Science Societies

Managing soil N for productivity and sustainability: Understanding gains and losses

By Xiaoping Xin, Jaya Nepal, Jessica Bezerra de Oliveira, Gustavo Roa Acosta, and Haseeba Maryam

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Broadcast urea fertilization in corn within a N Use Efficiency study that evaluates different N sources and application rates. Photo courtesy of Sofía Cominelli, Kansas State University.

Nitrogen is essential for crop growth but difficult to manage because plants rely on soil-based N sources that are easily lost through leaching, volatilization, and other pathways. As fertilizer costs rise and environmental risks increase, efficient N use has become critical for both farm profitability and sustainability. Understanding where soil N comes from and where it goes enables farmers to use smarter tools—like precision technologies, soil health practices, and biological inputs—to better synchronize N supply with crop demand.

When we think about what makes crops grow, sunlight, water, and healthy soil often come to mind. But there's another key player quietly fueling the food on our plates—nitrogen (N). The cornerstone for crop productivity, N is needed in the largest amount and often the first nutrient that becomes limiting when a natural ecosystem is cultivated. Corn, soybean, and other staple food crops require N for protein synthesis, to drive photosynthesis, and to transform sunlight into harvestable yield. Without sufficient N, plants exhibit leaf chlorosis, stunted growth, and sharply reduced harvestable yield. With adequate N supply, cereal grains such as wheat, corn, and rice that supply 50% of the world calories achieve optimal growth and yield, supporting global food production.

Yet, N is a tricky nutrient to manage. Even though it makes up most of the air (78%), plants can't uptake it directly. They rely primarily on the soil to supply N in forms they can absorb, usually provided by inherent minerals, fertilizers, organic matter, or natural soil microbes. Getting the balance right is critical: too little N stunts crop growth while too much runs off into rivers, seeps into groundwater, or escapes into the air, creating environmental problems.

Recent research studies showed that the economic optimum N rate (EONR) for corn in the U.S. has been increasing by about 2.7 kg N/ha per year from 1991–2021 (Baum et al., 2025). This means farmers must apply more N to sustain yields, raising both costs and the risk of pollution if it isn't used efficiently, particularly given the high price of fertilizer. According to a report from USDA's Agricultural Marketing Service, by August 2025, average prices in Illinois had climbed to $786/ton for anhydrous ammonia, $594 for ammonia, and $431 for liquid N, well above historic averages. In 2021, corn growers in the Midwest were already spending about 40% of their production costs on fertilizer (Paulson et al., 2025). When N doesn't translate into higher yields, that money is essentially wasted.

Studies in Midwest soil, especially coarse or sandy-textured soils under continuous corn or corn–soybean rotations, show that even when applying N at economical optimum, substantial nitrate leaching still occurs. Photo courtesy of Sofía Cominelli, Kansas State University.

From the environmental perspective, N poses greater risks than phosphorus (P) and potassium (K) due to its high mobility in soil. For example, after application, a portion of N is transformed into nitrate, which is highly susceptible to leaching into shallow wells, streams, and rivers. The U.S. Geological Survey classified multiple regions as high risk for nitrate contamination, especially where the land is flat, the soils are sandy or well drained, and cropland stretches for miles (USGS, 2025).

Studies in Midwest soil, especially coarse or sandy-textured soils under continuous corn or corn–soybean rotations, show that even when applying N at economical optimum, substantial nitrate leaching still occurs. These losses ripple far beyond the farm. Nitrate contamination threatens drinking water supplies, degrades stream ecosystems, and fuels the sprawling "dead zone" in the Gulf of Mexico each summer, a vast area starved of oxygen where marine life struggles to survive.

Efficient management of crop N is essential for both farm profitability and environmental sustainability. Nitrogen fertilizer prices are highly volatile and strongly influenced by global market conditions, making economic efficiency a priority for growers. At the same time, N must be managed carefully to meet crop requirements for maximum yield without overapplication since surplus fertilizer increases the risk of environmental contamination. Nitrogen that is not taken up by the crop represents both an economic loss and a potential pollutant. Thus, agriculture faces the dual responsibility of ensuring food production while also minimizing environmental impacts. By tracking where N comes from and where it goes, we can use it more efficiently, producing abundant harvests while protecting the natural resources we all depend on.

Where soil N comes from

Understanding the sources of soil N is fundamental for effective management. Nitrogen that supports crop growth originates from multiple sources, each playing a critical role in maintaining soil fertility and agricultural productivity, as illustrated in the N cycle (Figure 1).

