

Improving Nitrogen-Use Efficiency in Idaho Crop Production

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Introduction

Environmental and socioeconomic issues have underlined the urgent need to better understand the role and fate of nitrogen (N) in crop production systems. Nitrogen is the nutrient that most often limits crop production, and its proper application can result in substantial economic return to growers. However, adding more N to the soil than crops need may result in economic loss and negative environmental impacts, as well as pose substantial risk to human health. Managing N inputs to achieve a balance between profitable crop production and environmental quality is a goal—and a challenge. The behavior of N within the plant-soil system is complex, and an understanding of the basic processes that regulate its fate is essential for developing an efficient N management program.

This publication aims to improve agricultural professionals' knowledge and understanding of agronomic and cultural practices that could help to improve the efficiency of their nitrogen fertilizer use and to enhance their farming operations' competitiveness. The publication summarizes the most current applied scientific information on practices and methodologies available to growers.

Why is N Important?

Everything that lives needs nitrogen

Nitrogen is tricky! It is a vital component of all living cells, and without N, there would be no life as we know it. It's the most abundant (78%) element in the Earth's atmosphere. In its molecular form (N₂), however, it is

unusable for the majority of plants and animals.

Nitrogen is a key component of chlorophyll, the compound used by plants to convert sunlight into sugars from water and carbon dioxide through the process of photosynthesis. The sugars are then stored and used for plant growth and development. Nitrogen is also an important component of nucleic acids, including DNA—the genetic material that allows plants to grow and reproduce. Many N-containing molecules are so vital that if even a single one is lacking, it may result in an organism's death.

Nitrogen is needed to feed people

Currently, at least 50 percent of food produced worldwide is possible only through the use of

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commercial fertilizers containing N, phosphorus (P), and potassium (K). Food grown with N fertilizers feeds 2 billion people. By 2050, the world population is expected to grow by 2 billion, totaling more than 9 billion people, which means food production must increase by 70 percent to 100 percent to meet the global demand for human sustenance.

Intensifying use of agricultural land for food production dictates a greater need to use fertilizer efficiently to increase crop productivity and quality, while avoiding nutrient depletion and maintaining soil quality and environmental integrity.

In the past, the principal solution to food shortages has been to use more land for agricultural production. Some of that agriculturally productive land has now been lost to urbanization and other human uses, desertification, salinization, and soil erosion. Further land losses are expected to occur due to climate change. This means that more food will have to be produced on the same amount of land, or even less. As an example, grain production has more than doubled over the past 50 years, and the amount of arable land globally has increased by only about 9 percent.

While advances in plant breeding and genetics are resulting in significantly greater crop yields, fertilizer (and water) use efficiency will have to increase dramatically in order for food production to keep up with population growth.

How Much N is Used vs. Lost?

Reactive N

The nitrogen in our atmosphere (N_2) must be transformed into reactive nitrogen before most living organisms can use it. Reactive forms of N are ammonia (NH_3), ammonium (NH_4), nitrite (NO_2) and nitrate (NO_3), nitrogen oxides (NO_x), and nitrous oxide (N_2O). Reactive forms of N are those capable of supporting life directly or indirectly.

Plants primarily obtain reactive N from soil, where N exists in three basic forms: organic N compounds, ammonium, and nitrate. Between 95 percent and 99 percent of the potentially available N in the soil is present in organic forms: in plant and animal residues, in soil organic matter, and in living organisms such as soil bacteria. Organic N is not readily available to plants until soil microorganisms convert it to available

forms. Only a tiny portion of organic N exists as soluble compounds that may be available for plant uptake. The majority of plant-available N—often referred to as mineral N—is in the inorganic forms of ammonium (NH_4) and nitrate (NO_3).

The supply and demand

The supply of plant-available N and the rate of N losses from the plant-soil system ultimately determine the sustainability of crop production. Available soil N and crop yield potential determine the crop's need for additional N, and both are essential to quantify optimum N application rates.

Making precise N prescriptions is difficult because tremendous variability exists in available soil N and crop yields across time and space. However, N will have little impact on crop yield if other factors present a greater limitation. The availability of the most abundant soil nutrient is only as good as that of the least abundant nutrient. Nitrogen can be a yield-limiting nutrient in cropping systems; used wisely, it also provides one of the greatest returns on investment in terms of yield and quality.

