N losses through denitrification.

Some mineral fertilizers add nitrate directly to the soil. Ammonium nitrate is equal parts NH_4-N and NO_3-N. Potassium nitrate or calcium nitrate are used for some specialty fertilizers. Finished composts do not contain a lot of mineral N, but most of what is present are in the nitrate form. This N is immediately available for uptake but also immediately available for loss. Fertilizers with N in the nitrate form will be most beneficial if applied when the crop can use the N immediately. You can read more about nutrient availability in composts in our factsheet **How to Interpret a Compost Analysis Report**.

Nitrogen Management Practices to Increase NUE

There are technologies available to protect nitrogen fertilizers from loss, but these will have the greatest impact if they are combined with the principles of 4R Nutrient Stewardship. This means paying attention to applying the Right Source of N at the Right Rate, Right Place and Right Time.

These concepts will be expanded on in the factsheets on **Enhanced Efficiency Nitrogen Fertilizers** and **Nitrogen Management Practices to Increase Nutrient Use Efficiency**.

Summary

How nitrogen inputs for crop production are managed has a large bearing on both the economic and environmental performance of your farm. This is challenging because N keeps shifting among different forms, so some loss is inevitable but can be minimized. NUE_{crop} is a good indicator of how well your nitrogen management is performing and can point toward areas of improvement.

References

EU Nitrogen Expert Panel. (2015). Nitrogen Use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems. **http://www.eunep.com/**

Ladha, J. K., Pathak, H., J. Krupnik, T., Six, J., & van Kessel, C. (2005). Efficiency of Fertilizer Nitrogen in Cereal Production: Retrospects and Prospects. In Advances in Agronomy (Vol. 87, pp. 85-156). Academic Press. **https://doi.org/https://doi.org/10.1016/S0065-2113(05)87003-8**

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