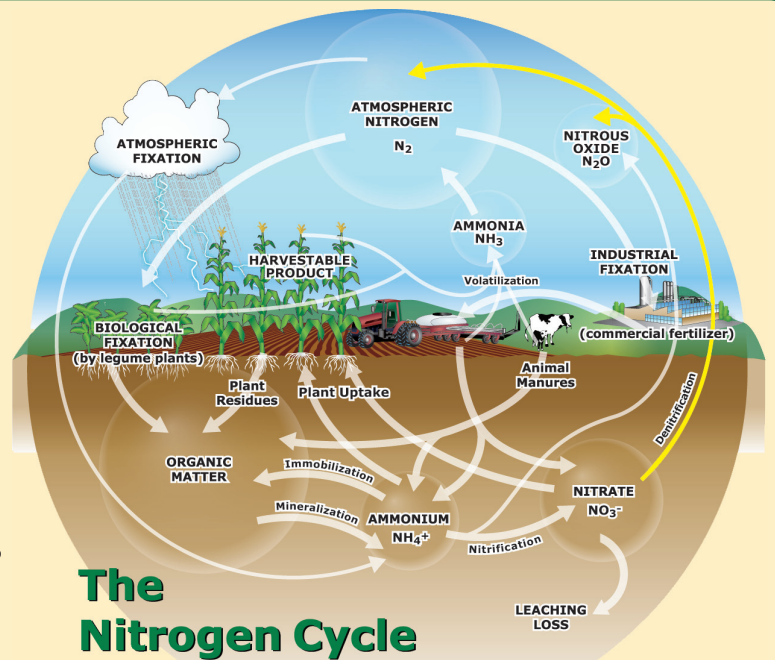


DENITRIFICATION

Denitrification is a natural soil microbial process where nitrate (NO_3^-) is converted to nitrogen (N) gases that are lost to the atmosphere. Denitrification occurs when soil bacteria use nitrate for their respiration in the place of oxygen in the air. This process occurs most rapidly in warm, wet soils with an abundance of nitrate.



What is it?

Soil microbes are capable of converting nitrate into various gases under certain conditions. This loss of nitrate by denitrification has negative economic consequences for crop production since valuable N fertilizer is lost to the air. However in many aquatic systems and for wastewater treatment, denitrification has a positive benefit of lowering the nitrate concentration in water. Denitrification can be viewed as either desirable or detrimental depending on the objectives.

Denitrification results in the reduction of nitrate to a variety of gases (including NO , N_2O , or N_2). One of these gases is nitrous oxide (N_2O), a potent greenhouse gas that can remain in the air for over 100 years. Nitrous oxide has also been linked with depleting stratospheric ozone. Although losses from the process may have global implications, the total losses from denitrification are generally less than 1% of total fertilizer N applied to agricultural soils. In unusual conditions, denitrifica-

tion losses of added N fertilizer may exceed 50%.

Why Does It Occur?

When the oxygen (O_2) supply in soil becomes limited, a variety of bacteria use the oxygen in nitrate for respiration. Denitrification most commonly occurs in wet or waterlogged soils where the oxygen supply for respiration is restricted. Some fungi can denitrify, but they are not considered significant.

When Does It Occur?

Denitrification proceeds rapidly when water-filled pore space in soils exceeds 60%. The end-product gas depends on the soil conditions and the microbial community. As the oxygen deficit increases, microbes tend to convert more of the nitrate to N_2 gas. For the purposes of nutrient management, denitrification results in a loss of valuable N, but the impact in the atmosphere will vary.

Nitrogen Notes is a series of bulletins written by scientific staff of the International Plant Nutrition Institute (IPNI). This series was supported by a grant from the California Department of Food & Agriculture and through a partnership with the Western Plant Health Association. This series is available as PDF files at www.ipni.net/publications.

