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Nitrogen Cycling in Soils within a Dairy Production System

Introduction

Nitrogen (N) is one of the most important nutrients for plant growth, which in turn provides the N needed in a dairy cow's diet. Nitrogen is a major constituent of amino-acids, which are the building blocks of protein. To maintain optimal soil N levels for crop growth, it is common to amend soil with additional N sources, such as inorganic commercial fertilizer, animal manures, or green manures. Increasing the application of N fertilizers generally results in higher crop yields (Figure 1). However, after land application, N undergoes a series of transformations in the soil and can be lost to air and water before plant uptake. Thus, it is crucial to understand the N cycle in soils and the different loss mechanisms to implement practices that mitigate these losses and increase N efficiency in soils.

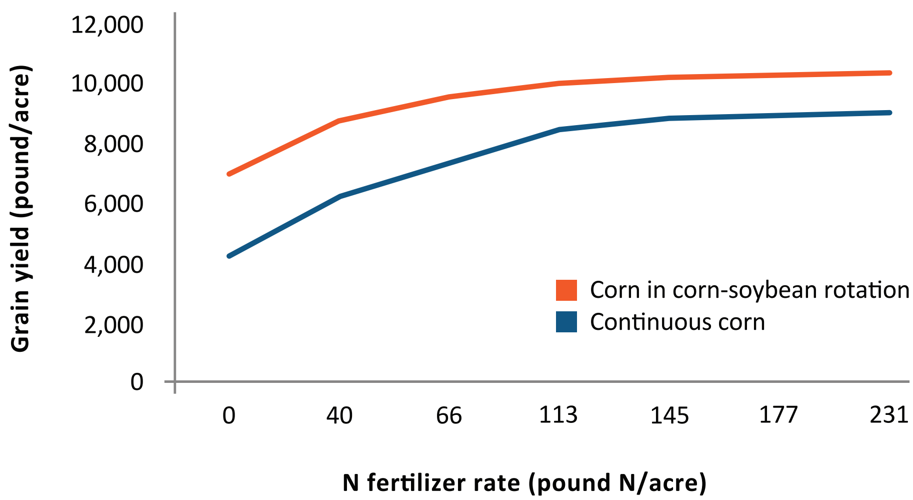

Figure 1. An example showing how the nitrogen (N) fertilizer application rate affects corn yield in Iowa (modified from Poffenbarger et al. 2017).

Nitrogen cycling in soil

Nitrogen can be present in different forms in the soil and can undergo a variety of transformations within the soil. These transformations are influenced by different factors, such as microorganisms that live in the soil, climatic conditions, and the characteristics of the soil itself (Cameron, Di, and Moir 2012). Within the N cycle, atmospheric N (dinitrogen) can be fixed into the soil by soil bacteria, lightning, rain, or industrial processes. Decay of plant residues and application of animal or green manures can also add N to the soil (Figure 2).

Nitrogen fixation mechanisms and sources on a dairy farm

As shown in Figure 2, there are different inorganic N sources supporting plant growth that are fixed from atmospheric N, which constitutes approximately 78% of the Earth's atmosphere. Atmospheric N is not directly available to most plants, but legumes (e.g., soybeans and alfalfa) can fix atmospheric N through symbiotic bacteria that live in their roots called Rhizobium in a process known as biological fixation. Some atmospheric N is also fixed in the soil by lightning, rain, and snow in a process called atmospheric fixation. Lightning breaks N into molecules that combine with oxygen in the air to form N oxides. These N oxides are dissolved into nitrates by rain and snow.

