Nitrogen: The Essential Element

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Use of Nitrogen as a Fertilizer

In 1898, the president of the British Association for the Advancement of Science, Sir William Crookes, startled a distinguished scientific audience when he declared during his presidential address that "England and all civilized nations stand in deadly peril of not having enough to eat." The deadly peril that Sir William foresaw was the inability of farmers to satisfy the increasing demand for food given current supplies of nitrogen.

At the time of Sir William's address, the main sources of nitrogen fertilizers were sodium nitrate and ammonium sulphate. Sodium nitrate was obtained from immense deposits of nitrate-bearing rocks, called caliche, that had been discovered in Chile at the beginning of the nineteenth century. Ammonium sulfate was obtained from coal gas. Other sources of nitrogen included sewage, guano (bird droppings), and manure, but these were of declining importance.

Sir William suggested that to meet the world's increasing nitrogen needs, chemists must develop methods for artificially fixing atmospheric nitrogen. A successful response to this challenge was made by the German scientist Fritz Haber. Haber created a method for synthesizing ammonia from nitrogen and hydrogen, which was later developed into an industrial process by the industrial chemist Carl Bosch and became known as the Haber-Bosch method.

At the outset of the First World War, the estimated world annual production of nitrogen fertilizers was about 0.6 million tons, compared to a world production of 2.5 and 1.0 million tons of phosphorus and potassium fertilizers, respectively. Today, primarily because of the Haber-Bosch process, this trend has been reversed. Currently, the United States alone annually produces about 12 million tons of nitrogen fertilizers, compared with 10 million tons of phosphorus and only 2 million tons of potassium fertilizers.

With today's high inputs of nitrogen fertilizers, American farmers routinely achieve levels of crop productivity that would have seemed improbable to Sir William Crookes and his fellow scientists. In the past fifty years, for example, the average annual yields of corn in the United States have increased by a factor of four or five. This advance in agricultural productivity, and the fertilizer use upon which it depends, is indispensable if the world's population is to be sustained. Unfortunately, these gains have incurred environmental costs; some nitrogen applied to crops escapes to ground and surface waters, sometimes with damaging consequences.

Nitrogen in Plants, Soil, and Groundwater

Good crop yields depend on an adequate supply of nitrogen. Most nonlegume crops require added nitrogen to achieve the yields required today. Lacking sufficient nitrogen, plants usually become yellow and stunted, with smaller than average flowers and fruits. For example, grain crops grown with inadequate nitrogen produce a poor yield with low protein content. Without nitrogen fertilizers, an estimated one-third of our current agricultural production would be lost.

Under most conditions, however, farmers supply more than twice the nitrogen required by a crop to achieve the best yields. Unfortunately, much of the applied nitrogen is mobile in soil and may be carried to groundwater, possibly contaminating drinking water supplies. (See Cornell Cooperative Extension Fact Sheet 400.02, Nitrate: Health Effects in Drinking Water, for a discussion of this issue.) Understanding the chemistry of nitrogen in soils can help farmers supply sufficient nitrogen for crop needs without losing excessive amounts to underlying groundwater.

Forms of Soil Nitrogen

Nitrogen occurs naturally in many forms. In the soil, it exists in two major classes of compounds:

- Organic nitrogen, such as proteins, amino acids, and urea, including nitrogen found within living organisms and decaying plant and animal tissues.

- Inorganic nitrogen, including ammonium (NH₄⁺), ammonia gas (NH₃), nitrite (NO₂⁻), and nitrate (NO₃⁻).

Within these two forms, there are many different nitrogen compounds. Some are soluble and others are relatively insoluble; some are mobile in soil and others are immobile; and some are available for plant uptake and others are not. Nitrogen in soil is continually being transformed among these various forms through a complex network of physical, chemical, and biological reactions collectively called the nitrogen cycle.
The Nitrogen Cycle

The nitrogen cycle in soil includes the following processes, in which microbes play a crucial role (Fig. 1):

**Fixation.** Ninety percent of the earth's nitrogen is in the atmosphere in the form of dinitrogen gas (N₂). Gaseous nitrogen is chemically stable and unusable by most biological organisms. Some species of bacteria absorb atmospheric dinitrogen gas and convert it into ammonium, which plants can use. This process, called nitrogen fixation, is the principal natural means by which atmospheric nitrogen is added to the soil.

**Mineralization.** As plant and other organic residues decompose, nitrogen is converted to ammonium by soil microorganisms through a process known as mineralization. Plant roots absorb some of the ammonium, and some is chemically converted to gaseous ammonia and lost to the atmosphere.