Nitrogen NOTES

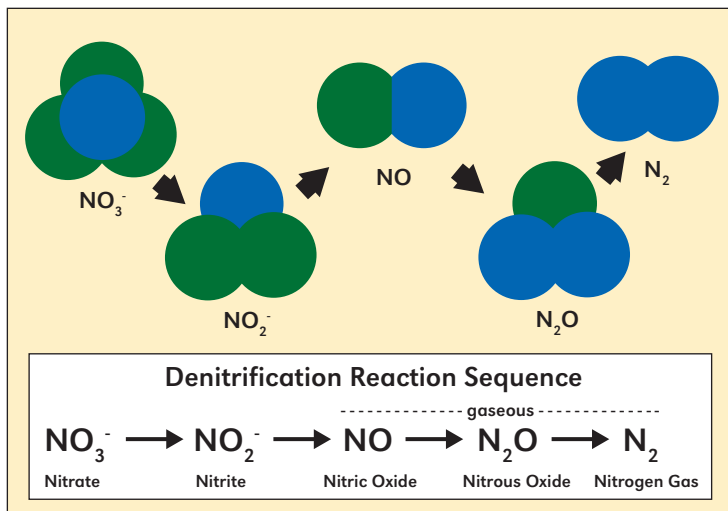


Figure 1. Nitrate must be present in the soil for denitrification to occur. The most common end products of denitrification are N_2O and N_2 gases that return to the atmosphere.

Controlling Factors

Presence of Nitrate: Denitrification only occurs when nitrate is present (**Figure 1**). One method for minimizing denitrification is to maintain a minimum concentration of nitrate needed to support healthy plant growth. This can be accomplished through techniques such as split fertilizer applications, fertigation, or the use of controlled-release fertilizers.

Another approach is the use of a nitrification inhibitor added to N fertilizer. Nitrification inhibitors temporarily restrict *Nitrosomonas* bacteria from converting ammonium to nitrite. Slowing this process reduces the rapid appearance of nitrate that commonly follows fertilization with ammonium-based fertilizer, or manure.

Temperature: Most soil microbial processes are strongly influenced by temperature. Studies show that denitrification is most rapid at temperatures between 80°F and 100°F, which is warmer than most soils, even during summer.

The relatively mild winter temperatures and rainfall patterns in California agricultural regions permit denitrification to continue year-round (although slower in the winter).

Soil wetness: The presence or absence of oxygen is one of the largest factors determining the extent and duration of denitrification. Denitrification can occur in aerobic (adequate oxygen) conditions, but to a relatively insignificant degree.

Wet soils are generally the trigger for denitrification to occur. Nitrogen gases can begin to appear as soon as 15 minutes after saturation if conditions are favorable. At higher soil moisture, N_2 tends to become the major product of denitrification, compared with N_2O (**Figure 2**).

In flooded rice production, there are usually very low concentrations of nitrate that can be denitrified because of careful fertilizer management. However during in-season draining events, nitrate may be produced which can be denitrified during subsequent flooding events.

Presence of dissolved carbon: Denitrifying bacteria obtain

their energy from soluble organic carbon. Therefore denitrification is enhanced in soils with a ready supply of organic carbon, such as manure, compost, cover crops, or crop residues. Soluble carbon also influences the end product of denitrification. Production of N_2 commonly dominates with an adequate supply of soluble carbon, while N_2O and NO production is more likely if soluble carbon limits microbial growth.

There have been experimental attempts to stimulate denitrification in the field to remove nitrate from water by adding soluble carbon (such as edible oil, molasses, and other rapidly degraded carbon sources) as energy sources for microbes. Similarly, passing nitrate-rich surface water through a reactor or through a constructed wetland to stimulate denitrification is a common technique for water treatment.

Soils that go through a prolonged dry period followed by rainfall or irrigation typically have a burst of soluble carbon that can support a spike in denitrification. Waterlogging also stimulates the release of soluble carbon into the soil that may support rapid denitrification.

Where Does It Occur?

Denitrification potential is greatest in the topsoil where microbial activity is highest. The topsoil contains the highest concentration of carbon, the microbial energy source. Nitrate moving below the topsoil is increasingly less likely to be denitrified with depth, as microbial activity generally drops rapidly beneath the root zone. One study reported that 68% of the denitrification potential occurred in the top ½ inch of the soil. A shortage of appropriate bacteria does not limit denitrification in most agricultural soils.

