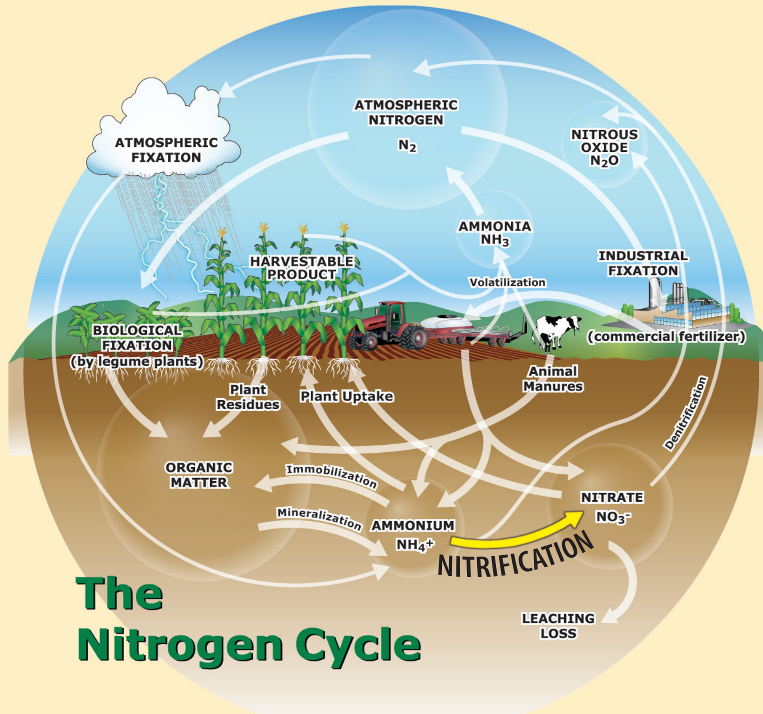
NUMBER 4

Nitrogen NOTES

NITRIFICATION

Nitrification is a two-step conversion of ammonium (NH_4^+) to nitrate (NO_3^-) by soil bacteria. In most soils, it is a fairly rapid process, generally occurring within days or weeks following application of a source of ammonium.



Ammonium in the soil comes from a variety of sources, including animal wastes, composts, decomposing crop residues, decaying cover crops, or fertilizers containing urea or ammonium. Regardless of the source, the soil bacteria will convert it to nitrate if conditions are favorable.

$$\underset{\text{Ammonium}}{NH_4^+} \xrightarrow{\textit{Nitrosomonas}} \underset{\text{Nitrite}}{NO_2^-} \xrightarrow{\textit{Nitrobacter}} \underset{\text{Nitrate}}{NO_3^-}$$

First Step:

Ammonium is initially oxidized to nitrite by a variety of "chemoautrophic" bacteria. These bacteria derive energy from changing ammonium into nitrite while using CO_2 as their carbon source. Although there are a variety of soil microorganisms that oxidize ammonium, most attention is given to bacteria in the genus *Nitrosomonas*.

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4H^+ + \text{energy}$$

Second Step:

The second step of the nitrification process is the conversion of nitrite to nitrate by bacteria in the genus *Nitrobacter*. This group of soil bacteria obtain their energy from the nitrite oxidation process. Other soil bacteria can also be involved in these transformations, but their contribution is generally less important. Nitrite can be toxic to plants, so it is important that nitrite completely converts to nitrate.

$$2NO_2^- + O_2 \rightarrow 2NO_3^- + \text{energy}$$

Nitrate is generally the dominant form of plant-available nitrogen (N) in soils and it requires careful management to keep it in the root zone of the growing plant. Most agricultural plants are adapted to utilize nitrate as their primary source of N nutrition. Some notable exceptions to this include crops such as rice and blueberries.

Nitrate that is not used for plant nutrition is susceptible

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.

IPNI International Plant Nutrition Institute
WPHA Western Plant Health Association
cdfa California Department of Food & Agriculture
FREP Fertilizer Research and Education Program

to leaching, runoff, or denitrification, so it is important to understand the nitrification process in soil.

Nitrification: How Fast?

There are a number of soil environmental factors that interact to influence the rate that ammonium converts to nitrate. The major factors are soil temperature, pH, water content, and the presence of oxygen. Other factors that can influence the process include soil salinity, texture, and the N source.

