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Review Article

Precision Nutrient Management Amid Climate Change Challenges: A Review

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Abstract

Increasing food demand and climate change present significant challenges to sustainable food production systems and environmental health. Nitrogen, crucial for plant metabolism and growth, also poses risks such as water pollution through nitrate leaching and the emission of nitrous oxide (N_2O), a potent greenhouse gas contributing to global warming. Despite ongoing efforts to reduce nitrogen fertilizer application, inefficient use persists. Precision agriculture emphasizes optimizing nitrogen application to mitigate climate change and enhance productivity, sustainability, profitability, and climate resilience. While soil testing has historically improved grain production, focusing on crop nutrient demands rather than soil nutrient levels is gaining traction. This approach synchronizes nutrient supply with plant needs more effectively, ensuring nutrients are applied when and where they are most beneficial. Implementing precision nutrient management enhances efficiency, maintains or increases yields, and minimizes nutrient runoff, safeguarding water supplies. This strategy adheres to the principles of the "4 Rs" – Right rate, Right source, Right application method, and Right timing – to deliver nutrients effectively. Advances in technologies like optical sensors and leaf color charts enable real-time nitrogen application adjustments during the growing season, supporting cost-effective and farmer-friendly practices. While developed countries lead in adopting precision nutrient management for nitrogen and other nutrients, developing nations are increasingly exploring similar strategies. Effective policies and programs are essential to address nitrogen fertilizer use and mitigate its impact on climate change in agriculture.

Keywords

Climate Change, GHG Emission, Judicious Nutrient Management, Omission Plot, Resilience, Sustainability

1. Introduction

Natural nutrient sources and recycling have proven insufficient to meet increasing human needs since the 19th century. Throughout the twentieth century, soil fertility and plant nutrition remained central to agricultural sciences. With a growing focus on sustainability and limited natural resources, the importance of soil fertility and plant nutrition is expected to multiply in the twenty-first century. The Green Revolution notably increased the use of synthetic fertilizers, which now contribute approximately 50% to current food production. Achieving global food security hinges on sustainable in-