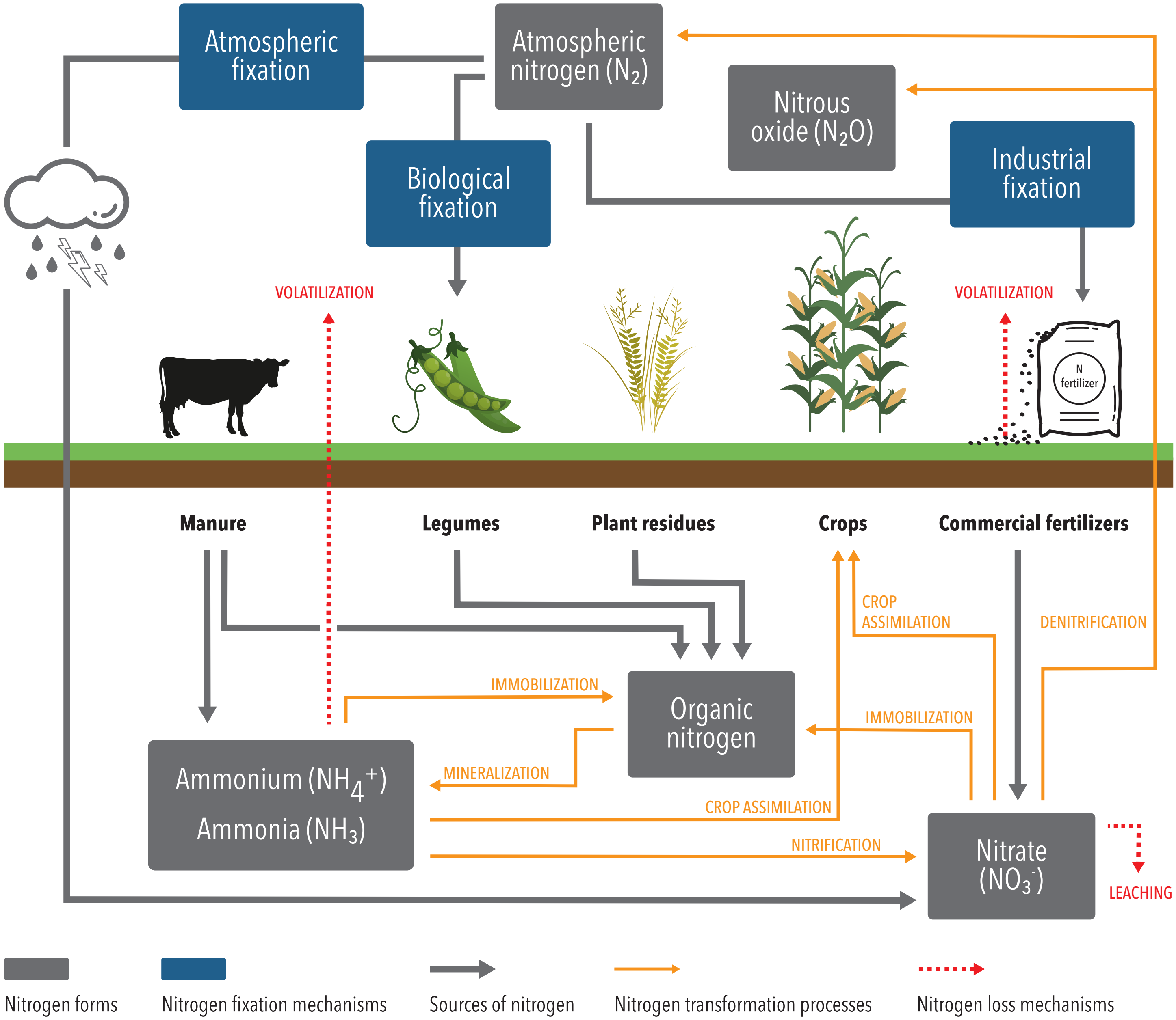

Figure 2. The nitrogen cycle emphasizing soil mechanisms.

There are also industrial processes that fix atmospheric N into forms that can be used to fertilize soils in a process known as industrial fixation. The most commonly used industrial fixation process, known as Haber-Bosch, is more economical than other industrial fixation processes. The Haber-Bosch process directly synthesizes ammonia from atmospheric N and hydrogen (usually derived from natural gas) using a metal catalyst under high pressures and temperatures. The resulting ammonia serves as the base to produce a wide range of N fertilizers such as urea, anhydrous ammonia, and urea-ammonium nitrate (UAN).