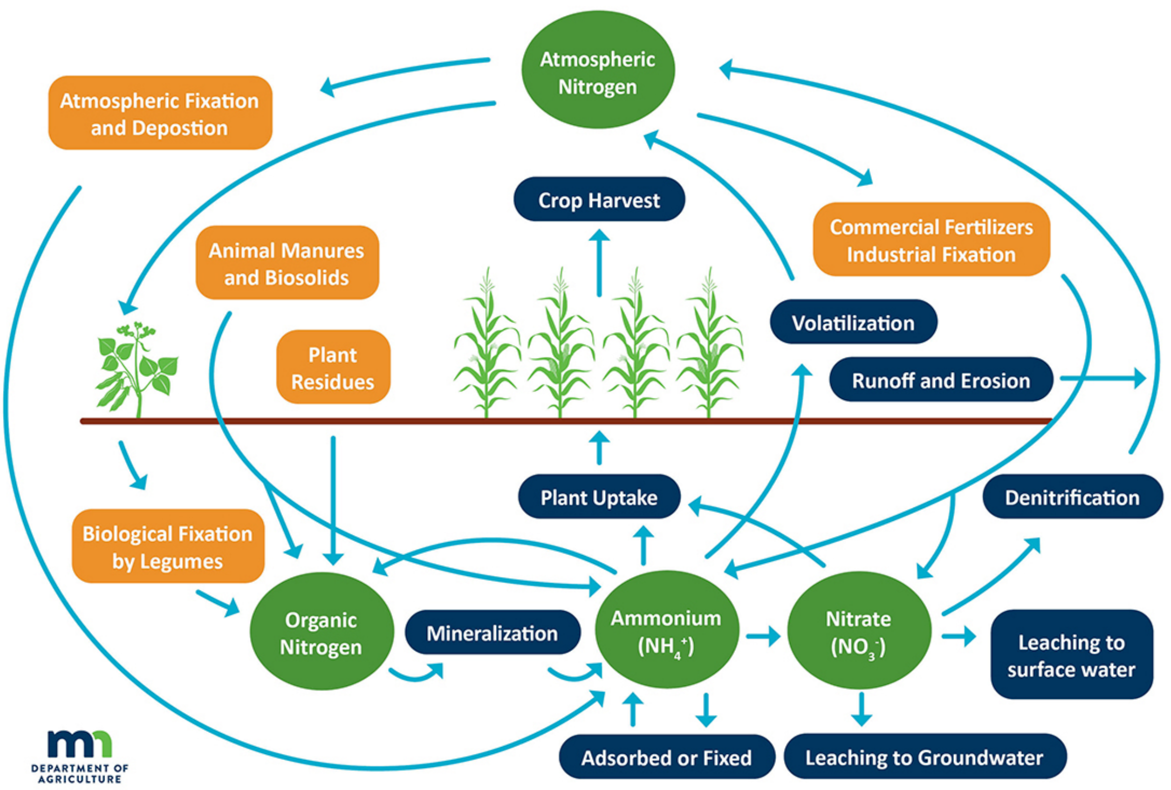


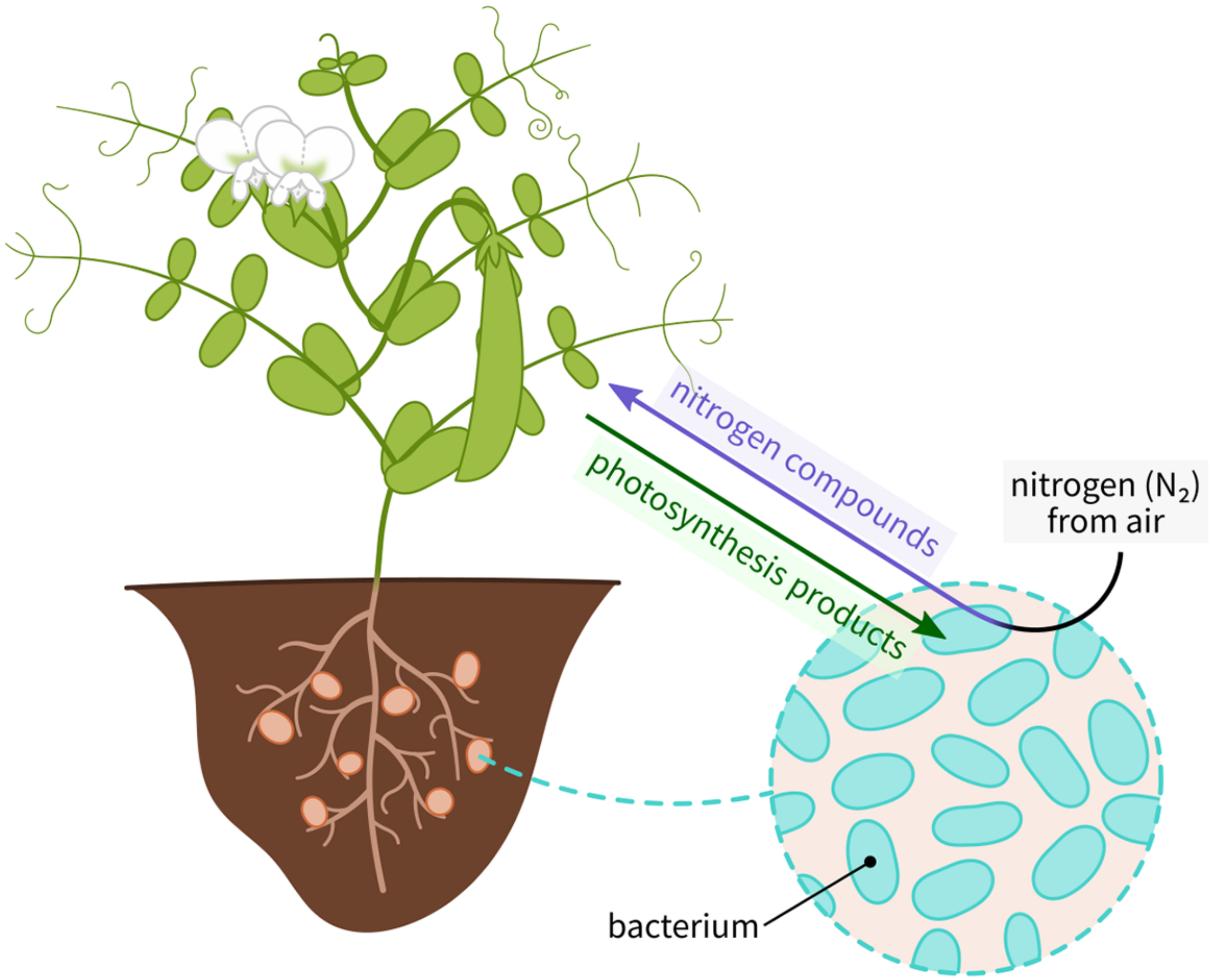
Figure 1. *N cycle: Where N comes from and where it goes. Source: Minnesota Department of Agriculture.*

A major natural source of soil N is the **mineralization** of organic matter, a process driven by soil microorganisms. When plant residues, manure, or compost are added to soil, microbes begin breaking down this organic material. Through mineralization, a process that includes **ammonification** and **nitrification**, organic N is converted into plant-available forms such as ammonium (NH_4^+) and nitrate (NO_3^-). The efficiency of this natural N factory depends on several environmental factors. Warmer soils generally support faster mineralization rates as microbial activity increases with temperature. Soil moisture also plays a crucial role too: little water limits microbial activity while waterlogged conditions can reduce oxygen availability and slow the process. Clay content in the soil matters too as fine-textured soils can physically protect organic matter from decomposition, leading to slower and more sustained N release.

Modern agriculture often supplements natural N cycling with fertilizers, which fall into two main categories: synthetic fertilizers and organic amendments.

- **Synthetic N fertilizers** (e.g., urea, ammonium, and nitrates) provide readily available N that plants can use immediately. These fertilizers have enabled the dramatic yield increases that characterize modern agriculture.
- **Organic amendments** (e.g., manure and compost) work differently from synthetic fertilizers. Rather than providing immediate N availability, they release nutrients gradually as soil microorganisms decompose organic materials.

An ecological process that can supply N for crop growth occurs biologically in nature and is known as the **biological N fixation.** It is the process by which certain bacteria convert atmospheric N into forms that plants can use. This biological process occurs in two main ways: through symbiotic relationships with legume crops and through free-living soil bacteria. The most significant contribution comes from legume–rhizobia partnerships. When legume crops like soybeans, alfalfa, or clover grow, they form specialized root nodules that house rhizobia bacteria. Inside these nodules, the bacteria use the enzyme nitrogenase to convert atmospheric N into ammonia, which the plant then incorporates into proteins and other compounds. This remarkable symbiosis allows legumes to thrive in N-poor soils while simultaneously enriching the soil for future crops (Sinharoy et al., 2024).



