

How Weather Affects the Nitrogen Cycle

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INTRODUCTION

The Atlantic provinces have variable weather patterns where the temperature, rainfall and season length can vary greatly from year to year. The winters often experience multiple freeze-thaw cycles and heavy rains. Summers are either wet and humid or experience times of drought. These changes in weather patterns can greatly impact the nitrogen cycle. The nitrogen cycle is microbe dependent and if extreme weather events impact the productivity of these microbes, the nitrogen cycle will be altered.

Nitrogen (N) is a key input for high-yielding crops and is the largest part of fertilizer expenses on many farms. Unfortunately, N is variable and keeps changing from one form to another, which makes it a challenge to manage. Adding complexity is that all these transformations, whether they are driven by biology, chemistry or physics, are affected by weather.

This can seem daunting and you may conclude that the simplest approach is to make sure to add more N than the crop will need just to be sure. Aside from the expense, N that the crop doesn't need will end up back in the wider environment in forms that can be harmful. We know that we cannot eliminate these losses, but understanding the transformations happening in the soil can help us to keep them to a minimum.

Before we dive into the impacts of climate and weather on the nitrogen cycle, we will first look at the nitrogen cycle as a whole.

POOLS OF NITROGEN

Nitrogen can be thought of as a series of pools of different chemical compounds and the transformations that move the N from one pool to another. The characteristics of the N compounds will determine where you will find them and how they might move. Figure 1 shows how N cycles through these various pools.

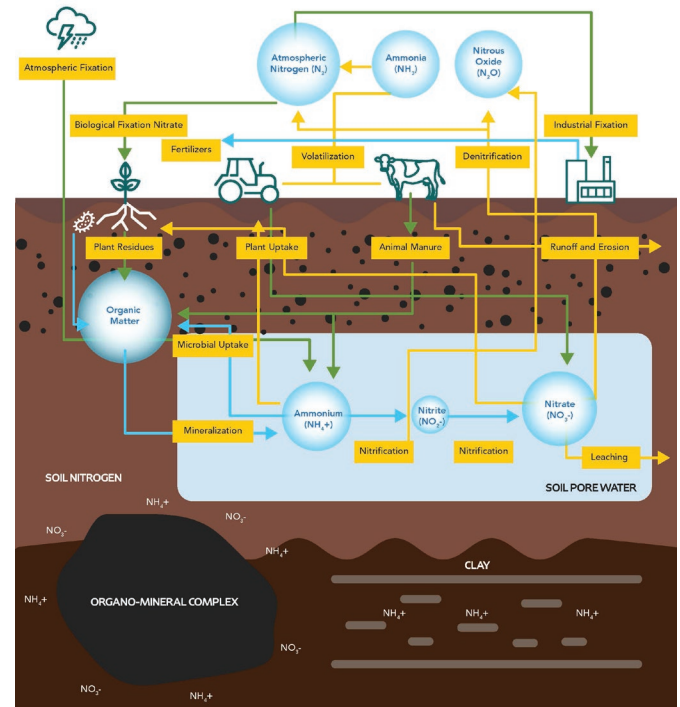


Figure 1. The Nitrogen Cycle.

The largest pool by far is the nitrogen gas (N_2) in the atmosphere (roughly 80,000 tonnes over every hectare on earth), where it makes up about 78% of the air we breathe. This gas is extremely stable so it is not available to plants in this form but it is where all the plant available N comes from and ultimately returns to.

The largest pool of N in the soil is in soil organic matter (SOM). Some of this is tied up in the living bodies of soil organisms, while the majority is a part of the variety of carbon compounds that make up SOM. The amount of organic N in the soil will vary with the amount of SOM, but a typical soil with 3% SOM would contain approximately 30,000 kg/ha of N. Plants can absorb some small organic molecules directly, but for the most part this organic N is not plant available.

The mineral forms of nitrogen, which plants can absorb, make up only a small fraction of what is in the soil at any time. These consist of ammonium (NH_4^+) and nitrate (NO_3^-) ions along with small amounts of nitrite (NO_2^-) and other nitrogen oxides (NO , N_2O , collectively termed " NO_x "). Because of its positive charge, NH_4^+ can bind to clay or organic matter in the same manner as calcium or potassium so there is little risk of leaching from the soil. Most of the NH_4^+ , however, is quickly converted to NO_3^- , which will move easily with soil water.