Organic fertilizers like animal manures and plant residues are also important N sources for crop production. Organic fertilizers have a mix of organic and inorganic N forms. The form and amount of N will vary depending on the type of organic fertilizer. For manure, some factors that affect N availability include livestock type, diet composition, and adopted manure management practices. Over time, the organic N will mineralize in the soil and provide additional inorganic N for plant uptake. Residue of crops other than legumes contain N in complex forms that take years longer to become available for plant assimilation. It is also important to remember that crop residues supply N back to the soil; not all the N in the plant biomass is removed from the field with harvest.

Nitrogen transformations and loss mechanisms

Crop removal constitutes the most significant source of N loss from soils and is the reason why N must be replenished to maintain soil N levels that support high crop yields year after year. After N is applied to the soil, either via fertilizer application or through natural N fixation mechanisms, it undergoes a series of transformation processes that generate different opportunities for N to be lost to air and water.

Nitrogen is present in the soil both in its organic and inorganic forms. Organic N (not available for plant uptake) is mostly provided by crop residues, manure, and the existing organic matter already built up in the soil. Soil bacteria can convert organic N into inorganic N in a process known as **mineralization** (bacteria break down organic material producing ammonium). Only inorganic N, predominately ammonium and nitrate, is available for crop **assimilation**, or uptake, as shown in Figure 2.

The rate of mineralization depends on different factors, including the quality of plant residues and organic matter, soil temperature, and water content. Nitrogen that exists as ammonium is stable and positively charged and bonding to negatively charged soil particles. Due to its strong bond with soil particles, it is unlikely that a significant portion of ammonium will be lost through leaching; however, ammonium is more likely to be lost to the environment as ammonia gas in a process known as **volatilization**. Ammonia volatilization can occur quickly when manure or commercial fertilizers are surface applied, especially when soil surfaces are moist, soil pH is high, temperatures are warm, and conditions are windy. The amount of volatilization that occurs is quite variable and can range from 0-65% of the N applied, depending on factors like soil and climate conditions and management practices (Bishop and Manning 2010).

Urea-based fertilizers and animal urine are more susceptible to ammonia volatilization because they can increase the soil pH after being land applied (Cameron, Di, and Moir 2012). Although increasing soil moisture can increase the rate of ammonia production, rainfall or irrigation soon after N application can reduce volatilization by washing N below the soil surface. Soil cation exchange capacity reflects the ability of a soil to retain ammonium ions. Clay soils have a high cation exchange capacity and thus have a generally lower risk for ammonia volatilization than sandy soils that have a low cation exchange capacity (Cameron, Di, and Moir 2012).

Ammonia lost to the atmosphere contributes to acid rain, is a precursor of nitrous oxide (a potent greenhouse gas, or GHG), can form particulate matter that poses serious health risks, and can irritate eyes and lungs in humans. In addition, ammonia can travel long distances before depositing in aquatic ecosystems where it can contribute to eutrophication. The risk for volatilization is high after land application of urine and urea fertilizers, as ammonia is an intermediate form of N in the conversion process between urea and ammonium. Ammonia will quickly volatilize if the applied urea is not incorporated into the soil.

Soil bacteria can convert ammonium into nitrate through a process known as **nitrification**, especially if soils are warm, moist and well aerated (Cameron, Di, and Moir 2012). The optimal soil temperature for bacteria that promote nitrification is between 77-86°F (25-30°C) (Haynes and Sherlock 1986). Nitrate is soluble in water, and unlike ammonium, it has a negative charge that impedes bonding to soil particles (which are also negatively charged). As a result, if roots do not take up nitrate, it can rapidly move through the soil and reach groundwater, posing environmental and health risks for humans and animals. This process of nitrate loss is known as **leaching**. Nitrate leaching is more prominent in coarsely textured soils where infiltration rates and drainage can be more rapid than in finely textured soils. However, leaching can occur in any soil when water moves through and past the root zone.