Soil nitrifying bacteria are generally more sensitive to environmental stresses than many other soil bacteria. Their growth rate is slower and their activity is lower than most other common bacteria. Total numbers of nitrifying bacteria have been estimated to constitute less than 0.01% of the total population of soil bacteria.

Nitrification rates in soil are measured by analyzing the appearance of nitrate after a period of time. However there are many complex reactions involving N that are simultaneously occurring. For example, within a single shovelful of soil there may be nitrification, denitrification, ammonia volatilization, mineralization, and immobilization all occurring at the same time. What is measured after nitrate production and consumption is interpreted as "net nitrification".

Soil Temperature

Like almost all biological reactions, nitrification is strongly influenced by soil temperature. The optimal temperature for nitrification has been reported to range from 60° F to 100° F depending on the specific conditions. In general, when soil temperatures exceed 75° F, nitrification is no longer limited (**Figure 1**).

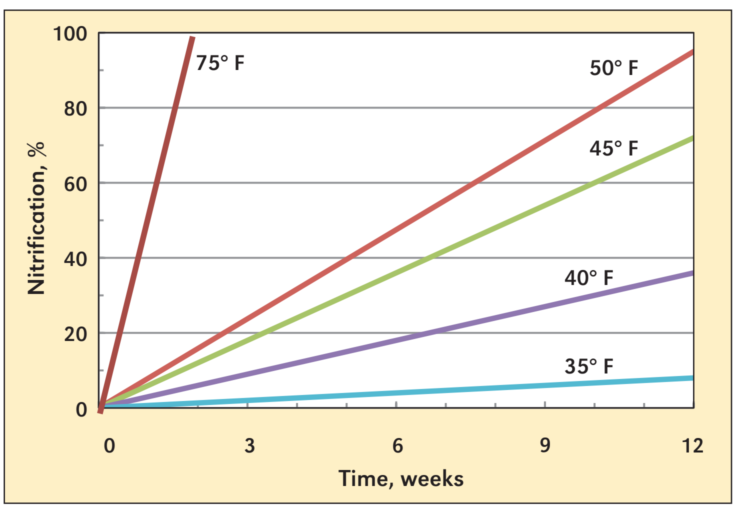


Figure 1. Generalized rate of nitrification at various soil temperatures (redrawn from Western Fertilizer Handbook, 2012).

Cold soil temperatures slow nitrification, with the process largely ceasing at soil temperatures below 40° F. Soils in the major agricultural regions of California rarely dip below that limiting temperature, so it can be assumed that some nitrate is being produced anytime there is a source of ammonium present (**Figure 2**).

In the Mid-West U.S., ammonium-based fertilizers are routinely applied to cold soils during the fall and winter after

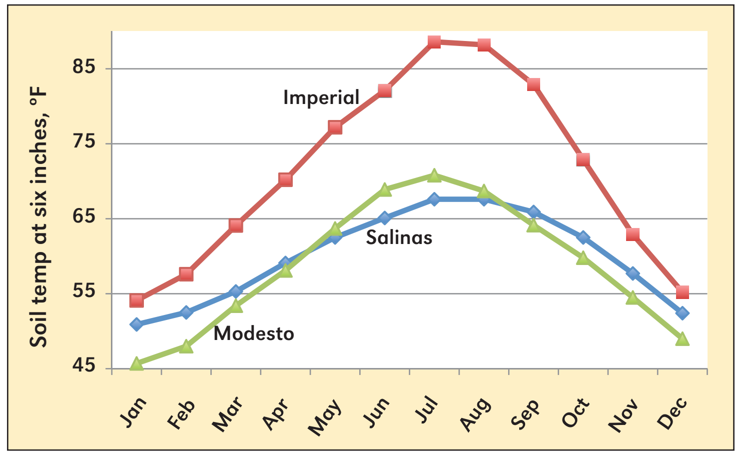


Figure 2. Soil temperatures at a six-inch depth in three regions of California (from the SIMIS weather network).

soil temperatures consistently drop below 50° F. It is assumed that little or no nitrification will occur during the cold winter months. This practice is not recommended for California conditions because soils are rarely sufficiently or consistently cold enough to inhibit nitrification to a significant extent.

Most nitrification takes place within the top few inches of soil. The soil temperature at this shallow depth is usually greater during the day and cooler in the night than the temperatures at a 6-in. depth. The plant canopy cover, soil surface wetness, and clouds can also influence the daily soil temperature fluctuations.