Current efficiency

So how efficiently is N fertilizer used in an average agricultural system? Currently, 100 million tons of N is applied as fertilizer to agricultural fields worldwide every year. Nitrogen use efficiency (NUE) has been estimated to be only about 40–50 percent at best for major food crops. That efficiency could be viewed as a 50–60 percent loss, as N is lost through runoff and leaching or as gas to the atmosphere, and is tied up by soil microorganisms and soil particles. (Loss will be discussed in greater detail below.)

Based on an average current cost of more than \$1,100 per ton of N fertilizer, a 10 percent increase in NUE would result in savings of \$5 billion per year. The NUE for key cereal crops such as wheat, corn, and rice is still relatively low, and increasing NUE is possible through efficient N management practices and adoption of precision technologies.

What Causes Nitrogen Loss?

Adequate levels of plant-available nitrogen in the soil stimulate plant growth, ensuring optimized crop yields and quality. Ideally, N fertilizers are applied to

make up the difference between N already present in the soil and temporary crop N demand. This balance is not always attained because of various logistical, economic, and biological limitations. Adding N to the soil as an “insurance” without considering the actual crop need for N results in N being lost from the soil-plant system into the environment.

Reactive N can easily cascade through atmospheric, aquatic, and terrestrial systems because of its high bioavailability. This can result in multiple negative environmental consequences such as soil acidification, eutrophication (enrichment of surface waters), and greenhouse gas emissions. The typical pathways for N loss include leaching and runoff, denitrification, ammonia volatilization, and crop/residue removal. Two other loss pathways—immobilization and exchange—are considered temporary because N stays in the soil and may become available for plant uptake in the future. In addition, luxury consumption of N has been noted for various crops. This bulletin examines each type of loss and possible ways to mitigate it.

Idaho’s N efficiency

Based on University of Idaho research in winter wheat and the N loss potentials shown in table 1, it has been estimated that only about 50 percent of the N applied as fertilizer is taken up by the crop, the primary cereal grown throughout the state. The chief pathways contributing to such a high N loss are a combination of leaching and denitrification (25%), plus immobilization (25%) due to wheat residue decomposition. Only about 5 percent of immobilized N is typically mineralized and made plant-available in the next cropping cycle, unless it is lost as a result of secondary leaching and denitrification due to high winter rainfall. Another study in Idaho showed how the loss potential differs for the various forms of N (table 1).

Other crops traditionally grown in Idaho have NUE values similar to that of winter wheat. For example, typical NUE in furrow-irrigated and drip-irrigated onions is only about 40 percent and 60 percent, respectively.

Leaching and Runoff

Mechanism of loss

Nitrate-N is highly soluble; it can readily move through the soil—easily passing through the root zone and percolating beyond it—and can reach the groundwater.

Leaching is simply a downward movement of nitrogen through soil with the water. Coarse-textured soils with higher sand content have a greater potential for leaching due to increased rates of water movement within the soil profile. Extreme precipitation events (3–6 inches or more) and excessive irrigation intensify the potential for leaching of N from agricultural fields.

Runoff is a physical drainage of N from the soil surface. It is often associated with abundant rain events, when a substantial amount of water is deposited in a short period. High-intensity rain events often don’t benefit the crop, as water (and N) run off without ever entering the root zone. Although runoff does not typically account for a large fraction of total N loss compared to other pathways, it’s certainly important for surface water quality issues.

Idaho implications

Idaho is ranked fifth in the United States in irrigated water use. Irrigated cropping systems have the highest potential for leaching and often account for a substantial portion of nonpoint source water pollution. Nitrate concentrations in groundwater continue to increase in many areas of the United States, which is raising human health concerns. This is particularly common in rural agricultural areas where shallow groundwater is used as a domestic water source. Groundwater provides more than 95 percent of Idaho’s drinking water supply.

The Idaho Department of Environmental Quality has developed a procedure for identifying and prioritizing areas where nitrate is impairing or degrading

Table 1. Nitrogen forms and associated pathways of loss and potential loss amounts for Idaho cropping systems

N forms	Pathways of N loss	Estimated N loss (%)
Organic, ammonium, nitrate, and urea	Leaching and runoff	0–40
Nitrate and nitrite	Denitrification	5–35
Ammonia and urea	Volatilization and plant loss	0–30
Organic, ammonium, and nitrate	Immobilization	10–40

Adapted from Johnson, R. D. 2011. The nitrogen cycle: Its transformation effects on water, soil, and air quality resource concerns in Idaho. Technical note TN MN no. 6. USDA Natural Resources Conservation Service, Boise, Idaho. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_046108.pdf

groundwater quality. An area is considered a nitrate priority area if 25 percent of the sampled wells have at least 5 ppm (which is 50 percent of the drinking water standard of 10 ppm). The number of nitrate priority areas has increased from 25 in 2002 to 34 in 2014. Many of these areas are associated with highly intensified agricultural activities.

