

Where, oh where, has my nitrogen gone?

By Keith Reid

GENERAL SUMMARY

Nitrogen fertilizer is often the largest single expense in growing corn, canola or cereal crops, representing about one fifth of the direct crop expenses (OMAFRA, 2024). On average, only about half of that nitrogen (N) makes it into the crop with the rest lost into the air or water. Some losses are inevitable but understanding how they happen will help you to sharpen your management to avoid these losses, putting more money into your pocket and reducing your environmental footprint at the same time.

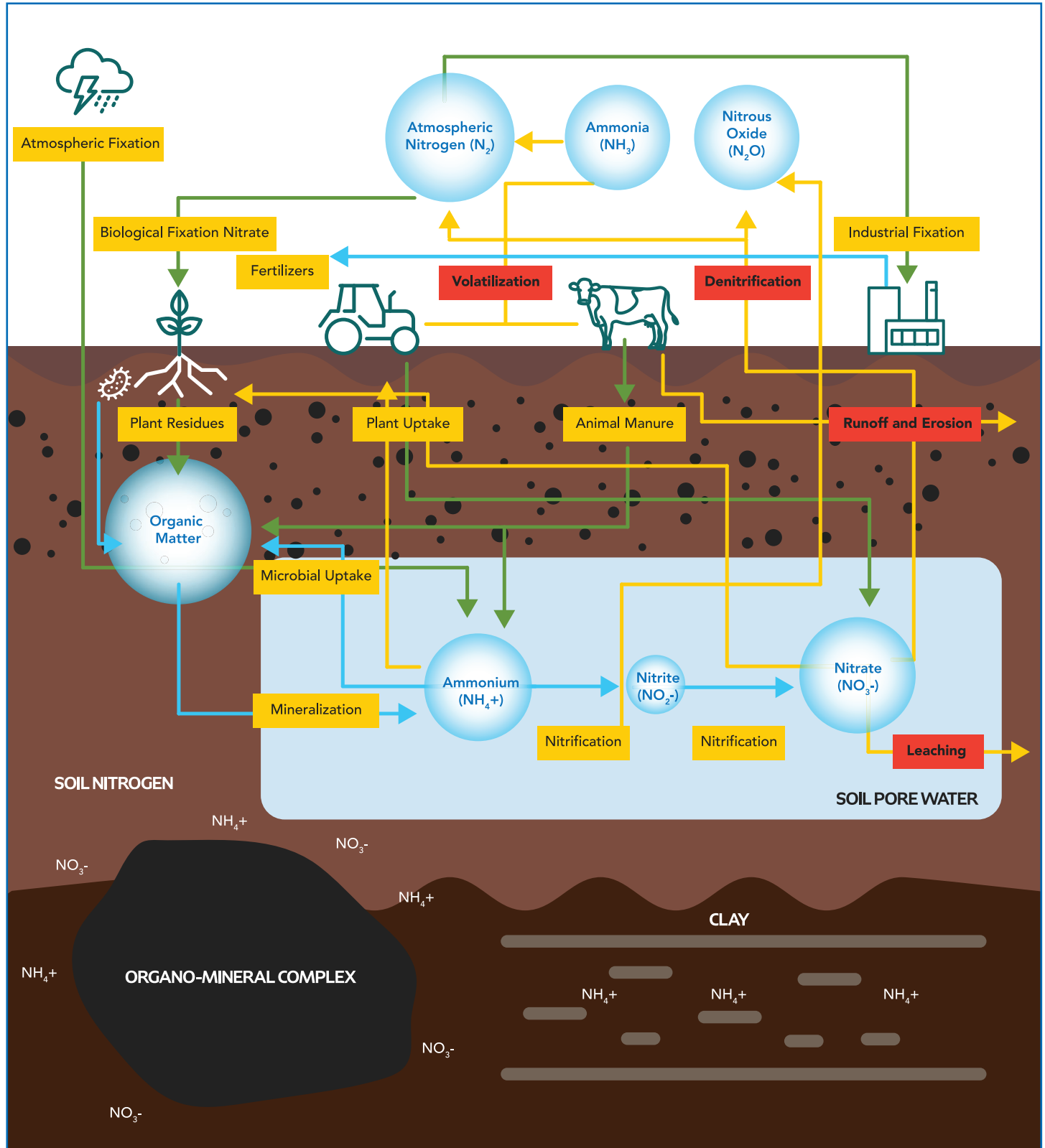
The three main pathways for N loss are volatilization into the air as ammonia gas (NH₃), denitrification that releases N₂O or N₂ gas and leaching of nitrate (NO₃). Nitrogen can also be tied up in soil organic matter through a process called immobilization; this is not strictly a loss since the N is still in the soil but it is temporarily unavailable to the crop. These processes are generally separated in time and space, with NH₃ volatilization occurring at the soil surface shortly after fertilizer application, denitrification and immobilization occurring in the soil whenever conditions are favourable for microbial growth and NO₃ leaching occurring primarily in the fall and winter months.