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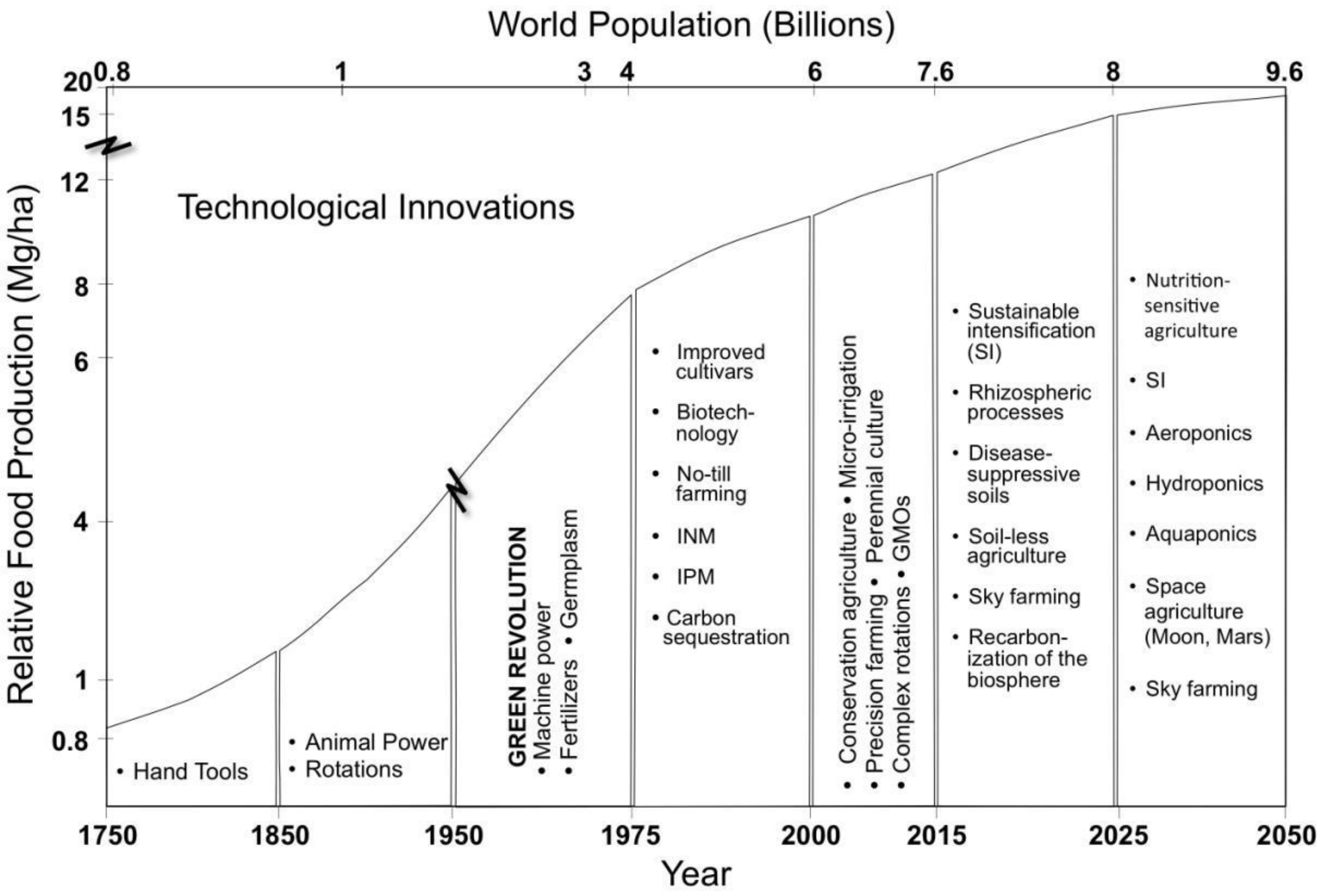
creases in productivity. Meeting the food demands of a rapidly expanding population is a formidable global challenge, especially considering projections that global crop demand will double within 30 years (Figure 1) [11, 22].

However, keeping pace with these demands amidst rapid population growth necessitates careful nutrient management. Over the past several decades, intensive agricultural practices and increased fertilizer use have led to significant negative environmental and social impacts. Improper use of fertilizers can pollute the atmosphere, hydrosphere, and lithosphere, threatening sustainability.