Management advice

- For highly erodible soils, conservation tillage can help to improve soil structure and reduce N loss through runoff.
- Planting a winter cover crop can help reduce leaching. Cover crops that build soil organic matter may also help to slow the release of N and provide continuous N nutrition to crops. Leaving the soil fallow over the winter months, especially after crops that tend to result in high residual soil N after harvest, will create a high leaching risk environment.
- Effective irrigation strategies that provide sufficient, but not excessive, water to the crop are an important factor in preventing N loss. Excessive irrigation, especially when applied at inappropriate times (such as after extensive rainfall or after crop uptake has declined), may result in significant N losses due to runoff and/or leaching.
- Furthermore, N concentrations in the irrigation water must be considered when making N fertilizer decisions. For example, only 15 ppm of NO_3^- in sprinkle-delivered irrigation water adds more than 40 pounds of N per acre-foot to the crop.
- Subsurface drip and sprinkler irrigation methods are not only much more efficient than furrow irrigation, but also help to minimize the potential for N loss through leaching and runoff.

Denitrification

Mechanism of loss

Denitrification can result in significant nitrogen losses as gaseous forms of N are released to the atmosphere, especially if warm soils are saturated for more than two days. Denitrification is a conversion of NO_3^- and NO_2^- to atmospheric nitrogen (N_2)—a process facilitated by heterotrophic bacteria: $\text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2$.

Soil bacteria produce reductases (enzymes that promote a chemical reduction); these soil microorganisms are adapted to use soil N (instead of oxygen) to produce energy in the process of respiration.

The greatest potential for denitrification is in the top 0.5 inches of the soil, where the microbial activity is highest. Denitrification tends to occur in water-saturated soils with a limited amount of air (anaerobic environments). Typically, denitrification occurs when soil water content exceeds 60 percent of water-filled pore space.

In addition to water/air balance, other factors affecting the rate of denitrification include nitrate-N concentration (due to high N fertilizer application rate), soil pH, temperature, and organic carbon content. Interestingly, because denitrification is largely associated with “hot spots” in agricultural soils, it has the highest spatial and temporal variability of all the N cycle processes. These “hot spots” have been tied to patchiness in soil characteristics such as microbial biomass and activity, organic carbon concentrations, and microclimate.

Many studies have found that no-till practices may increase the potential for N loss via denitrification due to greater soil moisture and microorganism activity. However, research has suggested that higher denitrification rates are associated with systems recently converted to no-till; soils that are continuously managed under no-till have the same denitrification rates as conventionally tilled soils.

Another variable that affects denitrification rates is soil acidity. Liberal N application in excess of crop need often results in soil acidification. Acidity has a noted impact on many chemical and biological processes in the soil and will be discussed in greater detail regarding volatilization.

Idaho implications

Increased soil denitrification rates following irrigation have been reported for various cropping systems worldwide. Denitrification conditions—anaerobic environments with wet soils, especially those rich in organic carbon—correspond to most furrow-irrigated fields. Sprinkler irrigation use has increased dramatically, and is now the most widely used method throughout Idaho—with 87.9 percent of acreage irrigated with sprinklers and only 12.6 percent with furrows.

Furrow irrigation, however, is still predominant for most crops in the southern part of Idaho. Anaerobic conditions can be more prevalent in furrow-irrigated systems due to prolonged flooding within the furrows and at the edges of the fields. Very hot summer temperatures, in combination with the air-limited conditions, may create concentrated areas for N loss through rapid denitrification.

Management advice

- In general, a combination of farming practices that promote adequate soil aeration, reduce soil water saturation, and maintain a neutral soil pH would help to significantly decrease denitrification.
- Soil acidification has become a persistent problem in northern Idaho. Maintaining soil pH within a range of 5.5 to 7.0 may help to slow the process of denitrification.
- Converting from inefficient irrigation practices (such as surface flood/furrow) to sprinkler and subsurface drip irrigation based on plant need (accounting for plant evapotranspiration/plant loss) will help to conserve water while minimizing saturated soil conditions, and thus reduce N losses associated with denitrification.
- Biochar, a fine-grained, highly porous charcoal produced from agricultural waste, has been utilized as a soil enhancer. Studies have shown that adding biochar significantly reduced N loss through denitrification in 15 agricultural soils. When biochar was applied, the total amount of N denitrified varied highly among soils—from 4 percent to 232 percent.