When legume crops grow, they form specialized root nodules that house rhizobia bacteria. Inside these nodules, the bacteria use the enzyme nitrogenase to convert atmospheric N into ammonia, which the plant then incorporates into proteins and other compounds. Photo courtesy of Wikimedia Commons/Nefronus.

Free-living soil bacteria also contribute to N fixation though to a lesser extent than legume symbioses. These bacteria, including species like Azotobacter and certain cyanobacteria, fix smaller amounts of N but help maintain baseline soil N levels across diverse ecosystems (Qiao et al., 2024).

All these N sources depend on healthy, biologically active soils to function effectively. Soil health is enhanced by good physical structure, high organic matter content, and diverse microbial communities, forming the foundation for efficient N cycling.

Healthy soils support larger, more diverse microbial populations that modulate N mineralization. Research has shown that soil microbial biomass is the strongest predictor of N mineralization rates across ecosystems. These microorganisms not only decompose organic matter, but also regulate N transformations that influence plant availability and environmental losses (Li et al., 2019).

Soil organic matter content is particularly crucial as soils with higher organic matter can store more N and release it more steadily over time. Organic matter also improves soil structure by creating pore spaces and stable aggregates that support microbial activity and root growth. This improved structure enhances water infiltration and retention, helping regulate the moisture conditions that drive N transformations.

Conservation practices such as cover cropping, reduced tillage, diverse rotations, and organic matter additions build soil health and create positive feedback loops in N cycling. As soil health improves, N mineralization becomes more efficient, biological fixation increases, and fertilizer use efficiency improves.

Where N goes

Nitrogen removal in the harvested portions of grain crops is a key consideration when determining fertilizer application rates. During harvest, N is exported with the grain at an average rate of about 0.9 lb N/bu of corn, 3.8 lb N/bu of soybean, and 1.2 lb N/bu of wheat (Nafziger, 2023). Studies show that crops utilize only approximately 50% of applied N fertilizer effectively with the remainder lost through various pathways. Major N loss mechanisms include **ammonia volatilization**, **denitrification**, **leaching**, and

surface runoff (Table1 and Figure 1). These losses create substantial economic costs for farmers while causing environmental damage through water eutrophication, greenhouse gas production, and soil acidification.

Table 1. Key processes and microbial drivers in the nitrogen cycle.

Process	***Main drivers (conditions/inputs)***	***Temperature range (°C)***	***Key microorganisms***
N fixation ($N_2 \rightarrow NH_3/NH_4^+$)	Low oxygen, presence of N_2, availability of carbon sources	15–30 (optimal for most diazotrophs, but some fix at wider ranges)	Free-living: *Azotobacter*, *Clostridium*; Symbiotic: *Rhizobium*, *Bradyrhizobium*, *Frankia*; Cyanobacteria (*Anabaena*)
Ammonification (mineralization) (Organic N → NH_4^+)	Organic matter (proteins, nucleic acids), decomposer activity	Broad (5–40), mesophilic peak ~25–35	Heterotrophic bacteria (*Bacillus*, *Pseudomonas*) and fungi (*Aspergillus*, *Penicillium*)

Nitrification (NH_4^+ → NO_2^- → NO_3^-)	Aerobic conditions, NH_4^+ availability	15–30 (optimal ~25–28)	Step 1 (ammonia-oxidizing bacteria/archaea): *Nitrosomonas*, *Nitrosospira*, *Nitrosopumilus* (AOA); Step 2 (nitrite-oxidizing bacteria): *Nitrobacter*, *Nitrospira*
Denitrification (NO_3^- → N_2O/N_2)	Low oxygen or anoxic conditions, NO_3^- as electron acceptor, organic C source	20–30 optimal (but active 5–40)	*Pseudomonas*, *Paracoccus*, *Bacillus*
Anammox (anaerobic ammonium oxidation: NH_4^+ + NO_2^- → N_2)	Strict anoxic, presence of NH_4^+ and NO_2^-	20–43 (optimal ~30–37)	*Candidatus* Brocadia, *Candidatus* Kuenenia (Planctomycetes)
Assimilation (NO_3^-/NH_4^+ → Organic N)	Presence of inorganic N, energy from photosynthesis/respiration	Broad (0–40 depending on organism)	Plants, algae, fungi, bacteria (general metabolic function)