**Nitrification.** Bacteria transform the ammonium in the soil to nitrite and then to nitrate in a sequence of steps called nitrification.

**Plant uptake.** Nitrate is a negatively charged anion and therefore usually remains in the soil water rather than being adsorbed to soil particles. Plants readily absorb nitrate through their roots and use it to produce protein.

Leaching. The nitrate not captured by plant roots is free to move with soil water. This can result in significant leaching, or movement of the nitrate to deeper soil depths.

Denitrification. Where there is a deficit of oxygen in the soil, called an anaerobic condition, some bacteria meet their energy needs by reducing nitrate to dinitrogen gas or to nitrogen oxide (N₂O). This biological process is called denitrification. It results in a loss of nitrogen from the soil and the return of nitrogen to the atmosphere.

Fate of Nitrogen in the Field

In the soil of any farm field, nitrogen is in a continuous state of flux. Losses occur when crops are removed for livestock feed or human food, which often is consumed far from the land on which it was produced. Surface runoff and consequent soil erosion can also cause significant losses of soil nitrogen. Other losses occur through volatilization of ammonia and leaching or denitrification of nitrate.

Three types of inputs can compensate for nitrogen losses in farm fields: (1) fertilization, (2) nitrogen fixation by legumes, and (3) supplementation with manure or other organic material rich in nitrogen. Farm management of soil nitrogen depends on an understanding of these inputs and outputs so that crop needs can be adequately met without excessive nitrogen losses to the environment.

Gaseous Losses of Nitrogen

In cultivated fields, nitrogen is converted into gas and released into the atmosphere in two ways. First, when urea and ammonium forms of fertilizers (such as anhydrous ammonia, ammonium nitrate, ammonium sulfate, and ammoniated phosphates) are deposited on moist surfaces, they may undergo a series of chemical conversions to ammonia. The ammonia gas then escapes to the atmosphere rather than becoming a plant nutrient. This loss, termed volatilization, is reduced if the fertilizer is washed into the soil by rain or irrigation or if the fertilizer is drilled into the soil to a depth of an inch or more.

The second route by which nitrogen is lost to the atmosphere is through denitrification. If pockets in the soil become saturated with water so that oxygen is excluded, denitrifying bacteria can reduce the nitrate to dinitrogen or nitrogen oxide gas. Poorly drained and heavy soils are particularly prone to denitrification, and a substantial amount of applied nitrogen may be lost to the atmosphere.

In some nonagricultural cases, denitrification is beneficial. In septic tanks and leaching fields, for example, denitrification releases nitrogen to the air as a gas, reducing the amount of nitrate available for potential contamination of ground and surface waters.

Conversion of Nitrogen to a Plant-Available Form

Only inorganic nitrogen can be absorbed by plants. The greater part of nitrogen in the field, however, is usually in organic form such as proteins and amino acids. Under normal conditions in the northern hemisphere, only about 2 or 3 percent of the organic nitrogen in soil is converted to inorganic nitrogen each year. The natural decay of organic matter provides a slow but continuous supply of nitrogen, which tends to be taken up by plants rather than lost to the atmosphere or to water.

Legumes can supplement soil nitrogen supplies by fixing nitrogen from the atmosphere. This is accomplished by nitrogen-fixing bacteria living in nodules on the plant roots.

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**Fig. 1.** Nitrogen losses (A) and inputs (B) in farm fields.
Leaching of Nitrate

Nitrate does not adsorb strongly to soil particles. If not taken up by plants, nitrate will be either denitrified or carried below the root zone, perhaps to groundwater. Factors that determine whether nitrate will reach groundwater include:

- the amount of nitrate in the soil,
- the quantity and timing of rainfall or irrigation,
- the soil's capacity to hold water,
- the presence and density of plants,
- the rates of infiltration and percolation of water through the soil,
- the rate of evapotranspiration relative to precipitation and irrigation, and
- the soil temperature.

In the eastern United States, the opportunity for nitrate leaching is greatest in early spring and in the fall. Rainfall tends to be frequent and heavy during these seasons, and the low rates of plant growth and evapotranspiration permit more of the added water to percolate downward to groundwater. Plant uptake of dissolved nutrients also is low during these periods, so leaching losses tend to be high.

Soil type is a major factor influencing the degree to which nitrate is lost to groundwater. Sandy or other very well drained soils are most vulnerable to leaching losses.