Ammonia Volatilization and Plant Loss

Volatilization

Urea is the most widely used nitrogen fertilizer in the United States; it is used in granular form and as a liquid (urea ammonia nitrate, or UAN). Once urea comes in contact with water (moist soil, rain, irrigation water), it rapidly dissolves (is hydrolyzed) and is converted to ammonium bicarbonate by the urease enzyme. (Urease occurs naturally in soils as a by-product of many soil microorganism-related reactions.) When urea is hydrolyzed, the majority of ammonium is converted into ammonia gas. This volatilization results in a high risk for loss.

The magnitude of N loss via volatilization depends greatly on the products formed when ammonium-containing fertilizers react with the calcium carbonate in the soil. Nitrogen can be lost in this way from both natural (manure) and synthetic (fertilizer) products containing urea.

Table 2 summarizes low- and high-risk conditions for N loss due to volatilization. Substantial losses from some surface-applied ammoniacal N fertilizers were reported, as N is lost in the form of ammonia (NH₃) gas. Ammonia volatilization is greatest when N fertilizers are surface applied (without incorporation) to calcareous soils. Loss of N from volatilization is also greater when soil pH is higher than 7.3, the air temperature is high, the soil surface is moist, and there is a lot of residue on the soil.

Reports by the National Research Council recognized ammonia volatilization as a key air quality concern at regional, national, and global levels. The negative environmental impacts of deposition of atmospheric ammonia include eutrophication, causing rapid algal growth and decline of aquatic species, including those with commercial value. Systematic deposition of ammonia on soils with a low buffering capacity (ability to resist change) tends to cause soil acidification.

Earlier studies postulated that volatilization is minimal at temperatures less than or equal to 50°F. However, most current work in the Pacific Northwest has shown that significant N losses via ammonia volatilization may occur even when fertilizers are applied in cooler conditions. An increase in temperature from 45°F to 60°F can double N losses, even if the soil moisture content is the same. However, cooler temperatures don't

Table 2. Low- and high-risk conditions for N loss due to ammonia volatilization from urea applied to agricultural fields.

Low risk for urea volatilization	High risk for urea volatilization
Low soil temperature (< 50°F)	High soil temperature (> 70°F)
Dry soil	Moist soil
Low soil pH (< 6.0)	High soil pH (> 7.0)
Silt or clay-dominated soil	Sandy soil
High soil cation exchange capacity (CEC)	Low soil CEC
Bare soil	Crop residue, perennial forage

Adapted from Jones, C., Brown, B. D., Engel, R., Horneck, D., and Olson-Rutz, K. 2013. Factors affecting nitrogen fertilizer volatilization. EB0208. Montana State University Extension. <http://landresources.montana.edu/soilfertility/documents/PDF/pub/UvolfactEB0208.pdf>

necessarily reduce N volatilization risk. In 13 evaluated winter wheat fields in Montana, N losses approximated 20 percent, when urea was surface applied between October and April. Furthermore, the greatest N loss was recorded for soil with surface temperatures below 41°F. This may have been caused by the reduced ability of frozen soils to bind ammonium-N.

Plant loss

Plant shoots may be a substantial source of N loss in many crops, as volatile N (mainly in a form of ammonia) is released from plant tissue. A two-year study estimated that plant N losses varied from 3.5 pounds to 25 pounds per acre, accounting for between 8 percent and 60 percent of total forage N content during flowering.

The plant growth stage with the highest potential for gaseous N loss differs for various crops. Studies in corn and wheat showed that the peak N loss from the stems and leaves coincides with early reproductive growth stages (between flowering and maturity). Interestingly, research in spring wheat showed that similar amounts of N are lost from leaves, independent of N fertilizer application rate and leaf N concentration. Nitrogen use efficiency and plant N losses tend to vary even from one wheat variety to another. Plant N loss can be viewed as a mechanism the plant employs to buffer against N accumulation when N is applied in excess.