The loss of N as nitrate (NO_3–N) is a leading cause of ecosystem degradation and freshwater eutrophication in the United States. This loss can be mitigated by reducing residual soil N after harvest or synchronizing N supply with crop N demand. The following are the major pathways through which N can move within the system:

Crop uptake and grain removal

Nitrogen uptake by crops refers to the process through which plants absorb N from the soil solution, primarily in the forms of nitrate (NO_3^-) and ammonium (NH_4^+). This N is essential for plant growth as it is a key component of amino acids, proteins, chlorophyll, and enzymes that drive photosynthesis and metabolism. Throughout the growing season, plants take up N through their roots and distribute it to leaves, stems, and reproductive tissues. As the crop matures, a large portion of this N is translocated from the vegetative parts to the developing grains where it contributes to protein synthesis.

When the crop is harvested, the N contained in the grain is physically removed from the field, a process known as grain N removal. The amount of N exported depends on both grain yield and protein concentration. While grain removal represents a desirable outcome of nutrient use, it also signifies a loss of N from the system that must be replenished through fertilization or organic amendments to maintain soil fertility and sustain future yields.

Leaching

Leaching is the downward movement of dissolved substances through the soil profile as water from rainfall or irrigation percolates beyond the root zone and sometimes into groundwater. As water infiltrates the soil and moves through its pores, soluble compounds such as nitrate, potassium, or dissolved salts travel with it. Soil microbes drive the key N transformations that create soluble forms prone to leaching. When crop residues or organic matter decompose, microorganisms mineralize organic N into ammonium (NH_4^+). Nitrifying bacteria, such as *Nitrosomonas* and *Nitrobacter*, then oxidize ammonium to nitrite (NO_2^-) and finally to nitrate (NO_3^-). Nitrate is highly soluble and does not bind strongly to soil particles, so when rain or irrigation water percolates downward, it can be easily carried below the root zone.

Denitrification

Denitrification is a microbially driven process in which nitrate (NO_3^-) or nitrite (NO_2^-) is reduced stepwise to gaseous forms of N—mainly nitrous oxide (N_2O) and dinitrogen gas (N_2)—which are then released to the atmosphere. It is a key part of the global N cycle because it permanently removes reactive N from soils and aquatic systems. Typically, this process occurs in wet places or right after rainfall events and when temperatures are higher than 15°C.

Volatilization

Nitrogen fertilizer volatilization is primarily the escape of ammonia gas after urea-based fertilizers are applied. It is driven by urea hydrolysis and a localized pH spike, and it can be minimized by prompt soil incorporation, well-timed irrigation or rainfall, or the use of urease inhibitors. One type of volatilization that is not well explored is the volatilization of plants. Volatilization of N from leaves refers to the release of gaseous N compounds—primarily ammonia (NH_3)—directly from plant foliage into the atmosphere. Although most N loss from cropping systems occurs through soil processes (e.g., ammonia volatilization after fertilizer application or denitrification), plants can emit N gases under certain conditions.

Runoff

Losses of N through runoff and erosion occur when rainfall or irrigation water moves across the soil surface instead of infiltrating into it. This surface runoff can carry away both dissolved and particulate forms of N. The dissolved losses occur mainly as nitrate (NO_3^-), which is highly soluble in water and can be easily transported when water flows over the soil.

Erosion

Erosion physically detaches and removes soil particles that are rich in organic matter and ammonium (NH_4^+), both of which are forms of N bound to the soil. As sediments are washed away, the N attached to them is also lost, reducing the soil's fertility.

Together, runoff and erosion represent significant pathways of N loss from agricultural fields. Photo courtesy of JJ Gouin/Alamy.

Together, runoff and erosion represent significant pathways of N loss from agricultural fields, contributing to decreased nutrient availability for crops and to environmental problems such as water contamination and eutrophication. Management practices such as maintaining vegetation cover, reducing soil disturbance, and using cover crops or buffer strips can help minimize these losses by protecting the soil surface and improving water infiltration.