Below is a table of nitrogen losses in agricultural systems, how these losses occur and common methods of mitigation (Table 1), as well as a diagram to help visualize the nitrogen losses and a detailed description of each of the main N loss pathways.

Table 1: Nitrogen loss pathways in agricultural systems

Nitrogen Loss Pathway	Conditions prone to loss	Methods to decrease the risk of loss
Ammonia Volatilization	<ul style="list-style-type: none"> • Soils with higher pH • In warm, breezy conditions • Increase of crop residue increases the urease enzyme and the breakdown of urea • Unincorporated manure 	<ul style="list-style-type: none"> • Band fertilizer below the soil surface • Incorporate soil amendments • Plan to apply directly before a rainfall • Use enhanced efficiency fertilizer
Denitrification	<ul style="list-style-type: none"> • Saturated soils • High compaction • Oversupply of nitrate • Medium to fine textured soils • Low lying areas • High microbial activity in warmer temperatures 	<ul style="list-style-type: none"> • Delay fertilizer application to directly before planting • Split-apply fertilizer • Maintain good drainage in your soils • Reduce and prevent soil compaction • Nitrification inhibitors • Target optimal soil nitrogen application rate • Cover Cropping
Nitrate Leaching	<ul style="list-style-type: none"> • Low water-holding capacity soils such as sandier soils • Excess moisture, typically in late fall and early spring • Overapplying nitrogen • High residual nitrogen in the fall 	<ul style="list-style-type: none"> • Apply an appropriate amount of nitrogen • Cover Cropping • Improve manure management • Increase soil organic matter to improve water holding capacity
Runoff and Erosion	<ul style="list-style-type: none"> • Low water holding capacity • High compaction can lead to runoff • Steep slopes • Heavy rainfalls 	<ul style="list-style-type: none"> • Reduce soil disturbance • Plant cover crops to help retain nitrogen and improve soil structure • Improve soil structure and reduce or prevent compaction

Figure 1. The nitrogen cycle in soil with the nitrogen loss pathways highlighted by a red box.



DESCRIPTION OF EACH NITROGEN LOSS PATHWAY

Ammonia Volatilization

Ammonium (NH_4^+) is a part of many N fertilizers (e.g., ammonium nitrate, ammonium sulfate) and is also released when urea is broken down by the urease enzyme. When these fertilizers are dissolved in the soil solution, the positive electrical charge on this ion means that it sticks to the clay and organic matter in the soil. This protects the N from loss until it is converted to nitrate by bacteria in the soil. This protection is absent for ammonium that is sitting in solution on the soil surface, so there can be significant losses when spread on alkaline soils (see box).

The situation is more extreme for urea. When urea is broken down by the urease enzyme, the chemical reaction releases a lot of hydroxyl ions so the pH around the urea granule can go above 8.0 (100X more OH^- in solution than H^+). This means a lot more H^+ pulled off the ammonium and a lot more NH_3 lost to the air. This reaction is happening right at the fertilizer granule (or droplet) so the pH of the soil below it has almost no effect. In one trial on a slightly acidic clay soil in SW Ontario, half of the N applied as broadcast urea was lost as ammonia to the air (Drury et al., 2017). Since UAN (28-0-0, Urea Ammonium Nitrate Solution) is half urea, the losses from UAN are about half those of urea but can still be one quarter of the N applied.

The impact of pH on NH_3 volatilization

The behaviour of ammonium is driven by the pH of the solution around it. pH is a measure of the number of H^+ ions in solution; water is mostly H_2O but always has a small number of free H^+ and OH^- , with the same number of each at pH of 7. Acidic solutions (pH below 7) have more H^+ , while alkaline solutions (pH above 7) have more OH^- . The concentrations of H^+ and OH^- both change with pH and, since it is a logarithmic scale, each unit of pH means the concentrations of each change by 10X (one up and one down) so the relative concentrations of each will change by 100X.