Farmers relying on mineralization and nitrification of organic composts and manures to supply plant-available nitrate can occasionally encounter temporary nutrient shortages during prolonged cool periods.

Soil Moisture

Nitrifying bacteria are sensitive to changes in soil water content since it influences the abundance and activity of bacteria. It also impacts the equilibrium between soluble and exchangeable ammonium, the concentration of salts in the water, and the oxygen content (**Figure 3**).

Immediately after rainfall or an irrigation event, soil pores may become filled with water and the oxygen supply may be temporarily restricted. Nitrification rates decline under these conditions since the presence of oxygen is essential for the process. If the soil remains saturated for more than a few days and low oxygen conditions persist, any nitrate that was present may be at risk for loss through denitrification as nitrous oxide or dinitrogen gas. Because of the absence of oxygen in flooded soils, nitrification is not an important part of the N cycle in these systems (except in oxygenated microsites such as surrounding plant roots).

It is estimated that nitrification becomes restricted when the water-filled pore space is greater than 60%. However, as water drains and oxygen re-enters the soil, nitrification quickly resumes as the bacteria population recovers.

Nitrification rates are also limited by a lack of water. As soils dry through evaporation or drainage, the dissolved salts in the soil solution becomes increasingly concentrated. The resulting salinity stress increases the energy costs for maintenance of

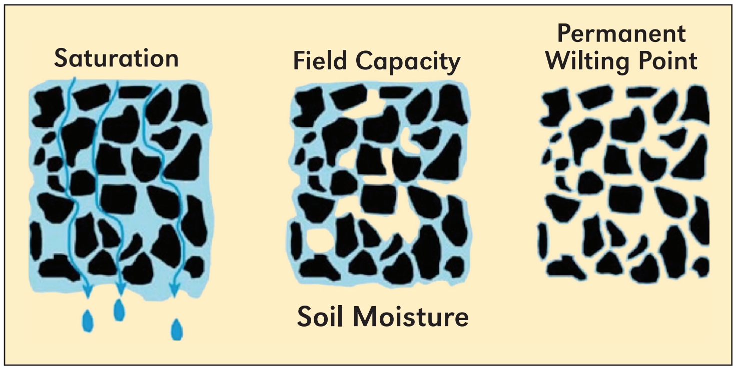


Figure 3. No nitrification occurring, dentrification possible (left); optimal moisture condition for nitrification (middle); dry soils have reduced nitrification rate (right).

the nitrifying bacteria and slows their activity. The water films on the soil surfaces become thinner as the soil dries, slowing the movement of solutes in the soil. Dry soils also cause cell dehydration, which inhibits all microbe activity.

In dry environments, a surge in microbial activity (including nitrification) is commonly seen when a soil is rewetted by irrigation or rainfall following a prolonged dry period. However even during dry periods, nitrification may still occur, although at a reduced rate.

Soil Properties and Tillage

The greatest number of nitrifying bacteria are found near the soil surface, although smaller numbers can sometimes be found at depths of many feet. The number and activity of nitrifying bacteria are typically greater in soils with a higher content of clay and organic matter. Soils with a high clay content have a greater cation exchange capacity to retain ammonium, clay particles provide a large favorable surface area and more soil micropore space which is favorable for bacteria attachment and growth.

Tillage practices affect soil organic matter content, soil aggregation, and microbial ecology. General trends indicate that nitrification activity is higher with no-till and reduced-till cultivation compared with conventional tillage practices. This may be caused by changes in soil physical properties and improved water relations that are associated with reduced tillage practices.

Soil pH

Nitrification occurs over a wide pH range in soil, although the optimal pH has been estimated to be between pH 6.5 to 8.8. Nitrification rates are slower in acid soils, and the addition of limestone to reduce soil acidity often results in more rapid nitrification. In high pH conditions (>8), the activity of *Nitrobacter* can be reduced. This condition allows conversion of ammonium to nitrite, but not the second step of nitrite conversion to nitrate. This can potentially allow an undesirable accumulation of nitrite in the soil.

Presence of Ammonium and Fertilizer Source

Without ammonium present in the soil, there is no nitrification. Ammonium does not typically accumulate to high concentrations during the growing season, since nitrification generally proceeds quickly. However, because of the nature of fertilizer application and the tendency of ammonium to remain close to the point of application, localized high ammonium concentrations can occur.