Sandy soils, with their larger pores, promote faster water movement and therefore have a greater leaching potential than heavier clay soils. The risk increases when large amounts of water move through the soil in a short time, such as after heavy rains or excessive irrigation, and when nutrients are in highly soluble forms like nitrate, which leach more readily than ammonium. Active crop uptake can help reduce losses, but when plant demand is low, nutrients are more vulnerable to being carried away.

When N is lost from fields, farmers face a direct economic cost because fertilizer, which represents a substantial portion of crop production expenses, is wasted. For example, each pound of N lost to leaching, volatilization, or denitrification reduces the potential yield return on that fertilizer investment. In addition to economic losses, lost

N has environmental consequences. Leached nitrate can contaminate groundwater, volatilized ammonia contributes to air pollution, and gaseous N compounds such as N_2O are potent greenhouse gases. Therefore, managing N efficiently is crucial both to reduce input costs for farmers and to minimize negative environmental impacts.

Tools for smarter N management

Effective N management is as much about timing and context as it is about quantity. Over the past decades, farmers, researchers, and policymakers have converged on a guiding principle: N must be supplied in synchrony with crop demand while minimizing opportunities for loss of N. While no single one-size-fits-all solution exists, achieving this balance requires a mix of complementary tools that combine agronomic principles, diagnostic technologies, and ecological practices.

At the foundation lie the **"4R" principles**—supplying the **right source** at the **right rate**, **right time**, and **right place** (IFA, 2009; Johnston & Bruulsema, 2014) or the best management practices (BMPs) principle (Bruulsema, 2008). Although these guidelines sound simple, each represents a decision point that strongly shapes both productivity and environmental outcomes based on using BMPs for the local context. For instance, fertilizer formulations range from conventional urea to enhanced-efficiency products that slow N transformations, each with trade-offs in cost and effectiveness. Application rates once set by broad regional

At the foundation of effective N management lie the 4R principles—supplying the right source at the right rate, right time, and right place. Photo courtesy of Wikimedia Commons/Michael Trolove. CC BY-SA 2.0.

averages are increasingly fine-tuned using site-specific data. Synchronizing supply with crop demand through split applications or fertigation reduces excesses while placement methods such as banding or injection bring nutrients closer to roots and away from pathways of volatilization or runoff.

A growing suite of **decision-support tools** can assist in translating the 4R principles from abstract guidelines into field-level strategies. Dynamic simulation models such as **Adapt-N** combine soil, crop, and weather data to generate seasonally responsive fertilizer recommendations, adjusting the “right rate” and “right time” to shifting climatic conditions. Similarly, the **Maximum Return to N (MRTN)** approach draws on large multi-site trial datasets to identify economically optimal rates, helping farmers balance yield gains with diminishing returns and environmental risks. On the technology side, **variable-rate application (VRT)** systems bring the “right place” principle to life by tailoring inputs across zones of a single field, informed by yield maps, soil grids, or remote-sensing imagery. **Unmanned aerial vehicles (UAVs)** with multispectral sensors can increasingly be used for N management.

These digital and mechanical innovations are increasingly integrated with cloud-based platforms that assimilate sensor streams, forecasts, and historical records to anticipate N needs before deficiencies manifest. When combined with traditional diagnostics and ecological practices such as cover crops, these tools enable a more adaptive and resilient N management system—one that learns from variability rather than being undermined by it.

Postharvest soil nitrate sampling to inform a mass balance approach within a wheat N use efficiency study. Photo courtesy of Julio Leiva Rivarola, Kansas State University.

Translating these principles into practice needs timely **measurement and monitoring.** Soil testing remains a cornerstone, offering estimates of residual nitrate at planting, but single measurements rarely capture the dynamic nature of N cycling. The N nutrition index (NNI) provides a physiologically based diagnostic framework that enables real-time assessment of crop N status relative to critical dilution curves, allowing farmers to optimize fertilizer timing and rates by matching N supply to actual crop demand rather than applying excess fertilizer as insurance against uncertainty (Lemaire et al., 2008). In-season assessments of plant status—whether through leaf tissue analysis, handheld chlorophyll meters, or canopy reflectance sensors—provide a more immediate window into crop nutrition.

The rapid expansion of precision agriculture is transforming such diagnostics into actionable management strategies. Satellites, drones, and proximal sensors can now map variability in real time through UAVs while variable-rate technologies deliver inputs at sub-field scales. Increasingly, digital platforms integrate soil, weather, and yield data to generate predictive recommendations with machine-learning models beginning to anticipate N needs before deficiencies become visible.