Plant roots have a variable impact on denitrification. Roots release significant amounts of soluble carbon and sloughed root cells. Oxygen in the soil is consumed during root respiration. Conversely, plant roots dry the soil as they draw moisture for

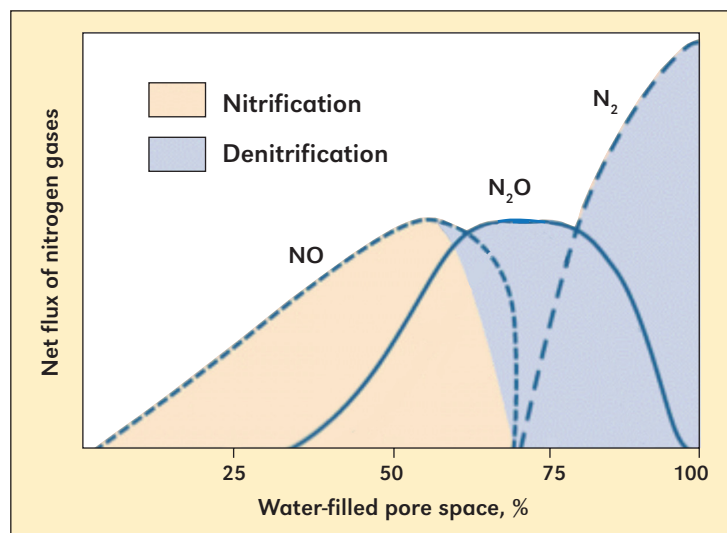


Figure 2. Nitrous oxide is produced through denitrification when the soil becomes wet and water-filled pore space begins to exceed 60%. In very wet soils, N_2 becomes more prevalent from denitrification. Adapted from: A.F. Bouwman, *Nature* 392, 866-867 (30 April, 1998).

Nitrogen NOTES

evapotranspiration and they deplete soil nitrate as the plant grows.

The process of denitrification ranges widely across a field. Many conditions, such as the random placement of crop residues, soil macropores and aggregation, and small-scale variations in soil organic matter and fertilizer distribution will all influence denitrification rates on a micro-scale. This variation makes accurate field measurements of denitrification challenging.

Denitrification Hotspots: Considerable confusion about denitrification results from the complexity of the process through the year, and variability across fields (**Figure 3**). Small areas (hotspots) and brief denitrification bursts often contribute most of the annual N_2O emissions from a field. For example, one study showed that more than 80% of denitrification from a soil core occurred in and around a single decomposing leaf, which comprised less than 1% of the soil core volume. Variations in soil texture and water holding capacity across the landscape will also influence denitrification losses.

Management factors such as fertilizer source, rate, timing, and placement as well as mowing cover crops, placement of crop residues, traffic compaction patterns, and irrigation uniformity will all influence these localized denitrification processes.

Similarly, sudden short surges of denitrification activity are commonly measured following a single rainstorm after an extended dry period. Freezing and thawing cycles can also have a similar stimulating effect.

Controlling Denitrification

Several field practices can be considered to reduce the loss of nitrate through denitrification. These include:

Soil Drainage: The farming problems associated with exces-

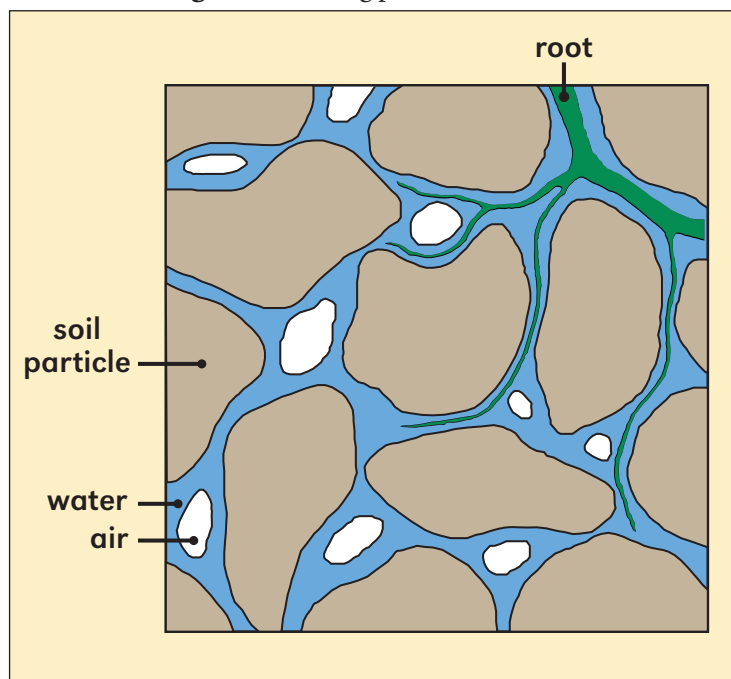


Figure 3. Within the soil, many different zones exist simultaneously. In a single soil aggregate, there can be wet zones, dry zones, nitrate-rich zones, and zones of abundant organic carbon.