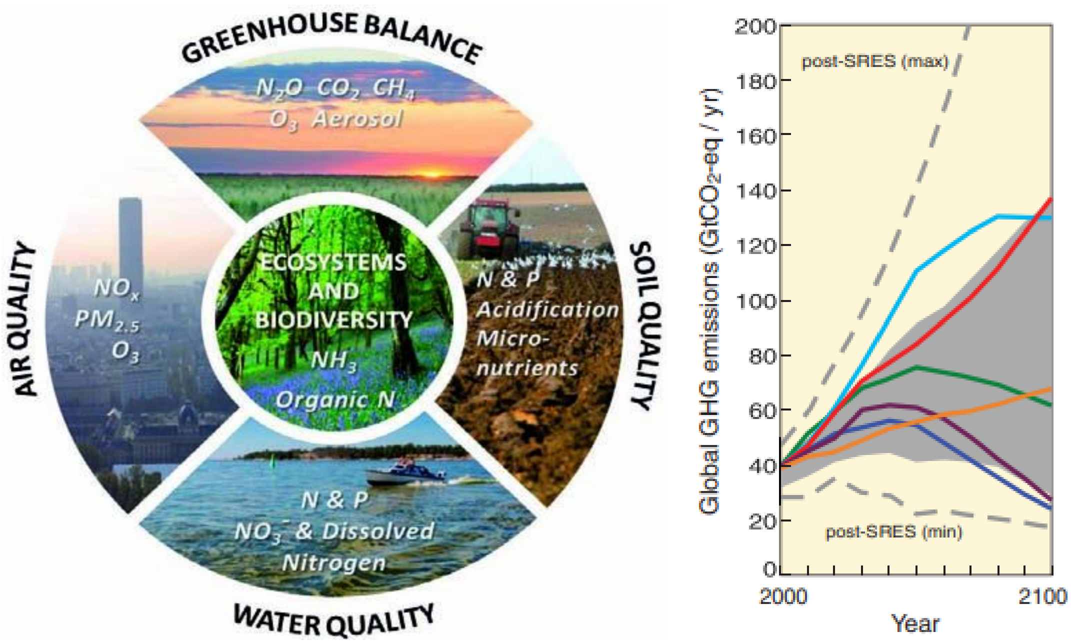


Adapted from: [22].

Figure 1. *Technological evolution and future innovative and emerging technologies.*

Agriculture plays a dual role in climate change, acting both as a contributor and a victim. It contributes to climate change through significant emissions of greenhouse gases (GHGs), particularly from the production and application of fertilizers during agricultural intensification. The Earth naturally retains some of the sun's warmth through greenhouse gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere, which is essential for maintaining a habitable temperature [5]. However, human activities have increased the concentration of these gases beyond natural levels, disrupting the Earth's equilibrium. This enhanced greenhouse effect is causing global temperatures to rise, a trend expected to continue according to the Intergovernmental Panel on Climate Change (Figure 2, Right panel) [5, 17].

Continued emission of GHGs at current or higher rates is projected to exacerbate global warming and lead to substantial changes in the climate system during the 21st century, surpassing those observed in the 20th century [5].



Source: [17].

Figure 2. *Left Panel: The five key threats of too much or too little nutrients. Right Panel: Global GHG emissions (in $GtCO_2$ -eq) in the absence of climate policies.*

Nitrogen (N) is the most vulnerable of the four major nutrients (N, phosphorus-P, potassium-K, and sulfur-S) applied through synthetic fertilizers, as it is prone to significant losses. It plays a crucial role in plant metabolism and growth but can lead to environmental pollution when it leaches into groundwater as nitrates. Additionally, nitrogen can contribute to global warming when emitted as nitrous oxide (N_2O), a potent greenhouse gas with 298 times the environmental impact of carbon dioxide (CO_2) per molecule. The release of reactive nitrogen species into the atmosphere and water systems has diverse ecological impacts, including groundwater pollution, surface water eutrophication, terrestrial biodiversity loss, soil acidification, and human health impacts [7, 12, 30, 42, 47].

Ammonia (NH_3) emissions, although not directly altering the greenhouse gas balance, can contribute indirectly to N_2O formation through microbial processes like nitrification and denitrification. Furthermore, atmospheric NH_3 deposition can lead to eutrophication in various natural ecosystems [48]. Soil nitrous oxide emissions primarily originate from microbial activity in soils (55%), organic manure applications (18%), and nitrogen fertilizer applications (27%) (Figure 2, Left panel) [10, 27, 30].

Given the inevitability of some degree of climate change, adapting agricultural practices is crucial. Emphasizing farming techniques that promote soil health, sustainable nutrient management, and environmental sustainability is imperative. As climate variability increases, the risks associated with crop and soil management strategies become more pronounced. Effective management of fertilizer and manure, including consideration of placement, timing, application method, and rate, can significantly influence nitrogen availability to plants and mitigate environmental losses. Implementing such practices not only reduces greenhouse gas emissions but also enhances economic efficiency and long-term soil productivity, thereby lowering agriculture's contribution to climate change [14]. This paper reviews practical on-farm practices and techniques aimed at reducing nitrogen losses to the hydrosphere and greenhouse gas emissions to the atmosphere [44].