Yet smarter N management is not only about better gadgets—it also depends on building the biological infrastructure of the soil. **Cover crops and diversified rotations** are among the most powerful and underutilized tools for balancing N supply and demand.

Non-legume covers, such as rye, scavenge nitrate after harvest and prevent leaching losses during fallow periods while legumes, such as clover or vetch, fix atmospheric N that can contribute to subsequent crop nutrition. Mixtures that combine grasses and legumes buffer the extremes: they capture excess N while providing a slow-release supply, aligning with the optimal carbon:N balance for microbial mineralization.

Non-legume covers, such as rye, scavenge nitrate after harvest and prevent leaching losses during fallow periods. NRCS/SWCS photo by Lynn Betts.

Over the years, rotations that include such covers enhanced organic matter, soil structure, and microbial activity, making the soil itself a more reliable source and reservoir of N. Employing other ecological tools, such as conservation to no-till practices, intercropping, green manure, etc., can provide additional avenues to build soil biochemical infrastructure for sustainable N management.

Recognizing this biological underpinning has sparked interest in using **soil health indicators** as predictors of N availability. Measures such as soil organic matter, potentially mineralizable N, microbial biomass N, or enzyme activity capture aspects of the soil's capacity to release N during the season. Although still evolving, these indicators move management beyond static chemical tests toward a more functional understanding of N supply to synchronize with crop demands. Emerging research even suggests that microbial community profiles or gene markers linked to nitrification and denitrification may one day help forecast pathways of N loss, offering another dimension of predictive capacity. These indicators could provide additional tools for precision N management, especially if they can be integrated in routine soil fertility tests.

Taking together, these tools provide a transition from traditional fertilizer recommendations to adaptive N management systems (Figure 2). The 4R principles provide the compass while diagnostics and precision technologies supply the navigational instruments. Cover crops and rotations build ecological resilience, and soil health indicators promise to link biological function with agronomic practice.