Farmers can do little to change the character of the soils in their fields. Likewise, they have no control over the vagaries of the weather. What, then, can farmers do to conserve a valuable crop nutrient while minimizing nitrate contamination of groundwater?

Fertilize Crops, Not Groundwater

To use fertilizer nitrogen correctly, take the following steps for nonlegume crops:

1. Establish a realistic goal for crop yield, and from this goal estimate the amount of nitrogen that the crop must accumulate.
2. Estimate the amount of nitrogen that will be supplied by the mineralization of soil organic nitrogen and crop residues.
3. Use any available manure nitrogen to supplement the soil and crop residue supplies.
4. If necessary, supplement these nitrogen sources with enough fertilizer to meet the yield goal for the particular crop.
5. Apply any needed fertilizer just before the period of most rapid crop uptake to minimize leaching and denitrification.

These steps are fully described in the Cornell Field Crops and Soils Handbook, the 1990 Cornell Recommends for Field Crops, and two fact sheets by Klausner and Bouldin (see “For Further Reading” for reference information).

One method of increasing the efficiency of fertilizer use and decreasing the amount lost to groundwater is to delay a portion of the nitrogen application until the crop is growing rather than applying it all at the time of planting (fig. 2). Field experiments have shown that splitting fertilizer applications can increase the efficiency of nitrogen use, maintain crop yields, and decrease fertilizer costs.

Another technique for meeting crop needs while decreasing leaching losses is to supply nitrogen in an organic form such as manure or legume residues. Because organic nitrogen is gradually converted into inorganic nitrogen, only small amounts are in a soluble form susceptible to leaching at any one time.

It is estimated that the amount of atmospheric nitrogen taken up by legumes roughly equals the amount removed by harvesting. If harvested hay is removed from the farm, then soil nitrogen should remain approximately constant. If the hay is fed to animals on the farm, about one-half of the nitrogen can be returned to the fields if the manure is handled carefully.

To avoid excessive losses through volatilization, runoff, and leaching, follow these procedures in handling manures:

- Collect manure as soon as possible after it is deposited, and conserve the liquid portion.
- Store manure under conditions that prevent drying or drainage.
- Apply manure to the field close to the time of planting, so that the available nitrogen will be taken up by plants rather than leached, lost to the atmosphere, or converted to organic forms.
- Plow manure under as soon as possible after spreading to minimize ammonia volatilization.

(See the two fact sheets by Klausner and Bouldin for more information on manure management.)

Conclusions

Nitrogen is likely to be in short supply for crop production unless supplemented by legume crop residues or by the application of fertilizers, manures, or other high-nitrogen materials. Nitrogen-fixing microbes replenish soil nitrogen by converting the relatively inert nitrogen of the atmosphere into a form that can be used by living organisms. Since biological fixation of nitrogen is not usually
sufficient to meet the needs of intensive crop production, however, additional sources may be needed.

Fertilization schemes should be designed to meet crop nitrogen needs without losing excessive amounts of nitrogen to groundwater. This is accomplished by estimating nitrogen needs and meeting these needs as much as possible with manure or other organic sources.

The greatest potential for nitrate leaching occurs if fertilizer is applied at a time when no crops are growing, such as during spring planting or in the fall after harvest. Leaching losses can be reduced by applying nitrogen in increments during the periods of rapid plant growth. Using manure or slow-release fertilizers also limits leaching losses because plant-available (and leachable) nitrogen is supplied gradually rather than all at once. Even with these sources, however, leaching can occur if the nitrogen supplied exceeds the ability of the crop to use it.

Growing legumes and using organic soil amendments enrich the soil with organic nitrogen, which does not leach and provides a continuous supply of plant-available nitrogen as it slowly decomposes. Adding organic matter to soil provides additional benefits by enhancing the soil's ability to retain water and dissolved nutrients in the root zone where they are available to plants. Protecting organic topsoils from erosion, providing organic soil amendments, and managing water and fertilizer applications for maximum plant uptake will lead to efficient fertilizer use and protection of groundwater quality.

For Further Reading


Other fact sheets in this series include:
- Modern Agriculture: Its Effects on the Environment (400.01)
- Nitrate: Health Effects in Drinking Water (400.02)
- Pesticides: Health Effects in Drinking Water (400.03)
- Groundwater: What It Is and How to Protect It (400.04)
- Water and the Soil (400.05)
- Pesticides and Groundwater: A Guide for the Pesticide User (400.07)

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