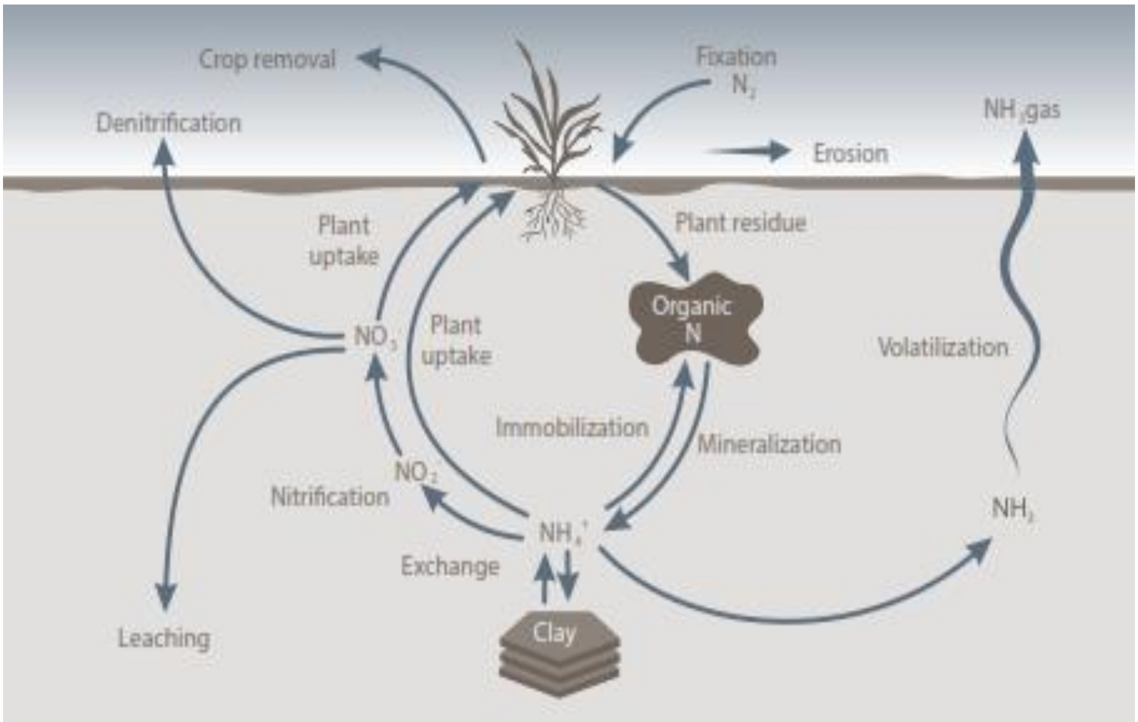
2. Fertilizer Best Management Practices: Addressing Climate Change Challenges

2.1. Nutrient Cycles

Nitrogen, one of the 16 essential nutrients for plants, presents distinct challenges in field crop systems due to its fluctuating availability, which is particularly affected by soil water status changes. To effectively manage nitrogen and reduce losses, including nitrous oxide (N_2O) emissions, it is crucial to understand the environmental factors influencing the nitrogen cycle. These factors determine nitrogen availability for crops and the various pathways of nitrogen loss, such as leaching and emissions of nitrogen gas (N_2) and nitrous oxide (N_2O) [12].

Nitrogen continuously cycles through plants, soil organisms, organic matter, water, and the atmosphere, undergoing complex biochemical transformations (as shown in Figure 3). Multiple processes, such as leaching, surface runoff, soil erosion, ammonia volatilization, and denitrification, can lead to nitrogen loss from the plant-soil system. Healthy soils facilitate complete nitrogen cycling, reducing the formation of nitrous oxide (N_2O), a potent greenhouse gas produced from incomplete nitrogen cycles [10, 27].

