for Irrigated Agriculture
in the Southwest

BASIC PHYSICAL, CHEMICAL AND BIOLOGICAL FACTORS AFFECTING NITROGEN TRANSPORT THROUGH SOILS

A supporting document for the
UC Center for Water Resources (http://www.waterresources.ucr.edu)
Nitrate Groundwater Pollution Hazard Index

Nitrogen use at the land surface has no effect on ground water quality unless the N is transported to the ground water. Water flowing through the soil toward ground water is the major mechanism for chemical transport. The chemical form of N is also critical. For example, nitrate (NO_3^-) is very mobile and will be freely transported by flowing water. Conversely, ammonium (NH_4^+) and organic forms of N (ON) are sorbed by the soil and not readily transported by flowing water.

N can be in many chemical forms in the soil. Significantly, chemical transformations continuously occur that change the chemical form of N in the soil with time. The main transformations with approximate rate of reaction are as follows:

Mineralization

$ON \rightarrow NH_4^+$ (weeks to years)

Nitrification

$NH_4^+ \rightarrow NO_3^-$ (days)

Denitrification

$NO_3^- \rightarrow NO_2 \rightarrow N_2O \uparrow \rightarrow N_2 \uparrow$ (days)

Requires bacteria and absence of oxygen

Immobilization

NH_4^+ or $NO_3^- \rightarrow$ plant or microbial tissue (ON)

Ammonia volatilization

NH_4^+ in alkaline solution $\rightarrow NH_3 \uparrow$

These transformations are temperature dependent and tend to increase with increasing temperature.

The basic mechanisms and flow paths for N in the ecosystem, commonly called the N cycle, are illustrated in Figure 1. About 79 percent of the atmosphere is composed of N_2 gas, which is generally not available for biological production. Some plant species, such as alfalfa, have rhizobium bacteria associated with their root system. The rhizobium is capable of utilizing N_2 and producing nitrogenous compounds, which they use and are also made available for the host plant. The N in the plant tissue is passed on to animals that eat the plants and the N is subsequently released to the soil in the form of animal waste or dead body parts. Likewise, dead plant tissues containing N are deposited on or within the soil. These organic materials are subject to decomposition by microorganisms, which release NH_4^+ to produce NO_3^-. If the ratio of C to N in the organic matter that is to be mineralized is too great, the microorganisms utilize mineral forms of N from the soil to achieve the desired ratio. This process reduces the mineral N concentration in the soil and the process is referred to as immobilization of N.

During pre-industrial times, nitrogen was commonly deficient and a limiting factor for maximum crop production. Crop rotations, which included N fixing crops, were required to provide a N supply for crops. Diverse farming systems, which included animals, were common and the manure from the animals was applied to croplands as a fertilizer source. Mineral N availability for crops by symbiotic fixation and/or mineralization was a continual process and the growing crop tended to take up the mineral N as it became available. As such, large concentrations of NO_3, which could be leached, did not develop in the soil. Therefore, ground water degradation was not a big problem.

Nitrogen fertilizer production in factories freed the farmers from many of the constraints imposed by the “natural” nitrogen cycle. Manufactured N could be applied directly to the cropland, thus removing N as a limiting factor for increased yields. In the United States, the use of N fertilizer increased twenty fold between 1945 and the early 1980s and then leveled off (USGS, 1999). Increasing crop production paralleled this increase in fertilizer application. The large addition of N to the cycle (Fig. 1) increased the amount of N in each compartment within the cycle, including the amount leached to ground water. Thus, present agricultural management must consider the potential for ground water degradation as well as crop production.

The proliferation of combustion engines, which under high temperature and pressure, convert N_2 into other nitrogenous compounds, has also increased the availability of N in the ecosystem. The atmospheric deposition of nitrogenous compounds probably is of little significance to agricultural systems, but can affect natural landscapes and lakes. Therefore, this pathway is included in the N cycle (Fig. 1).

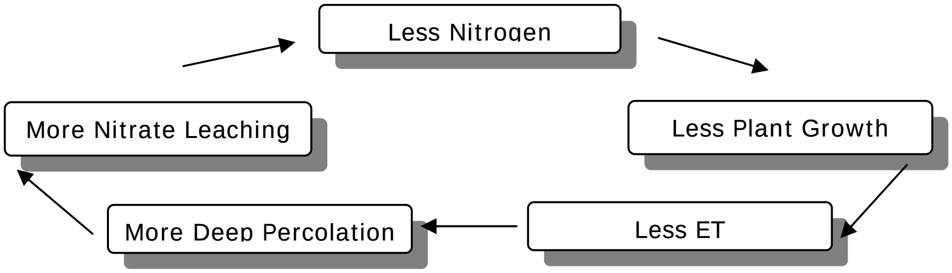
Water is the transporting medium so water flow, particularly below the root zone, is equally if not more important than N application rates in affecting the amount of NO_3^- transported to ground water. Not all water entering the soil flows to the ground water. Some or all of it may be retained and ultimately returned to the atmosphere through evapotranspiration. Plants extract water via roots and transpire it to the atmosphere through the leaves. Water at depths much below the root zone will not be retrieved by the plant and will flow toward ground water.