If nitrate is neither assimilated by crops nor lost into groundwater through leaching, soil bacteria can transform it into gaseous compounds like nitrous oxide and dinitrogen through a process known as **denitrification**. Bacteria responsible for the denitrification process are anaerobic (i.e., they live and reproduce in the absence of oxygen) and use nitrate instead of oxygen to break down organic matter (PASSEL 2017). As a result, denitrification primarily occurs in soil conditions with limited oxygen, which is common in wet and warm soils. Complete denitrification results in the formation of dinitrogen, or atmospheric nitrogen, which returns N to the atmosphere in a form with neither environmental nor health implications. However, nitrous oxide can also be produced during the denitrification process. Nitrous oxide is one of the most potent GHGs, with a global warming potential 265-298 times that of carbon dioxide (IPCC 2014).

Bacteria can also mediate the **immobilization** of N, where ammonium and nitrate in the soil are converted into organic N during the decomposition of plant residues high in carbon and low in N. This results in an immediate but temporary reduction of available N, which becomes available once again for future crop production when residue decomposition is complete.

Environmental factors (e.g., temperature, moisture, soil pH) highly influence these bacterial processes. All these N-loss mechanisms are related to each other, and trying to limit the conditions of one may trigger another within the N cycle. For example, oxygen is required for mineralization and nitrification. In its ammonium form, N is more prone to volatilization, and in its nitrate form, N is more prone to loss through leaching. On the other hand, the absence of oxygen may promote denitrification, resulting in nitrous oxide or dinitrogen emissions. Understanding the principles governing these N-loss mechanisms and their relationships is important when identifying strategies and management practices to minimize N loss.

Improving nitrogen use efficiency

Improving N use efficiency and reducing N losses to the ecosystem is of crucial importance, as these losses can trigger negative environmental and health effects in terrestrial, aquatic, and atmospheric ecosystems (Galloway et al. 2003).

In soils, N can be lost through volatilization, leaching, runoff, and denitrification. Perhaps the most impactful and easy-to-adopt strategy to reduce N losses and increase N use efficiency in soils is to match fertilizer and manure application rates to crop N demand through nutrient management planning. This strategy considers many factors, including the type of N applied, crop N uptake, yield goals, farm characteristics, management practices, environmental characteristics (e.g., temperature, rain, wind), and soil characteristics (e.g., soil organic matter, plant residues). Such planning is also promoted as the "4R" approach: right rate, right source, right timing, and right placement (Nutrient Stewardship 2017). Due to significant variation in crop and livestock production systems, implementing a nutrient management plan that includes soil and organic fertilizer nutrient analysis can greatly improve N management outcomes.

One of the most effective strategies to reduce ammonia emissions is to incorporate manure and fertilizers into the soil, avoid accumulation of ammonia and ammonium on the soil surface, and to facilitate crop uptake. As ammonia volatilization occurs during the first hours after application, producers should either incorporate manure the same day of surface application or inject it with specialized equipment. Placing fertilizers 1-2 in. (3-5 cm) below the soil surface can significantly reduce the risk of ammonia volatilization (Cameron, Di, and Moir 2012). When applying urea, a urease inhibitor (e.g., N-(n-Butyl) thiophosphoric triamide (NBPT), phenyl phosphorodiamidate, or hydroquinone) can be used to reduce the rate of urea conversion into ammonia in the soil (Bishop and Manning 2010). NBPT is the most widely studied urease inhibitor.