At the concentrations from fertilizer application NH_4^+ will stay dissolved in the soil solution but if it reacts with a hydroxyl ion (OH^-) the extra H^+ will get pulled off the NH_4^+ leaving ammonia (NH_3) gas. The ammonia may react with a free H^+ and revert to ammonium, or it may float off into the air. The higher the soil pH is, the greater the conversion to ammonia and the higher the rate of loss. The pH of a solution on the soil surface will mirror the pH of the soil beneath it, so there will be more ammonia loss from an ammonium-based fertilizer spread onto an alkaline than an acidic soil.

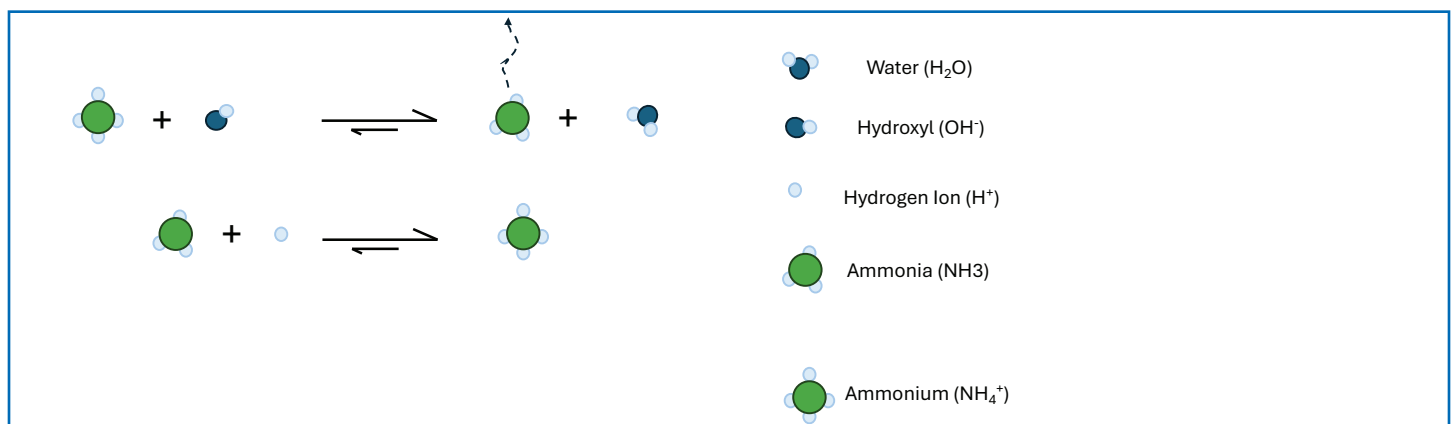


Figure 1: Ammonium and ammonia will move between forms depending on the pH of the solution. In alkaline solutions, where the amount of OH^- is much larger than the amount of H^+ , most of the ammonium will be converted to ammonia gas.

Crop residue on the soil surface contains the urease enzyme, so the urea will break down faster. Warm, breezy conditions will carry the ammonia gas away from the soil surface and increase the rate of release. Leaving a band of urea or UAN on the soil surface will increase the pH effect and create more losses. But the biggest factor by far is whether the fertilizer is left on the soil surface or placed in a subsurface band or incorporated. Ammonia losses are virtually eliminated where fertilizer is banded at least 5 cm (2") below the soil surface or incorporated by tillage within a day of application. Rainfall after application (>10 mm) will dissolve the urea and move it into the soil but rainfall forecasts are not always reliable and a heavy rain can wash the fertilizer away.

Enhanced Efficiency Fertilizers (EEFs) can also reduce NH_3 volatilization from surface broadcast fertilizers. These include polymer coated urea and fertilizers treated with a urease inhibitor. Polymer coated urea (PCU, e.g., ESN) slows the release of urea by protecting each granule with a coating that allows water to diffuse into the granule and then gradually carry the dissolved urea out where it can soak into the soil. A urease inhibitor (e.g., Agrotain, Super-U) blocks the action of the urease enzyme temporarily, slowing the conversion of urea into ammonia. Both types of products will reduce NH_3 volatilization compared to broadcast urea but not as effectively as incorporation.