Idaho implications

While ammonia volatilization can be minimized by applying N fertilizer to dry soil, incorporating it, and adding it with irrigation water, the timing of the application is also an important consideration to ensure optimal uptake. A study of irrigated winter wheat and winter barley in southern Idaho found lower grain yields when N fertilizer was incorporated in the fall (80 bu/acre to 100 bu/acre), compared to N broadcasted in the spring (90 bu/acre to 120 bu/acre). This indicates that lower yields resulted from greater N losses due to leaching and immobilization over the winter months, not due to higher N volatilization. For this reason, spring application of N is recommended in irrigated cropping systems, unless slow-release N sources are used.

Management advice

- In general, higher pH, higher temperature, presence of crop residue, and moist soil conditions result in

greater N volatilization. On the other hand, tillage, fertilizer incorporation, adequate precipitation, and regular irrigation help to decrease N volatilization risk.

- Urease inhibitors can be used to temporarily reduce the activity of the urease enzyme responsible for urea hydrolysis. This was estimated to minimize volatilization risk by 50–90 percent. Urease inhibitors have been shown to inhibit ammonia volatilization, but yield implications depend highly on the magnitude of loss. Moreover, many novel fertilizer technologies containing the inhibitors are often not economically feasible.
- If N fertilizer is applied to the soil surface without incorporation, non-urea N sources (such as ammonium nitrate or ammonium sulfate) are recommended.
- The mechanisms of plant N loss, as well as specific factors that may affect its rate, are not understood well enough to develop a sound methodology for reducing the loss.

Crop/Residue Removal

Mechanism of loss

Crop removal represents a loss because nitrogen in the harvested parts of the plant is removed from the field. In fact, crop removal accounts for the bulk of the N leaving the soil. Crop removal loss is calculated by multiplying yield by nutrient concentration in the harvested portion. In most crops, this value is not the same as the amount taken up by the crop and is only distantly related to the plants' total need for nutrients.

For many forage crops, vegetables, and some cereal grains, the nutrient removal at harvest can be used to estimate nutrient use efficiency. For example, harvesting a 250-bushel-per-acre corn crop results in removal of about 175 pounds of N. Table 3 shows more examples of how much N is removed at harvest for various crops.

The N use efficiency and N removal at harvest are much higher for multiple-purpose crops, where different plant parts are harvested for different uses. For example, crop residues can be recycled if they are incorporated into the soil after harvest. However, many crop residues, like wheat straw, are also harvested for animal feed or bedding, or to be used as feedstock for biofuel production; these are better thought of as recycled,

rather than removed. Much is eventually mineralized and may be reused by a crop. Substantial amounts of N are lost from the soil system through crop removal.

Idaho implications

Consider potatoes—one of the crops vital for Idaho agriculture. The amount of N removed by a potato crop is linked to yield. For example, twice the yield tends to result in approximately twice the N removal. The vines account for a substantial portion of the N required for crop production; the rest of the N is assimilated into the tubers. The potato vines take up about 90 pounds of N per acre. About 86 pounds of N per acre are removed with the tubers, at a yield of 200 cwt per acre; with a yield of 600 cwt per acre, the amount of removed N is estimated to be about 215 pounds per acre.

Management advice

- Knowing the amount of N removed often helps to estimate crop need for N. Even using the most cutting-edge crop management methodologies, such as remote sensing, to derive fertilizer recommendations, producers still must know the actual or estimated amount of N removed at harvest. Information about N removal is available for most crops and regions through University Extension resources. Growers can quantify N removal for their individual cropping system by taking several representative samples to a lab to be analyzed for total N content.

Table 3. Estimated nitrogen losses from the soil-plant system caused by crop harvest

Crop	Typical yield (ton/acre)	N loss (lb N/ton of yield)
Wheat, grain	3	58
Barley, grain	2.5	37
Corn, grain	5	29
Sorghum, grain	4	50
Oats, grain	1.6	44
Cotton	3 (bales)	35
Sugar beets	30	8.5
Safflower	2	100
Alfalfa, hay	8	60

Adapted from Pettygrove, G. S., and Bay, I. 2009. Crop Nutrient Harvest Removal. In UC Manure Technical Guide Series for Crop Management Professionals. University of California Cooperative Extension. <http://manuremanagement.ucdavis.edu/files/134365.pdf>

- Several universities and other organizations have developed crop nutrient removal calculators and/or apps. These enable growers to estimate the amount of nutrients, including N, removed via their crop based on locally or regionally collected data and systematic field research trials. A good example is a crop nutrient removal calculator by the International Plant Nutrition Institute (<https://www.ipni.net/app/calculator/home>). The removal rates are calculated based on user-selected yield goals for more than 50 various crops.