The storage capacity for water of a given soil is a function of soil profile characteristics and root depth. Irrigation or precipitation in an amount exceeding the storage capacity during any one event will migrate to the aquifer. As a simple approximation, the distance water moves toward the ground water is the amount percolating below the root zone divided by the soil volumetric water content expressed on a fraction basis. For example, if the deep percolation is 10 centimeters of water and the volumetric water content is equal to 0.25, that water would move 40 centimeters towards ground water. Subsequent deep percolation continues to move the water further downward.

Irrigation and precipitation are discrete events. Evapotranspiration (ET) is a continuous process. Assume at time zero that the soil storage capacity is fully recharged, thereafter ET proceeds and extracts water from the soil and increases the unused storage capacity. The available storage capacity at any time is the integral of the continuous ET function at that time. If irrigation or precipitation does not exceed the available storage capacity that has been created by evapotranspiration, no deep percolation occurs. Conversely, if irrigation or precipitation exceeds the storage capacity, deep percolation occurs. Therefore, the timing and amount of irrigation or precipitation events are important and not just the total annual amount.

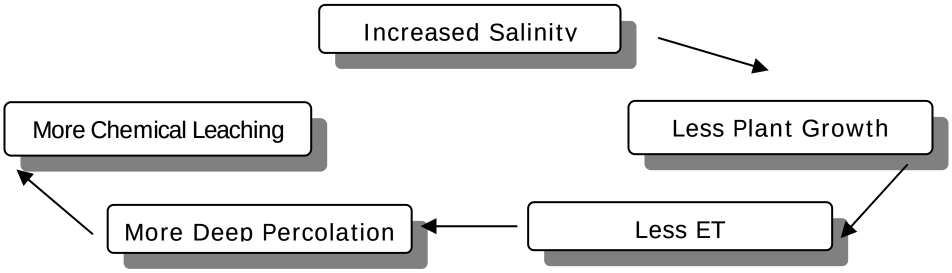
ET is recognized to be a function of climate and crop. Almost always ignored or unrecognized is the fact that ET is also a function of plant growth. A rapidly growing plant will transpire more water than a slower growing plant. Failure to account for this factor can lead to serious errors in estimating potential ground water degradation.

Irrigation and N fertilizer application are codependent management factors. Irrigation provides water for both plant growth and is a potential carrier of NO_3^- to ground water. Fertilizer application provides N for both plant growth and is a potential N source for ground water degradation. ET is a function of plant growth; therefore, ET is a function of both irrigation and fertilizer management. Although reduction in N fertilizer application would appear to be an obvious method of reducing the potential for ground water degradation by NO_3^-, this result may not be achieved if the reduced N application also reduces plant growth. A negative feedback loop could be initiated as illustrated in the following diagram.



This diagram is drawn with the assumption that the amount of irrigation is constant. By mass balance, a reduction in ET must be accommodated by an increase in deep percolation.

Salinity of the irrigation water can also affect the amount of chemical transport to ground water by its effect on plant growth. The following diagram illustrates this effect.



This is a self-correcting mechanism for salinity. The increased salinity, which induces reduced plant growth, initiates a process causing more salt leaching in an attempt to correct the problem. However, other chemicals such as NO_3^- are also leached with the salts. Therefore, irrigating crops with waters of higher salinity stimulates a higher amount of chemical transport to ground water.

Complications arise in the analysis of N transport because plant growth, N uptake by the plant and ET are continuous functions that are not constant with time, and water and N applications are discrete events. Therefore, the timing, as well as the amount of application, is important. For example, a one-time N application requires that the entire crop N requirement be applied before the crop is established. The N is thus available for leaching at any time during the growing season when excess water is applied. The amount of N leaching, however, would be much greater if the excess water was applied early in the season when most of the N was still in the soil. The same amount of excess water later in the season would leach less N because the crop would have already taken up much of the N.

In principle, increasing the frequency of discrete events to make them closer to a continuous function is advisable. Drip irrigation provides the opportunity to irrigate frequently with controlled amounts of water during each irrigation event. Applying fertilizer through a drip system (fertigation) allows frequent N applications to match the crop uptake pattern. This approach allows the greatest potential for high crop yield and low ground water degradation. However, there may be economic as well as other constraints to implementing this strategy.

The multiple, complex, time-dependent factors involved in determining the effects of a given management practice on crop growth and ground water degradation require numerous computations of chemical, physical and biological interactions. Fortunately the advent of high-speed computers provides an opportunity to achieve this goal. The development of a multi-component model for crop yield and potential ground water degradation applicable for irrigated agriculture is required to utilize the benefits of computers.