NITROGEN TRANSFORMATIONS IN THE SOIL

For the most part, N in the soil does not stay within a single pool for long but is constantly transforming. The following are the major transformations, along with the impact of weather conditions on each of them.

Fixation

The collective term for processes that convert N_2 gas into mineral N forms that could be absorbed by plants is fixation. A small amount of fixation occurs in the atmosphere during thunderstorms where the intense energy of lightning strikes rips apart the N_2 molecule and combines it with oxygen to form nitrate. A single lightning strike might fix 10 kg of N, but spread over the entire land area, the deposition from this process averages less than 0.3 kg/ha.

Most N fixation is either industrial, using the Haber-Bosch process, or biological. Biological N fixation may be either non-symbiotic by free-living bacteria in the soil (relatively small, adding only 0.01-5 kg/ha of fixed N, Son, 2001) or symbiotic fixation by legumes like alfalfa, clover or soybeans (Figure 2). These processes convert N_2 to NH_4^+ . In industrial fixation, this can be combined with CO_2 to produce urea or further processed to nitrate and combined to produce the range of mineral N fertilizers.

Symbiotic N fixation depends on the carbohydrates fixed during photosynthesis so any weather that reduces plant growth will reduce N fixation in the nodules. Drought stress in particular has an outsized impact on N fixation, both by reducing nodule formation and the efficiency of N fixation within the nodules while the plant is short of moisture (Serraj, Sinclair and Purcell, 1999). Perennial forage legumes will have the opportunity to compensate for this shortfall later in the season when soil moisture improves, but annual grain legumes like soybeans can suffer significant yield losses from dry conditions.



Figure 2: Clover and grass mix with plenty of moisture to fix nitrogen.

Immobilization

Soil organisms (bacteria, fungi and actinomycetes) need N for their growth and reproduction. If there is ample supply of carbon compounds in the soil (crop residue, added manure or compost), they will absorb NH_4^+ and NO_3^- out of the soil to meet their requirements. With the billions of microorganisms in every gram of soil, these critters can get to the mineral N much faster than any plant root and tie it up in organic forms. Some of this tie-up is temporary but it can also sequester N for long term storage in soil organic matter.

The limit on the amount of immobilization in the soil will be the supply of food for the microorganisms (carbon compounds) but because the entire process is biological, the weather will have significant impacts on how rapidly it happens. Incorporating corn residues into the soil in late fall when the ground has cooled will not do much to change the soil mineral N content until the following spring when the soil warms up.

Mineralization

The N that has been tied up in organic matter by biological activity is also returned to mineral forms in the process called mineralization. This may be through the excretion of ammonium as a waste product of metabolism in much the same way as we excrete N compounds in our urine, or it may be through the release of cellular fluids when microbes die. The N that is released through mineralization is almost all in the form of NH_4^+ .

As with immobilization, the rate of mineralization depends on how comfortable the conditions are in the soil for microbes: warm and moist but with enough drainage that there is air in the soil as well. Cold, wet soils will slow down mineralization. This can be an issue where the crop is being fertilized with solid manure or legume plowdown; there is lots of N there but not in forms that plants can use so the crop suffers a setback until the weather warms up.

Nitrification

Some groups of bacteria use NH_4^+ as food and oxidize them as a source of energy to release nitrate (NO_3^-). This process of nitrification is actually in two steps, with bacteria in the Nitrosomonas family converting NH_4^+ to NO_2^- (nitrite), while a second family of bacteria (Nitrobacter) complete the oxidation to NO_3^- . Nitrite is toxic to most plants so it is fortunate that under most conditions the second step in the process is faster than the first preventing nitrite buildup.

The biggest limitation to nitrification is the oxygen supply in the soil, so under waterlogged conditions it will virtually stop. On its own, this does not remove N from the soil but it leaves it the ammonium form where it cannot as easily be transported to the crop roots.