Crop and Soil Management Practices for Controlling Denitrification

1. Minimize fertilizer and manure N applications in excess of the crop requirement to avoid surplus nitrate in the soil.
2. Time N fertilizer application for when plants are rapidly growing and have a requirement for the applied N.
3. Apply irrigation water to properly meet crop needs. Avoid overwatering and waterlogging as much as possible. Non-uniform irrigation can result in saturated zones in the field.
4. Use appropriate N sources, including controlled-release fertilizers, nitrification inhibitors, or urease inhibitors when they fit within the management plan.
5. Avoid soil compaction that can impede water flow and result in ponding and waterlogging; improve drainage in fields with excessive wetness.
6. Use urea or ammonium-based fertilizers where denitrification is anticipated.
7. Plant cover crops to reduce the concentration of residual nitrate in soil between cultivated crops.
8. Mow or kill cover crops as close to the time of planting the next crop as possible to minimize nitrate accumulation during decomposition.
9. Time applications of animal manure and compost to avoid wet soils. Manure provides a source of carbon and nitrogen that can stimulate denitrification.

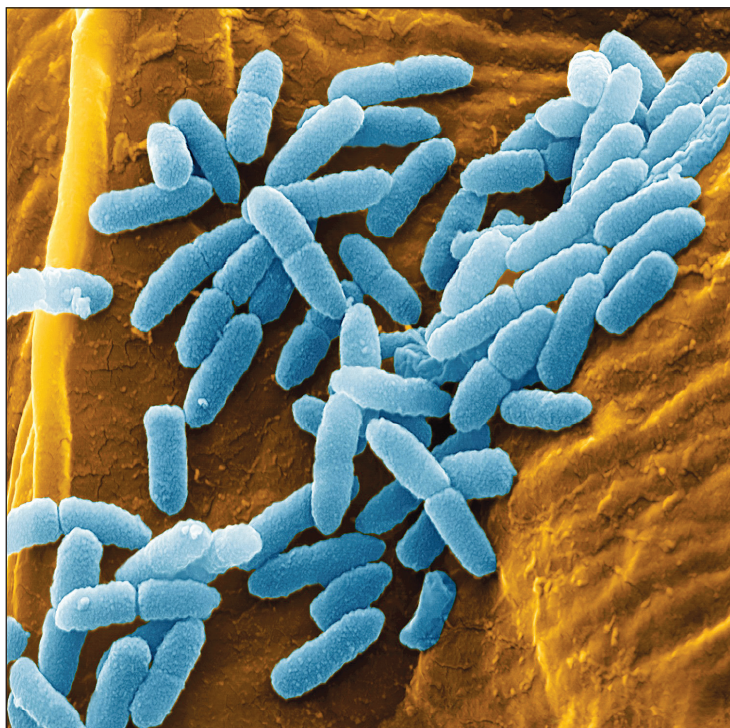
sively wet soils have led to placing drainage pipes and ditches in many fields, which reduces the potential for denitrification. In some areas, drainage water is intentionally held in the field for a prolonged time during the winter, which helps to stimulate denitrification and enhance nitrate removal from the water.

Inhibitors: The use of nitrification inhibitors has been consistently shown to lower denitrification and N_2O emissions. By slowing the conversion of ammonium to nitrate, there is less exposure of the N fertilizer to denitrification processes at any one time.

Irrigation Practices: The soil water content and the duration of wetting both have major impacts on denitrification. Irrigation practices that provide smaller and more frequent applications of water result in less denitrification. For example, subsurface drip irrigation has been demonstrated to have less N_2O emission compared with flood irrigation and surface drip irrigation. Only a small fraction of the soil is wetted when using drip irrigation, compared with furrow, flood, or sprinkler irrigation, reducing the extent of overly wet soil. However, in flood-irrigated alfalfa, very little N_2O is produced, except immediately following each irrigation event due to low soil nitrate concentrations.

The impact of irrigation techniques on denitrification is not always simple to predict. For example, nitrate commonly moves with added water to the fringe of the wetting front, where soil saturation is less likely. One study found that the largest losses of N_2O did not closely correspond to fertigation events. Instead, the largest losses occurred after shredding crop residues (input of soluble carbon), and following the first rainstorm after harvest (wetting and drying cycles).