Denitrification

In most soils, the majority of mineral N (as opposed to organic N) is in the nitrate form. It may have been added directly as fertilizer (e.g., ammonium nitrate, calcium nitrate) but most is the result of oxidation of ammonium to nitrate by bacteria. This is advantageous for most plants because NO_3 will move easily with water flowing into the roots but it leaves the N open to another loss pathway through denitrification.

Denitrification happens when the microbes in soil run short of oxygen gas; unlike you and I, many species can switch to other molecules to get the oxygen they need for respiration. The easiest alternate source of oxygen is the nitrate ion (there is a progression of more difficult oxygen sources after nitrate is depleted, including sulphate, iron oxide and even carbon dioxide) and these microbes make the switch to using the oxygen from nitrate. The end products from this process are gases that diffuse out of the soil and into the atmosphere: either nitrous oxide (N_2O) or nitrogen gas (N_2). Both represent a loss of the N fertilizer you have applied, but N_2O is the bigger concern as a pollutant since it a greenhouse gas with roughly 325X the impact of the same amount of carbon dioxide. Nitrogen gas is innocuous, since it already makes up 78% of our atmosphere, but this also makes it very hard to track exactly how much N is lost through denitrification.

The conditions leading to denitrification depend on three factors: restricted entry of oxygen into the soil, high demand for oxygen from an active microbial population and a supply of nitrate. The most common cause of oxygen restriction is from saturated soils where the pores that would normally carry air into the soil are flooded but extreme soil compaction will have a similar effect (as well as making the soil more susceptible to saturation). Medium and fine textured soils are more susceptible to saturation than coarse textured soils. An active microbial population will arise when there is lots of food (soluble carbon molecules) and warm temperatures. High nitrate supply will occur whenever the supply of N to the soil is greater than the rate of plant uptake. This N supply may be from soil organic matter, added manure or legume plowdown, or added fertilizer, as long as there have been conditions to convert the organic and ammonium N to nitrate (as often happens in the spring before crop growth really takes off). Nitrate can also accumulate in the soil after crop maturity if more N has been supplied than the crop can use or if N is applied in the fall as fertilizer or manure, so there is a second risk period in the fall. The biggest headache with denitrification is that the conditions for the biggest losses are erratic (i.e., only when there are heavy rains during the periods with high soil NO_3) and will vary across each field depending on topography with more saturation in low lying areas than in uplands. Research in Nebraska and Iowa found that about 2% of the nitrate in the soil was lost each day it was saturated when soil temperature was below 12°C , and 5% per day when soil temperature was above 16°C with total losses after a heavy rain ranging from 20-50 kg/ha of N (Sawyer, 2011).

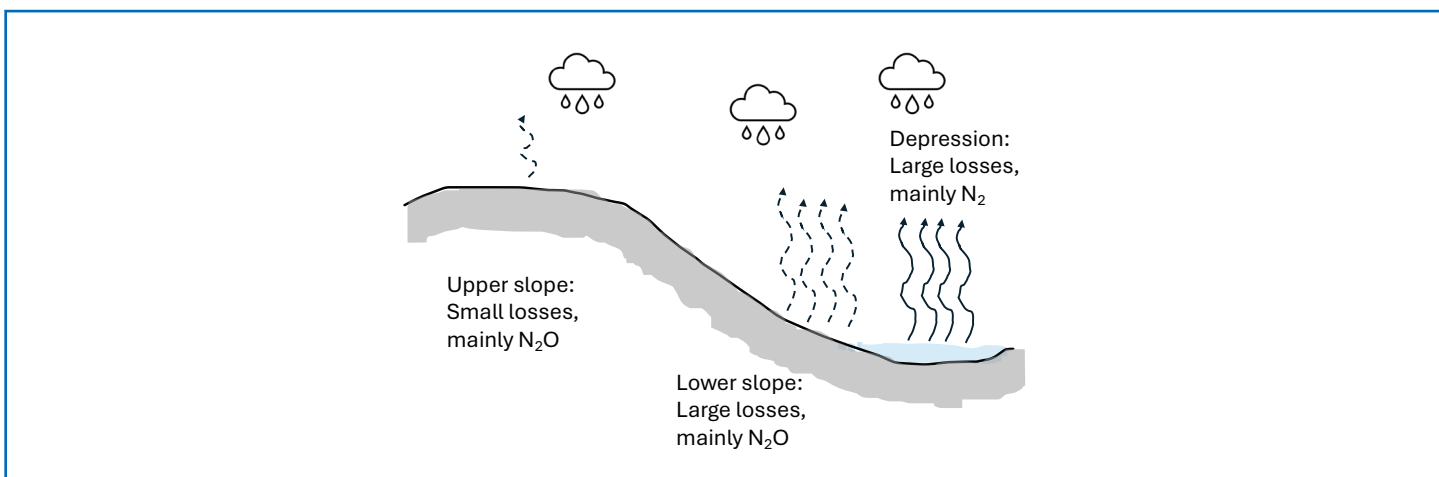


Figure 2: Denitrification losses following heavy rainfall.