Denitrification

Most organisms use oxygen for respiration and when O_2 is in short supply, some bacteria can switch to using the oxygen in nitrate. This occurs primarily when soils are waterlogged. This process of denitrification can release either N_2 gas (so back where we started in the atmosphere) or nitrous oxide (N_2O). Most of this comes from NO_3^- in the soil but some can also use the NO_2^- intermediary so there is some N_2O release from nitrification as well as denitrification. Nitrous oxide is a greenhouse gas with about 300 times the potency of CO_2 .

The big driver for denitrification is excess rain,

particularly when the soils are warm since that is when microbial respiration is greatest. If the microbes aren't using up the oxygen in the soil quickly, the rate of denitrification will be slow. The time of highest risk of loss is late spring, when there has been time for nitrification but not plant uptake, so the concentration of nitrate in the soil is relatively high and soil temperature is warm. Heavy rains at this time that saturate the soil will create conditions for a flush of denitrification. The amount of waterlogging will determine if the end product is nitrous oxide or N_2 gas. Moderately waterlogged soils will convert most of the nitrate to nitrous oxide, while in fully saturated soils almost all the loss will be to N_2 gas.

NITROGEN TRANSPORT

Most nitrogen transport is by way of water, although some forms also travel in gaseous form. This section describes the dominant transport pathways.

Plant Uptake

As farmers, we are hoping to get as much N as possible into the crop where it can be converted into marketable yield. Most of the N reaching the plant is in the NO_3^- form, carried with the water that flows to the plant roots. Plants can also use NH_4^+ and it is actually more efficient within the plant because it can be combined directly into amino acids, but because it is held to soil particles, the uptake is by the slower processes of root interception and diffusion.

Weather influences N uptake by plants in two ways. First, seasonal weather patterns directly influence the

The myth of thunderstorms feeding crops:

We often see crops "green up" after a thundershower, but is there enough N fixed by the lightning to account for this? The short answer is, "No."

Some of the improved appearance is simply the moisture absorbed by the plants as drought stressed plants have a faded appearance. Some will be the flush of N carried into the plants with that water, as the dry conditions preceding a summer thundershower are conducive for nitrate to accumulate. Well aerated soils allow nitrification to occur but dry conditions slow the transport of this nitrate into roots.

The amount of additional nitrate from lightning is insignificant compared to what is in the soil.

growth of plants. Larger plants support larger root systems, extending the reach of the plants to pull nutrients from the soil and also transpire more water pulling more NO_3^- into the roots with the water to support that transpiration. Second, adequate rainfall creates conditions where water can move easily through the soil to the roots and carry N with it. Under dry conditions, moisture moves in thin films around the soil grains rather than through larger pores, which is much slower. In contrast, if the soil is waterlogged the roots will lack the oxygen they need to survive and the root system will shrink.

Leaching

Because NO_3^- moves with soil water, if there is deep drainage of excess water below the rooting zone, it will leach the N deeper into the soil where it can eventually reach an aquifer. High levels of NO_3^- can impair drinking water quality.

Even in a wet growing season, there is rarely enough infiltration to move NO_3^- out of the rooting zone because evapotranspiration is removing more water from the soil than is replaced by precipitation. This situation is reversed in the late fall through early spring when plants are dormant so most leaching occurs during this time. Management of N to minimize the amount remaining in the soil at the end of the growing season will limit the losses through this pathway.

Runoff

When surface runoff occurs, any soluble form of N can be carried with it into streams or lakes. High levels of ammonia can be toxic to fish and other aquatic organisms. High levels of NO_3^- are problematic in marine ecosystems, where they can lead to harmful algal blooms and hypoxia (“dead zones”).

Nitrate can be mobilized from the surface of the soil into runoff water or picked up by water seeping through the soil that later moves to streams through tile drains or by lateral flow along an impervious layer. This transport pathway is episodic, occurring primarily during spring thaw or during large rain events in the summer.



Figure 3: Waterlogged soybeans from excess water in Nova Scotia 2023. In this case, N is impacted by various biological, chemical and physical transformations including denitrification, leaching and runoff.