Elevated concentrations of ammonium are common following application of fresh organic materials or many N fertilizers. Differences in nitrification rates have been identified between various manures and composts (related to application rates, ammonium concentration, the C:N ratio, etc.) but they are not usually important in field situations.

Very high concentrations of ammonia (such as surrounding a concentrated band of anhydrous ammonia) can temporarily inhibit nitrification. This is due to the toxic effects of ammonia gas on soil bacteria and elevated pH that temporarily surrounds concentrated bands of ammonia.

For common N fertilizers, the source of ammonium may influence the rate of nitrification. It is possible to measure differences in the nitrification rate among various sources of N fertilizers in the laboratory. For example, one study reported that nitrification rates decreased in the following order: urea > diammonium phosphate > ammonium sulfate > ammonium nitrate > monoammonium phosphate. These differences were attributed in part to an increase in acidity (for example, the pH of a DAP solution is approximately 8.0, while MAP is pH 3.5). In most field conditions, these differences are not significant for plant nutrition.

A study using a variety of California soils noted that nitrification rates generally followed the trend: ammonium hydroxide (aqua ammonia) > ammonium sulfate > ammonium nitrate, but it was not consistent among all soils tested (**Figure 4**).

Salinity

High concentrations of salt raise the osmotic potential of the soil solution. As salinity increases, nitrification rates drop. Elevated salt concentrations increase the energy required by microorganisms and plant roots to maintain their cell integrity and to move water across their membranes

The negative effect of salinity on nitrification that may follow the application of a concentrated fertilizer band is temporary. Fertilizer salts can impair nitrification, especially if they are applied in a narrow band.

Nitrification Generates Acidity:

The first step of nitrification results in the release of H^+ ions, increasing soil acidity. The degree of acidification depends on the ability of the soil to resist change (buffer capacity), and the amount of ammonium applied. This natural acidifying process occurs with all sources of ammonium, whether it is from animal manure, organic N sources, or inorganic N fertilizer.

One study conducted on coarse-textured (poorly buffered) soil showed a significant drop in pH when ammonium-containing fertilizers were applied through a drip irrigation system for almonds. Repeated application of ammonium to a small volume of soil will concentrate the effect of acid production near the zone where roots may be abundant (**Figure 5**).