This variability means that you may have almost no loss to denitrification in a dry spring, small losses from heavy rains early in the spring while soils are still cool or large losses from heavy rains in late June when soils are warm, most of the applied fertilizer has converted to nitrate and the crop is not growing rapidly enough to take up much of the N from the soil.

We cannot control the weather, but we can work to minimize the risk of losses through denitrification by avoiding high concentrations of nitrate in the soil. Application is a key tool in our toolbox; it may be tempting to get fertilizer or manure applied early so that job is out of the way, but if there is a long delay before planting much of that applied N will have had time to convert to nitrate. The longer that nitrate sits there, the higher the chances that there will be a rain event that will lead to denitrification. Delaying applications until just before planting will reduce this risk and splitting the N applications so most

is side-dressed or top-dressed into the crop will reduce it even more. Delayed application is particularly important for nitrate-based fertilizers, since there is no delay from the conversion from ammonium to nitrate.

Maintaining well drained soils and avoiding soil compaction will also reduce the incidence of saturated soils and therefore the risk of denitrification.

Nitrification inhibitors (e.g., N-Serve™, Instinct™, Super-U™) delay the conversion of ammonium to nitrate, which will ideally result in high NO₃ concentrations in the soil just as the crop is growing rapidly and needs the N. These have been shown to consistently reduce N₂O emissions and improve nutrient use efficiency (Burton, 2018).

The final but possibly most important management technique you can use is to target the optimum rate of added N for your crop, as this will affect the potential losses both in the spring and the fall. Adding extra N to cover off potential losses increases the losses but does not increase your crop yields. If you have applied more N than the crop requires, possibly through a manure application that does not release the N in time for crop uptake, planting a cover crop can help to soak up excess nitrate from the soil and reduce N₂O emissions in the fall or through the winter.

Nitrate Leaching

The negative charge on the NO₃ ion means that it moves easily with water, rather than being held by the soil like the positively charged NH₄ ion. This is an advantage when crops are actively growing since the N they need is carried along with the water flowing to the roots but becomes a drawback when water is draining down through the soil and leaches that nitrate with it. This drainage water can carry the nitrate out through tile drains or deeper into the groundwater where it could impair drinking water quality. Excess nitrate getting into oceans or brackish estuaries can trigger harmful algae blooms.

Leaching can occur anytime the water content of the soil exceeds the capacity of the soil to hold it and will be faster where there are large pores to conduct that excess water downwards. Coarse textured soils (sands and gravels) are at greater risk for leaching since they have a lower capacity to hold water and larger pore spaces relative to medium or fine textured soils, but it can happen in any soil type. The conditions of excess moisture can occur anytime there is heavy rainfall but the general pattern is that crops are transpiring more moisture during the summer months than the rainfall we get so the soil is drying out. This moisture deficit must be filled before any significant amount of water will drain below the rooting zone so typically the greatest leaching occurs during the late fall and early spring.

Since water movement is happening outside of the growing season, the NO₃ that is at greatest risk of leaching is what is in the soil either before or after crops are actively growing. In the spring, early applications of nitrate-based fertilizers would pose the greatest risk; organic or urea-based fertilizers would not normally convert quickly enough to nitrate to be at risk unless there was unseasonably warm temperatures or delayed crop planting. A greater and much more consistent risk is elevated NO₃ in the soil in the fall, which can come from several sources:

- Residual N from crop, which may arise from
 - » Applying more N than the crop requirements
 - » Unusually low yields due to drought or disease
 - » Catastrophic crop failure from hail or flooding
 - » Crops which leave large amounts of green residue at harvest (e.g. some horticultural crops).
- Mineralization of soil organic matter following harvest of an early season crop
- Summer application of manure or early termination of forage legumes

The most common of these by far is residual N from overly optimistic fertilization, so the key to reducing leaching risk in the fall is careful planning in the spring. The N that is at risk of leaching risk in the fall is N that did not contribute to added crop yield anyway, so it is as unneeded expense as well as an environmental risk.