Denitrification losses continue during the winter, although to a lesser extent than during the summer. The winter N_2O fluxes contributed about 10% to overall annual emissions in alfalfa, 10 to 25% in tomato, and 14 to 50% in lettuce. For



Juergen Berger / Science Source

An example of common soil bacteria (*Pseudomonas aeruginosa*) capable of denitrification.

winter wheat, most N_2O emissions occur during the winter growing season when N fertilizer is applied.

Nitrogen Fertilizer Source: The presence of nitrate is required for denitrification, so the selection of a N fertilizer source can be important. Fertilizer materials and practices that maintain N as urea or ammonium reduce the short-term risk of denitrification.

There are reports that the selection of specific N fertilizer sources can influence denitrification. For example, use of anhydrous ammonia is sometimes shown to have greater N_2O emissions than the use of UAN or urea. The selection of a particular soluble N fertilizer does not seem to consistently result in a significant reduction in denitrification. However there are consistent reductions in denitrification associated with the use of coated controlled-release N fertilizers. Nitrous oxide emissions from polymer-coated urea were reduced by as much as 50%, when compared with dry granular urea in several studies.

Placement of fertilizer can be important. When N fertilizer was applied in a concentrated band, N_2O emissions were 45% greater than when broadcast across the soil surface and incorporated. Similarly, denitrification losses from N applied through fertigation were less than equivalent broadcast N applications. Placing N fertilizer at least 2 inches beneath the soil surface will also help decrease N_2O emissions.

Cover Crops and Residues: The effects of winter cover crops on denitrification is not consistent. They can increase N_2O emissions, especially during the rainy season. Cover crops add significant amounts of soluble carbon and N when they

decompose, leading to a temporary surge in denitrification. In other situations, cover crops scavenge nitrate from the soil, leading to less denitrification. It is desirable to kill cover crops as close to planting a following crop as practical in order to minimize various N losses.

Mowing and grazing cover crops and pastures can indirectly influence denitrification by rapidly changing the N demand by plants and by introducing organic matter back to the soil, consequently increasing N_2O emissions.

Fertilizer Rate: A basic strategy for controlling denitrification is to maintain the minimum nitrate concentration required for plant nutrition. Nitrous oxide emissions are generally small if high N use efficiency is achieved, therefore an overabundance of fertilizer or manure should always be avoided. Nutrient management practices that optimize crop N recovery will also minimize N_2O loss and nitrate leaching. The concept of “yield-scaled N_2O emissions” focuses on obtaining the highest possible crop returns while simultaneously minimizing undesirable emissions.

Other Sources of Nitrous Oxide

Denitrification is generally the most important source of N_2O from soils, however there are also other pathways for producing N_2O (Figure 4). During the nitrification process, a small group of soil bacteria are capable of converting nitrite to N_2O (called nitrifier denitrification). In some soils, their contribution to overall N_2O emissions can be significant.

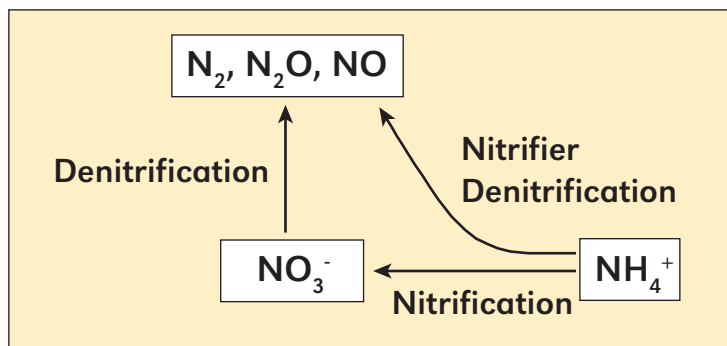


Figure 4. Nitrous oxide gas is emitted by soil bacteria during denitrification and also from leakage during the nitrification process.

Conclusions

Many interacting factors involving fertilizer, water, and soil management govern denitrification in agricultural soils. The two factors that can be most easily controlled are N fertilizer and water application. In general, practices that increase the presence of surplus nitrate will increase denitrification losses, especially in warm and moist environments. Using the appropriate source, rate, time and place of N fertilizer will reduce N_2O emissions. Improved irrigation practices that optimize soil moisture help minimize denitrification. Efficient use of applied N and water by the plant will reduce unwanted N_2O losses. ❖