Land applying fertilizers and manures when weather is cooler can reduce ammonia volatilization. In addition, irrigating the field after applying fertilizers can move N deeper into the soil to minimize volatilization. However, if too much water is used there is a risk of promoting denitrification and leaching. Tillage can also move N into the soil and reduce volatilization; however, tillage can have other adverse environmental impacts and can also promote nitrification depending on slope, texture, and organic matter. Surface application of N fertilizer should be avoided in soils where lime has been applied recently because lime increases soil pH.

Losses of N through leaching can be significant and increase when there is over-application of N (Figure 3). Excess rain and irrigation will exceed the soil's water holding capacity,

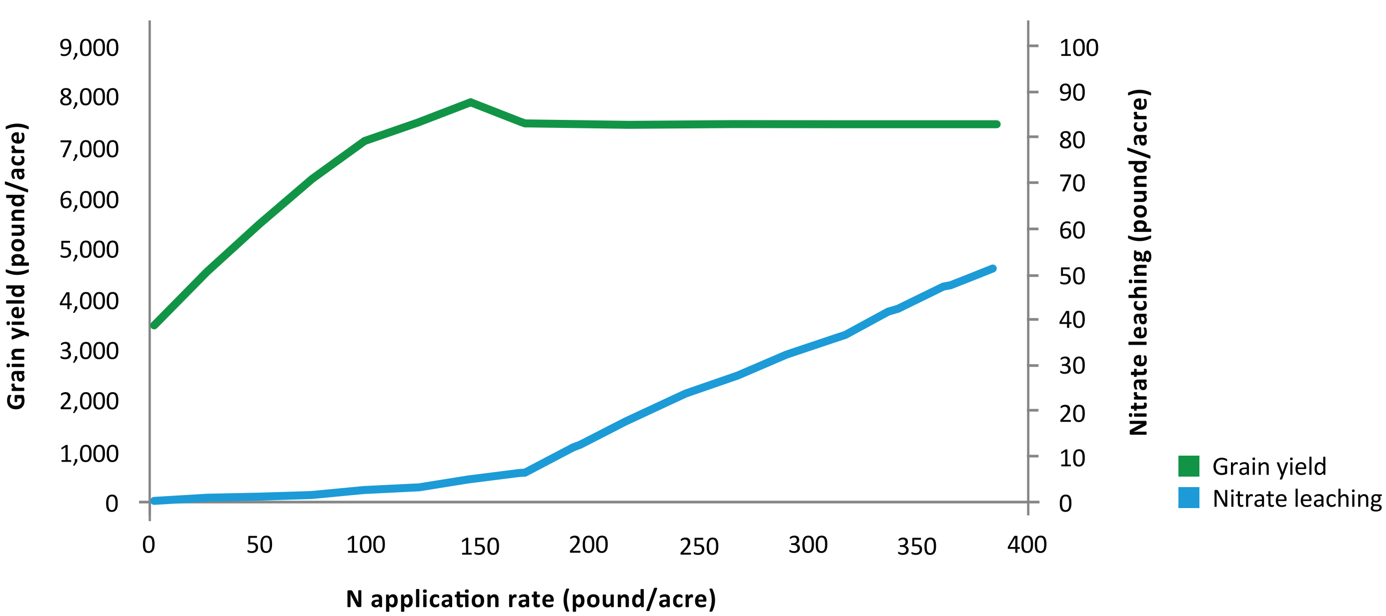

Figure 3. Response of grain yield and nitrogen (N) losses through leaching to different N application rates (modified from Zhang et al. 2015).

which causes nitrate to move through the soil profile and potentially reach groundwater, a common source of water for human consumption. Farms with coarsely textured soils need to pay special attention to leaching because even small amounts of ammonium can become mobile with excess water applications in these soil types. After rain and irrigation have saturated the soil, there is the risk for denitrification, as water pockets can remain in the saturated soil for days.