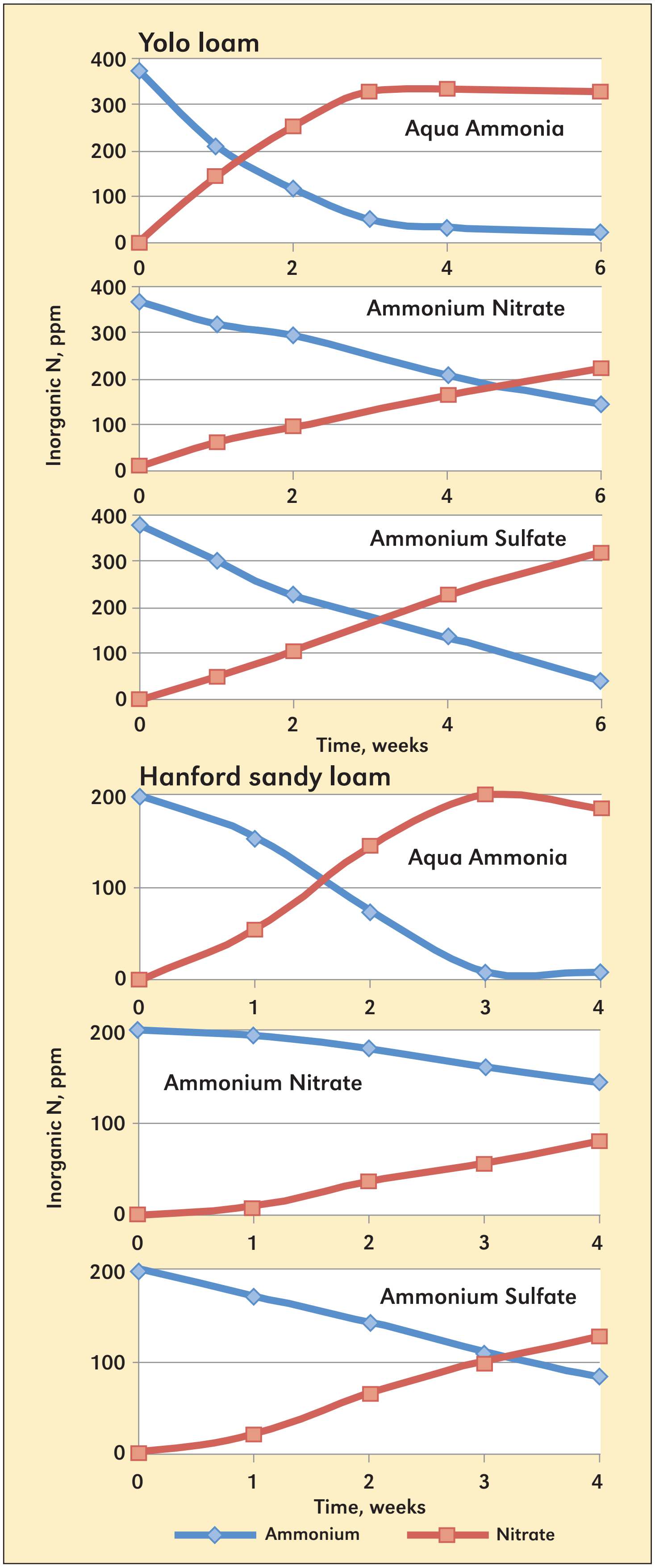


Figure 4. The effect of N fertilizer on the rate of nitrification in a Yolo loam soil (200 lb N/A) and a Hanford sandy loam (100 lb N/A) at 75° F. Broadbent et al., 1957.

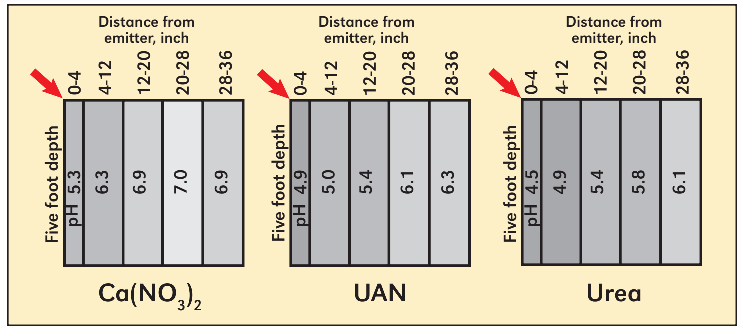


Figure 5. The effect of N fertilizer source applied through a drip emitter on soil pH (Arbuckle gravely loam). Meyer et al., 1994.

The following reactions represent examples of three commonly used N fertilizers and the acidity produced during the nitrification process.

Ammonium Sulfate:

$$(NH_4)_2SO_4 + 4\,O_2 \rightarrow 4\,H^+ + 2\,NO_3^- + SO_4^{2-} + 2\,H_2O$$

Urea:

$$(NH_2)_2CO + 4\,O_2 \rightarrow 2\,H^+ + 2\,NO_3^- + CO_2 + H_2O$$

Ammonium Nitrate:

$$NH_4NO_3 + 2\,O_2 \rightarrow 2\,H^+ + 2\,NO_3^- + H_2O$$

Nitrous Oxide Loss During Nitrification

During the first step of nitrification, a small portion of the ammonium may be converted to nitrous oxide gas (N_2O) during the decomposition of nitrite. This process is important because nitrous oxide is a potent greenhouse gas and efforts are made to reduce its loss. The absolute quantity of fertilizer that is lost as nitrous oxide during nitrification in aerobic soils is relatively small, but environmentally significant.

Nitrification Inhibitors

Nitrate is vulnerable to leaching loss and to gas loss through denitrification. There are occasions where it is desirable to maintain N in the ammonium form to minimize these losses. Many chemicals have been tested for selective inhibition of nitrification. Only two nitrification inhibitors are currently approved for use in California; DCD (dicyandiamide) and nitrapyrin. There is considerable variability regarding the economic return, the degree of inhibition, and the potential benefits associated with their use.

Understanding the process of nitrification is central to managing the soil nitrate supply. Environmental conditions and farming decisions influence the behavior of nitrate in soil. Attention to soil temperature, moisture, and soil properties will help maintain the appropriate amount of nitrate. Careful management of ammonium nutrient sources can help achieve the desired crop nutrient supply and minimize losses of nitrate. ❖

References

Broadbent, F.E. et al. 1957. Hilgardia 27: 247-267.
Meyer, R.D. 1994. Report of Almond Board California.