Immobilization

Mechanism of loss

The assimilation (immobilization) of inorganic nitrogen and the production of ammonium from organic N compounds (mineralization) are routinely carried out by microorganisms. Through immobilization, N remains in the soil but becomes temporarily unavailable to plants. This temporary decrease of plant-available N occurs because soil microorganisms tie up N. There are approximately 1 ton of active microorganisms within 1 acre of soil.

Decomposers are a large group of microorganisms especially important in the process of immobilization. In fact, decomposers help to decrease N loss from the root zone by assimilating and retaining N within their cells.

The immobilized N becomes part of the soil microorganisms' biomass, as they use it to build proteins, nucleic acids, and other cell components. In the natural process of microorganisms' death and decay, a portion of their biomass N is released as ammonia through the process of mineralization. The other portion of released N is converted into stable organic N compounds, becoming a part of the soil's organic matter. Because the stabilized organic N is not readily available for plant uptake, the net result of immobilization-mineralization is a decrease in N availability.

The balance between these two processes in agricultural soils is governed by the microbial population, its activity, and the relative demand of microorganisms for N and carbon (C). For example, decomposers that break down plant residues containing large amounts of C, but low amounts of N (such as small grain straw), will require additional N to digest the material. The decomposers get this extra N from the soil.

Idaho implications

Significant potential for immobilization exists in Idaho cropping systems. Many Idaho cereal grain farms disc the straw residue into the soil immediately following harvest. As noted above, many cereal straw residue materials have a wide C:N ratio (approximately 80:1). This results in net N immobilization because soil microorganisms require additional N from the soil in order to decompose the straw. A general recommendation is to add 15 pounds (up to 50 pounds total) of N for each ton of straw added to the soil to facilitate straw breakdown and help prevent the microbial immobilization. On the other hand, unless a winter crop is seeded following the cereal grain harvest, this N may be lost via other pathways such as runoff and leaching, before the N ever has a chance to be taken up by microorganisms or the crop.

In southern Idaho, crops traditionally seeded following cereals are corn, malting barley, and sugar beets. In the northern part of the state, wheat is typically grown in alternate years with spring peas or lentils, or with spring barley.

Manure is commonly applied to agricultural fields in many parts of Idaho. Extensive research has shown that the release of abundant, readily metabolized C from manure substantially stimulates microbial growth in the first year after application. Research results indicated that immobilization in manure-amended soils was higher (compared to the consequent years). University of Idaho research has shown the importance of the C:N ratio of manure for not only understanding the overall manure quality, but also for estimating potential N loss caused by immobilization.

Management advice

- Planting early-season crops into cool soils may help reduce N losses caused by immobilization, because microorganisms' activity is reduced in cooler soils. On the other hand, microorganisms' function is to promote release of certain nutrients (such as phosphorus) from the soil and make them available for plant uptake.
- For crops following small grains, to counteract the high C content in the incorporated straw, it's recommended that growers apply additional N at soil temperatures lower than 50°F, to minimize N immobilization losses.

- Keep in mind that soil testing for residual soil N is vital for determining appropriate N fertilizer recommendations. The best time to collect soil samples is immediately prior to a planned fertilization event. Fall-collected samples will typically have substantially higher nitrate-N concentrations, compared to spring-collected samples.

Exchange

Mechanism of loss

Exchange refers to the binding of nitrogen-containing molecules to soil particles, making them temporarily unavailable for plant uptake. Soils can be regarded as warehouses of plant nutrients. To understand the exchange, it is necessary to review one of the key chemical and physical properties of soils: their cation exchange capacity (CEC). Soils are comprised of sand, silt, and clay particles and organic matter. Soil organic matter and clay particles have a net negative charge. Like the opposite poles of a magnet, cations—positively charged molecules (such as ammonia-N, NH_4^+)—are naturally attracted to and are held tied-up on the negatively charged (or anionic) exchange sites in the soil. The CEC helps to quantify the number of cations that can be tied up by the soil particles: The higher the CEC, the greater the soil's ability to tie up cations (figure 1). Soils with higher clay and organic matter content, especially those with higher pH (alkaline soils), naturally tend to have higher CEC.

Although lower-CEC soils can sustain crop production, generally, soils with a substantial amount of negative charge are more fertile; they are able to retain more cations.

While they are held on the soil exchange sites, cations like NH_4^+ are removed from the soil solution—the pool of plant-available nutrients. However, this loss is temporary. Eventually the ammonia is converted to nitrite-N by soil bacteria and further to nitrate-N in a stepwise process of nitrification. Another point to consider is that the N tied up in the exchange minimizes the risk of N loss through other pathways, such as leaching. In fact, without the ability of soils to bind certain molecules, essential plant nutrients would be easily leached out.