Volatilization

Ammonium that is on the surface of the soil can convert to ammonia gas (NH_3) and float off into the atmosphere. This is more likely to occur under alkaline conditions than acidic so it is a common misconception that soils in Atlantic Canada are protected from volatilization by their low soil pH. This would be true for ammonium sulfate or ammonium nitrate, but when urea fertilizer is dissolved it creates a zone of alkaline conditions around the fertilizer granule or droplet leading to high risk of volatilization.

Ammonia volatilization will be greatest when the soil is moist, humidity is high, temperatures are warm and there is a breeze. If urea or UAN solution is going to be surface applied (not incorporated or injected), it is best done when conditions are dry and cool, ideally when rain is expected to dissolve the fertilizer and carry it into the soil. Urea below the surface is largely protected from volatilization.



Figure 4: Fresh manure stockpile in a wet January field. A winter thaw with a warm and breezy day in January brings opportune time for ammonia volatilization for nitrogen. Both the left-over N in the moist field and the initial surface of the manure pile are susceptible.

IMPACTS OF CLIMATE AND WEATHER TO THE NITROGEN CYCLE

Variable winters: Winters with higher overall temperatures and variable snow cover will impact the nitrogen cycle because the increase in snow melt throughout the season can increase nitrogen leaching and runoff, leading to N losses to water bodies.

Summer thunderstorms: N that is in the nitrate form is most susceptible to losses. Nitrate concentrations in the soil tend to peak in early summer when the soils have dried enough to be aerobic and warm enough to support lots of microbial activity but before full season crops are growing rapidly enough to absorb all the accumulated nitrate. Heavy rainfall during this period can trigger significant losses of nitrate. The primary loss pathway is denitrification, as the soil becomes temporarily saturated and anaerobic. Less commonly, there can be enough vertical movement of soil water to leach the nitrate below the rooting zone but most soils will retain the water and N in the topsoil where plants can still access it.

Drought conditions: Lack of moisture will generally impact N cycling by slowing down processes rather than increasing losses or reducing inputs. The one exception to this is N fixation by legumes, where drought stress on the plants will reduce symbiotic N fixation more and more quickly than it affected the growth of the plants. Dry conditions will slow the mineralization of organic nitrogen but because soil conditions are generally aerobic during dry periods, the conversion of ammonium from mineralization to nitrate will not be reduced. The lack of moisture also means that leaching and denitrification are reduced so the mineral N that is produced will tend to stay there. Since drought reduces plant growth and therefore the N demand, we would not expect reduced N supply due to dry conditions to be a major limiting factor on crops. There may be circumstances, however, where delayed mineralization may mean an accumulation of nitrate in the soil after crops have finished taking up N, leading to an increased risk of N loss in the non-growing season.



Figure 5: Drought stricken crops from August 2025 including oats (left) and soybeans (right).

NET IMPACTS OF WEATHER ON THE NITROGEN CYCLE

The complexity of managing N in the soil is that all of these transformations and transports are happening at once, but the impact of weather on each of them individually will vary with the exact weather conditions and the interaction of temperature and precipitation with the soil conditions. Despite this complexity, there are a few generalizations that can be made about the impacts of weather conditions on the N cycle:

- Cool conditions will slow N mineralization enough to cause temporary N deficiencies in crops, even if there is adequate N in the organic form.
- Adequate, well distributed rainfall through the first six weeks of crop growth will increase the availability of N to the crop, although it is not clear how much is due to increased N mineralization or reduced N losses (Xie et al., 2013).
- Heavy rainfall during the early part of the growing season will reduce N availability, with the greatest impacts on fine textured (clay) soils. The combination of relatively high nitrate accumulation, warm soil temperature and anaerobic conditions from excess water combine to increase denitrification.
- Excess N in the soil at the end of the growing season will be lost over winter under the climate conditions prevalent in Atlantic Canada (in contrast to the very dry and cold winters in the prairie provinces).

SUMMARY

Understanding the nitrogen cycle and the impacts that weather conditions have on the various transformations and transport pathways followed by N in the soil will help your management so more N ends up in the crop and less is lost to the environment. This is a win for both your bottom line and your environmental footprint.

REFERENCES

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