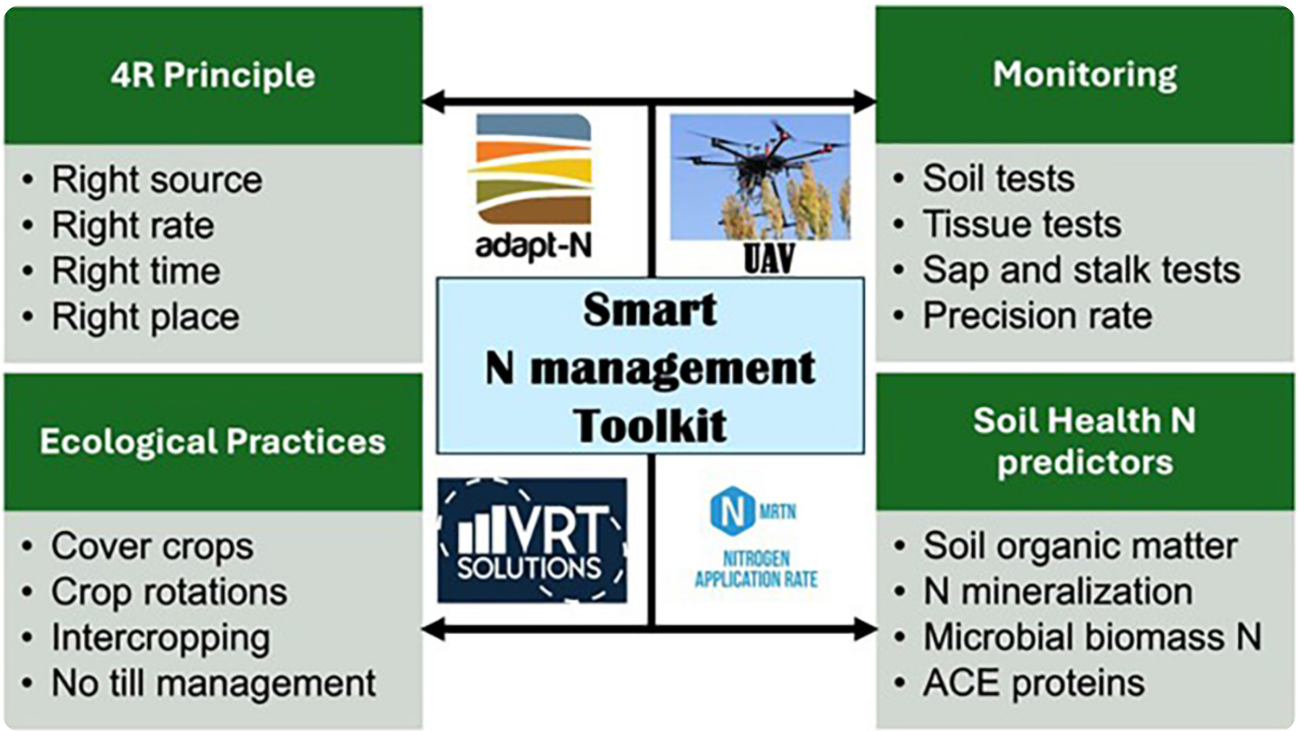


Figure 2. *Smart N management toolkit: Integration of multiple strategies should be localized and balanced for optimizing N efficiency.*

No single tool is sufficient on its own, but their integration can optimize N use efficiency, support yields, and reduce losses to air and water. Sustainable N management can rely on soil organic matter enhancement and conservation practices that sequester carbon to increase indigenous N supply and improve synchronization between N mineralization and crop demand, though precision timing and application methods remain more critical than the choice between organic and inorganic sources.

The fundamental principle for N management going forward is shifting away from "insurance" over-application toward precision management based on understanding your system's specific needs and constraints. Whether through ecological approaches, diagnostic tools, or enhanced-efficiency technologies, the common thread is matching N supply to actual crop demand rather than applying excess as a safety measure.

The challenge ahead is not the absence of solutions but ensuring accessibility, tailoring them to diverse farming contexts, and aligning incentives so that short-term decisions reinforce long-term sustainability.

Looking forward

The future of N management will be shaped by integrating soil health frameworks, biofertilizers, and emerging technologies. Smarter tools and practices are helping farmers not only improve fertilizer efficiency, but also strengthen the biological foundation of their soils.

- One promising direction is to integrate soil health frameworks into N management. Healthy soils, rich in organic matter, biologically active, and structurally stable, hold nutrients more efficiently and release them gradually to crops. By monitoring indicators like soil organic carbon, microbial activity, and aggregate stability, farmers and advisers can better align fertilizer use with natural soil processes.

- Another frontier advantage is the use of biofertilizers, which are living microbial inoculants that enhance N fixation, mobilize nutrients, or improve plant resilience. When paired with conventional fertilizers, these products can boost nutrient use efficiency and reduce the need for high application rates. Coupled with compost, cover crops, and other biological amendments, biofertilizers represent a growing toolbox for climate-smart farming.

- At the same time, new technologies are rapidly transforming how N is managed in the field. Precision sensors, variable-rate applicators, and decision-support models help farmers apply the right amount of N, at the right time, and in the right place. Emerging nanotechnology-enabled delivery systems, for example, have the potential to release nutrients more precisely in response to soil conditions or plant demand. These tools promise not just greater efficiency, but also stronger safeguards for water and air quality.

Precision sensors, variable-rate applicators, and decision-support models help farmers apply the right amount of N, at the right time, and in the right place. AI-generated image courtesy of Microsoft Copilot.

Farmers are at the front and center of transition from traditional fertilizer recommendations to adaptive N management systems, positioned as stewards of both food security and environmental sustainability.

Certain technologies, such as improved hybrids, have been developed through breeding for traits that enhance N use efficiency. These include deeper root systems that capture N from subsoil layers, improved remobilization of N from leaves to the grain during grain filling, and greater photosynthetic efficiency per unit of leaf N. Similarly, controlled-release fertilizers and nitrification inhibitors delay N transformations in the soil, improving synchrony between N availability and crop demand, and reducing losses through leaching and gaseous emission.

Such innovations can simultaneously raise crop yields and increase farmer profitability. In contrast, other strategies, such as sidedressing or variable-rate application, are more effective at reducing environmental losses but often provide limited direct economic incentives for adoption, which constrains their widespread use unless supported by targeted policies or market mechanisms.

The key take-home message is simple: *understanding how N moves through the soil is the first step toward managing it better*. By tracing how N enters, transforms, and leaves the soil system, we can design practices and technologies that capture more value in the field and minimize losses to the environment. Although we possess abundant scientific knowledge, technologies, and effective management strategies to improve N use efficiency, the real challenge may be applying them at scale. Finding the balance between feeding a growing global population and protecting the planet's air, water, and climate systems is at the heart of the N dilemma.

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