Idaho implications

Low-CEC soils are those containing less than 5 milliequivalents/100 grams of soil; high-CEC soils normally contain more than 20 meq/100 g of soil. Soil CECs in Idaho typically range from 15 meq/100 g to 30 meq/100 g, which is considered medium to high.

Some Idaho growers are using anhydrous ammonia as an N fertilizer source. Spring crops are often seeded as soon as possible following the ammonia application. The potential for ammonia to damage seeds and seedlings is often discussed. However, ammonia applied to the soil is quickly converted to the ammonium form, which becomes bound on the soil exchange sites. This eliminates any damage that could be caused to the seed, especially if the soil is moist at the time of application. A small fraction of the applied ammonia remains in the free ammonia form and can enter the seeding zone, particularly with shallower seeding depth and drier soil. Because of the high toxicity of free ammonia to young plant tissue, some young roots can be severely damaged, which may ultimately reduce yields. To take advantage of the soil CEC, growers are advised to seed slightly deeper and into wet soil whenever possible.

Management advice

- The higher the CEC, the greater the soil's ability to hold added cations and thus support plant growth. Soil CEC has a significant effect on soil fertility and, thus, fertility management. Therefore, the

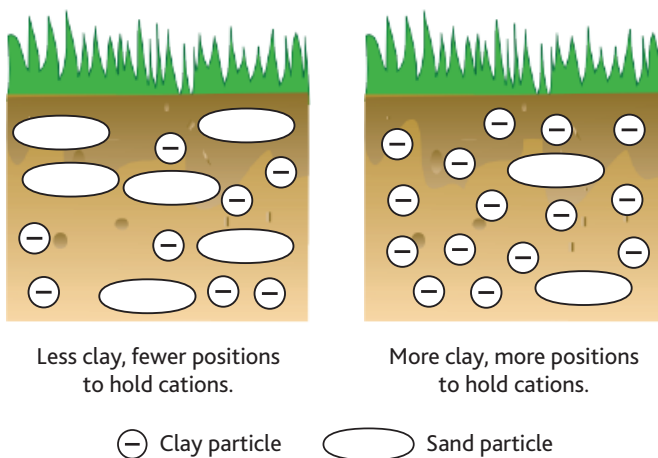


Figure 1. Soil CEC reflects its ability to hold cations— K^+ , Ca_2^+ , Mg_2^+ , NH_4^+ , Na^+ , and K^+ . Adapted from Kleinschmidt and McClure. 2009. Introduction to soil. <http://www.slideshare.net/andykleinschmidt/introduction-to-soil-science-presentation>

CEC must be considered when determining the sustainability of land for various crop applications.

- Growers commonly use liming to neutralize the acidity of agricultural soils. When determining application rates for lime (calcium- and magnesium-rich materials), soil CEC should be taken into account. High-CEC soils have an inherently high buffering capacity (a significant ability to resist a change in pH), and tend to change pH more slowly than low-CEC soils. This ultimately means that soils with higher CEC do not require as frequent lime application; at the same time, as their pH drops over time, higher lime rates will be required to balance the pH.
- Fall application of ammonium-based N fertilizers and potassium (K) is not recommended for soils with low CEC, due to higher risk of minerals leaching out of the root zone. Furthermore, topdress N fertilization on coarse-textured soils with low CEC is typically more effective for increasing crop yields, compared to fertilizer application at seeding, even when nitrification inhibitors are used.
- Soil CEC also can direct the frequency of N and K fertilization. For high-CEC soils, K fertilizers can often be applied for two consequent crops; multi-year K fertilizer applications are not advisable for low-CEC soils. Also, split or multiple N fertilizer applications within one growing season are viable options for crops grown in soils with low CEC—again, due to greater N loss potential.

Luxury Consumption

Crop nitrogen demand can be determined as the product of the expected crop yield and N requirement; in other words, it is the minimum amount of N required to produce maximum yield.

Although it cannot be always viewed as a direct loss, N that accumulates in plant biomass beyond what plants need for growth and development intensifies N loss due to crop and residue removal. Luxury consumption refers to N uptake in excess of the amount needed by the plants for metabolism and building structural compounds such as proteins. Figure 2 illustrates the relationship between crop yield and nutrient uptake. Luxury consumption of N—and its accumulation within the vegetative biomass—early in the growing season

often results in greater N losses via volatilization and plant loss. N uptake during early vegetative stages is very important for plant stand establishment, development, and reproductive growth. Luxury N consumption, however, tends to lead to higher N losses and, ultimately, lower NUE.