Different N transformation processes have different impacts on N availability for crops. Immobilization of N can reduce the rate of leaching, but it will temporarily reduce the availability of N to crops. Mineralization makes N more available to plants but may also increase the rate of leaching loss. As a result, one of the main strategies to reduce N loss without risking crop yields is to control the timing when organic and inorganic fertilizers are applied. The duration between N application and crop assimilation should be minimized so the opportunities for N loss are reduced. For example, corn needs N when it is 3-4 weeks old and again at grain fill, so N should be applied close to these periods. Applying N fertilizers throughout the growing season at critical uptake periods can further reduce N losses.

Application of N fertilizers should be avoided prior to precipitation or intense irrigation to avoid leaching. Soil conditions warmer than 10°C (50°F) (Cameron, Di, and Moir 2012) increase the chance that nitrate will form. Spring land application of N fertilizers may increase the formation of nitrate, as soils are moist and warm, but the risk of N loss can be reduced by matching the timing of application with crop uptake. Winter application should be avoided because freezing temperatures impede N binding to soil particles and increase runoff when the snow melts. This will also increase volatilization of N as ammonia. If winter application cannot be avoided, aim to avoid application during times of snowmelt or heavy rain and to apply to fields that have low potential for runoff to reach surface waters.

Leaching and denitrification could also be reduced by limiting the opportunities for nitrification so nitrate losses are minimized. When using inorganic commercial N fertilizers, one strategy is avoiding fertilizers that have nitrate as a constituent, such as ammonium nitrate and UAN, which would result in more N present in the soil as nitrate (Sawyer 2007). However, there are some limiting factors that could impede farmers from changing fertilizer types. These factors include fertilizer costs, availability, and additional equipment needed for application. In recent years, the use of nitrification inhibitors has received increased attention for slowing down the nitrification process and maintaining N as ammonium for later use by crops (Cameron, Di, and Moir 2012). Nitrification inhibitors can reduce the nitrate content in soil that could potentially be lost thorough leaching, but they may not be cost effective.

Maximizing N uptake to optimize crop growth is important not only for achieving high crop yields but for avoiding N losses to the environment. Efficient irrigation, controlling diseases and pests, and amending soil with other nutrients and lime to balance soil pH could be important to guarantee crop growth.

Proper soil management, such as reducing tillage, using cover crops, and adopting an appropriate crop rotation, can help improve the N use efficiency in soils:

- Tillage mechanically breaks up soil to create a good seed bed and facilitate the planting process. However, tillage may result in loss of N through leaching because it facilitates drainage. Tillage can also increase gaseous N emissions through nitrification because it aerates soils, breaking and exposing organic matter and plant residues. This makes N more accessible to nitrifying microorganisms.

- The use of cover crops can help capture excess N stored in the soil from residual plant material, reducing the potential for nitrate leaching. After grass cover crops are terminated, the N in the plant biomass is released slowly and will likely contribute to the soil organic matter. Legume cover crops tend to decompose quickly and release N in synchrony with corn N demand (Stute and Posner 1995). The amount of N released to the soil changes from crop to crop and depends on the carbon-to-nitrogen ratio (C:N). If crops are low in N, immobilization takes place as bacteria start consuming N from the soil making N temporarily unavailable for plant growth. On the contrary, when crops are rich in N (e.g., legumes), N is quickly released back into the soil. Thus, different cover crop species will have different effects on the N cycle, therefore selection of cover crop species should depend on farm needs.

- Crop rotation promotes healthy and fertile soils and reduces disease and pest pressures. For example, when alfalfa is in the rotation no tillage is needed. Also, alfalfa has a deep rooting system that can capture N from considerably deeper soils than other crops.

Conclusion

It is important to remember that there are many parts to the N cycle that are difficult to control. There are multiple opportunities for N to be lost to air and water, reducing N availability for crop production. Farmers should consider changes in their N management strategy to reduce environmental losses and improve N use efficiency. These strategies will be different not only from one agricultural sector to the next, but also between individual farm operations within the same sector. Given that N fertilizer is often one of the largest expenses for crop production, improvement in N use efficiency also results in economic gains for the farmer.

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