The other sources of excess soil NO₃ are less avoidable but can still be managed. These are the situations where cover crops really shine to soak up the excess NO₃ and tie it up in plant tissue. The amount of N tied up will be proportional to the amount of cover crop growth, so you will want to plant something that grows aggressively and is planted into good conditions. There has been good success with spring cereals, oilseed radish or fall rye. Some farmers are using a mix of radish and rye, since the radish will grow more vigorously in the fall, then the rye will capture the N released from the winter-killed radish in the early spring. These cover crops could also be harvested as forage or used for late season grazing, which removes the excess N from the field in the form of meat and milk.

Immobilization

Our focus for crop production is often on the release of mineral N (NH_4 and NO_3) from soil organic matter so plants can absorb it through the roots, but microorganisms in the soil can also use mineral N for their own growth and respiration. This immobilization of mineral N back into the organic form can tie up N temporarily and hurt crop growth.

Microbes in the soil are always hungry, so when a source of organic carbon is added to the soil, they will go into a feeding frenzy, rapidly multiplying to take advantage of the new food source. These microbes have a pretty constant ratio of carbon (C) to N in their bodies (about 8 parts C to 1 part N for bacteria, or 10:1 for fungi) so if there is excess C they will need to find enough N to maintain this ratio. Straw, corn stover or sawdust all have high C:N ratios, so when they are being consumed by the soil microorganisms the mineral N in the soil is used up to meet the demand and it will stay tied up until the excess C is used up. The C consumption is split between respiration (loss as CO_2) and growth (tie-up in microbial tissue) and as the excess C is consumed, the microbial population will begin to die off and release mineral N back into the soil solution. This suppression of available N can last for a few weeks to a few months.

The impact of N immobilization on crop growth is most frequently seen in spring during early growth, particularly if the weather is cool and following a crop that leaves a lot of residue behind or the application of a solid manure with a lot of bedding material. Cool weather slows microbial growth and respiration, so the excess C in the soil is not used up quickly enough to release N back into the soil. In most cases, the N supply to the crop will improve once the weather warms up without the need for extra N fertilizer. In extreme cases, like the addition of large amounts of a compost with wide C:N ratio, the release of N will be delayed until after crop uptake has finished, leading to high NO_3 levels in the soil in fall and increased N losses through other pathways.

Runoff and Erosion

Nitrogen can also be lost from the surface of soil through runoff and erosion. Heavy rainfall or wind events can strip away nutrient rich topsoil where much of nitrogen resides. Nitrogen can be lost through loss of soil organic matter, as dissolved nitrogen in water, and also compromise soil structure further decreasing the ability of soil to retain nitrogen. Steep slopes increase the risk of runoff and erosion. Sandier soils with low soil organic matter can be less effective at retaining moisture making it more prone to runoff. Runoff and erosion can lead to pollution in nearby water sources, causing harmful effects to aquatic ecosystems.

Managing for Maximum N Use Efficiency

Maximizing N use efficiency and therefore minimizing the potential for losses of N requires following all of the 4Rs® of nutrient management: the Right product applied at the Right time, in the Right place and at the Right rate. Of these four, getting the right rate is probably most important as well as most difficult because over-application of N is largely invisible. Adding “a little extra” to make sure there is enough for the crop after any losses has been cheap insurance with relatively low N prices, but it has made those losses inevitable. The only variable was which loss pathway would dominate.

Following 4R management means getting the N below the soil surface where it is protected from volatilization and then minimizing the time periods when there are high levels of mineral N in the soil. The greater the accumulated exposure, the greater the risk for loss. In practical terms, this means that split N applications with most of the N applied just before the time of maximum crop uptake and below the soil surface will have the smallest losses. The use of enhanced efficiency fertilizers can help to limit losses from fertilizers that are applied at less than optimum time or place.

Reducing N losses prior to crop uptake will mean that less total N will need to be applied to meet the needs of the crop (Drury et al., 2024). Many research studies have found that reducing NH_3 volatilization through subsurface placement or urease inhibitors has increased the losses of N_2O or NO_3 , but these studies also used the same rate of N without accounting for the retention of extra N that can be used by the crop. Nitrogen management is a system and only by considering all the parts together can gains be made in reducing N losses and increasing farm profits.

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