Various crops have been shown to take up more N than is needed to efficiently attain high yields. For example, while corn stalks typically contain about 250 ppm nitrate-N, some plants accumulated more than 10,000 ppm in an N-response study conducted in Maine. In wheat, luxury N consumption is most likely caused by excessive N in the soil (due to high residual N and/or over-fertilization) during early vegetative growth. High N application rates have also been reported to result in luxury N consumption in sugar beets and potatoes.

If the N-rich residue is left in the field and/or incorporated into the soil, a portion of the N may become available for the next growing season, and thus not be completely lost.

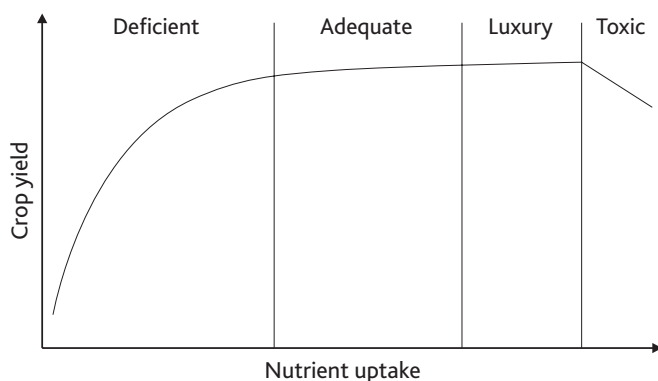


Figure 2. Typical crop-yield response to nutrient uptake. Adapted from Agvise Laboratories. 2012. Interpreting plant analysis reports. <http://www.agvise.com/wp-content/uploads/2012/09/Interpreting-Plant-Analysis-Reports.pdf>

Best Management Practices for Improved NUE

Nitrogen use efficiency can best be improved through careful consideration of fertilizer use, irrigation methods, and management of remaining vegetation after harvest. Here are some final overall recommendations to consider.

Fertilizer

Optimize rate, time, method, and source. A comprehensive approach is the key; focusing on just one factor, such as fine-tuning the N application rate based on crop need, is not enough. This is because both crop yields and potential N loss risks vary depending on weather and agricultural management practices.

Application rate

- Implement consistent and effective soil sampling to account for residual N.
- Review long-term farm/field production records to pinpoint realistic yield potential.
- Account for residue incorporation and credits from previous crops like legumes, cover crops, or green manure.
- Where applicable, use precision agriculture methodologies such as remote sensing to account for seasonal and geographic variability and apply N based on actual crop need.

Timing

- Many Idaho cropping systems apply N with the seed at planting time. Some have suggested that this is a successful soil management practice and that it has long been recognized to improve crop yields. Planters equipped with fertilizer attachments are enabling producers to efficiently combine seeding and fertilization into one operation. However, the best practice for timing N applications is to fertilize as close as possible to the period of rapid crop growth and when the N uptake is at maximum. This helps minimize potential N losses and ensures N availability at the time when the crop needs it most.
- Avoid long time periods between N fertilization and seeding.

(Continued on next page.)

Best Management Practices for Improved NUE, cont.

Method

- Follow application recommendations for your specific N source regarding variables such as temperature, soil moisture, growth stage, incorporation depth, and combining with other fertilizers/chemicals. For example, applying ammonium-based N fertilizers to cool soils helps to mitigate N losses caused by volatilization, leaching, and immobilization.

Source

- Although several N fertilizer products claim superior efficiency over traditional N sources, results from both small plot and large field scale trials are inconsistent. Considering the higher cost associated with these products, it's best to use traditional fertilizer sources such as urea and UAN.

Irrigation

- Avoid excessive irrigation to prevent leaching, runoff, and volatilization losses.
- Use more efficient irrigation methods, such as subsurface drip and sprinkler systems, and account for N in the irrigation water.

Crop Residue

Find alternative uses for crop residue/straw, such as:

- Animal bedding
- Feed
- Biofuel production

Growers are advised to seek guidance in developing a sound N management plan most suitable for their farming operations. Local University of Idaho Extension specialists, educators, and certified crop advisers can provide qualified advice on N management that accounts for regional differences, climatic conditions, and available technologies.

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