The ENVIRO-GRO model (Pang and Letey, 1998) was developed to simulate (1) water, salt, and N movement through soil with a growing plant; (2) plant response to matric potential (soil-water status), salinity, and N stresses; (3) drainage and salt and N leaching; and (4) cumulatively relative transpiration and relative N uptake, and consequently crop relative yield. Evaluation of the model was done by comparing simulated results with the results reported by Tanji et al. (1979) for an experiment that had N application rates of 0, 90, 180, and 360 Kg N/ha and water application rates of 21 cm (very dry), 63 cm (approximately crop ET), and 105 cm (very excessive). Agreement between simulated and observed corn relative yield and total N uptake was generally good. The difference between mean observed and predicted values was <0.06 for corn relative yield and 1.34 Kg N/ha for total N uptake.

A pesticide transport module was added to the ENVIRO-GRO model (Pang and Letey, 1999). The model was used to simulate the effects of salinity, irrigation, and nitrogen application on leaching of two pesticides. Increasing water amount, increasing water salinity, and decreasing N application contributed to a simulated increase in pesticide leaching. Those management variables that resulted in less crop yield and, therefore, more deep percolation contributed to more pesticide leaching. Two conclusions can be drawn from this study. First, the amount of chemical leaching was greatly affected by plant growth; so transport models that do not account for the effects of plant growth will produce faulty results. Second, a policy to protect ground water quality by regulating the application of agrichemicals may have limited benefit and may be counter productive if plant growth is reduced causing increased deep percolation.

References:

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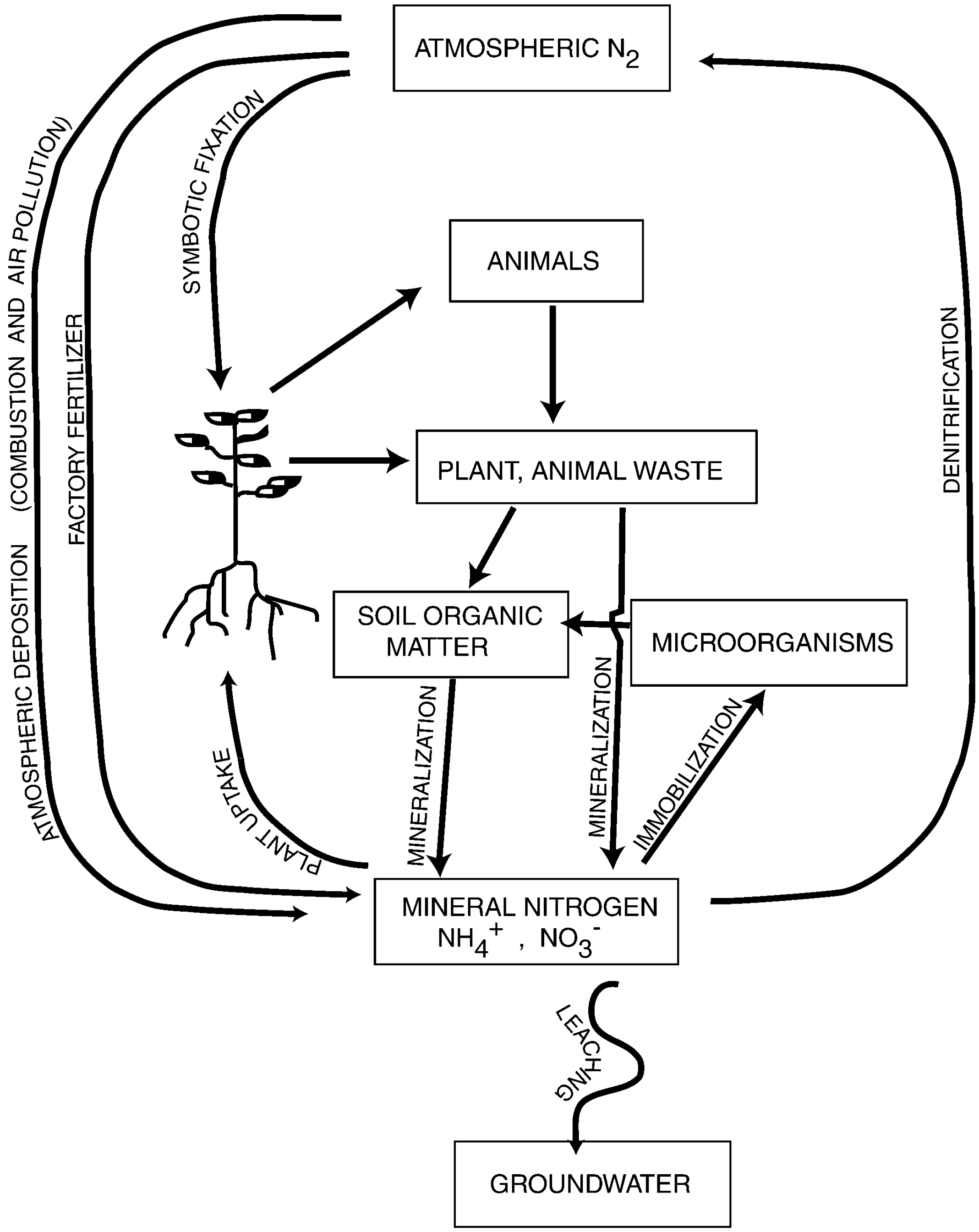

Figure 1. Schematic of the Nitrogen Cycle.