Understanding and managing these nitrogen dynamics is essential for maximizing crop productivity while minimizing environmental impacts like greenhouse gas emissions.



Adapted from: [10]

Figure 3. *The nitrogen cycle.*

2.2. Nitrogen Management Practices That Improve Nitrogen Use Efficiency

Co-benefits and trade-offs

Identifying and reducing excess nutrient applications can lead to significant savings in fertilizer use, thereby enhancing farm profitability by lowering input costs and potentially increasing crop yields and quality. Nutrient management planning, especially in situations where excess nutrients are currently being applied, can decrease the use of manufactured fertilizers, resulting in cost savings and reduced risks of air and water pollution. Improved nitrogen use efficiency, which decreases nitrogen loss from the soil, benefits both farmers and the environment when proper techniques are employed. Effective nutrient management planning ensures that the nutrient supply is sufficient for optimal crop growth [28].

Climate-smart agriculture (CSA) focuses on three key pillars:

1) Sustainably increasing agricultural productivity and incomes;
2) Enhancing resilience in agriculture to adapt to climate change;
3) Reducing agriculture's contribution to climate change by minimizing greenhouse gas emissions and potentially acting as a carbon sink.

Efficient nutrient management is essential for supporting sustainable farming systems by promoting efficient food production and minimizing diffuse air and water pollution from agricultural activities. Nutrient management plans utilize fertilizer recommendation systems to ensure the total nutrient supply meets but does not exceed crop requirements. Maintaining a balance between different nutrients is crucial for maximizing nutrient uptake efficiency and minimizing environmental losses. Although completely avoiding nutrient losses is impossible, significant improvements can be achieved by implementing one or more of the following management practices in the cropping system [7].

2.2.1. Soil Testing /Quantifying Soil Nutrient Supply/

The initial step to reduce nitrous oxide emissions from cropland involves testing the soil for residual nutrient levels. This includes determining the quantities of nitrogen, phosphorus, potassium (N-P-K), and other critical elements such as organic matter and pH in the soil. Pre-plant soil tests provide insights into the soil's nitrogen-supply capacity, while late spring or pre-side-dress nitrogen tests help determine additional nitrogen needs. Soil tests offer a comprehensive view of field fertility and guide appropriate nutrient application rates to maximize yield. Soil nitrogen supply can be assessed using information about soil type, typical overwinter rainfall (to evaluate leaching losses), nitrogen released from crop residues, and previous fertilizer and manure use. In cases of atypical previous management, soil sampling to 90 cm may be more effective for quantifying soil nitrogen supply on arable fields. Soil analysis is the most effective method for quantifying soil pH status and extractable phosphorus, potassium, and magnesium contents, recommended every 3-5 years [25].

2.2.2. Quantifying Crop Nutrient Requirement

Different crop varieties have varying abilities to extract nitrogen from the soil and improve nitrogen use efficiency. Crop requirements vary with species (and sometimes variety) and depend on soil nutrient supply, soil type, and overwinter rainfall. Fertilizer recommendation systems, such as AHDB's Nutrient Management Guide (RB209), provide comprehensive guidance on nutrients required for optimal crop production. Breeding crops for efficient nitrogen uptake is also important [45].

2.2.3. Quantifying Nutrient Supply from Organic Materials

Understanding the nutrient content of organic materials and determining application rates are crucial for optimizing manure nutrient use. The nutrient content of organic materials depends on various factors. For livestock manures, these include livestock type, feeding regime, diet, rainwater dilution during storage, and bedding used. For digestates and composts, the feedstock source, and for biosolids, the treatment processes are key factors. Typical nutrient content figures are available in [1, 6], but laboratory analysis can provide a more accurate assessment. Nutrients in organic materials exist in two forms: readily available soluble forms, immediately available to crops and at high risk of environmental loss, and organic forms, which become available over time as organic matter mineralizes in the soil. Managing applications to maximize nutrient availability and utilization over time is essential [1].

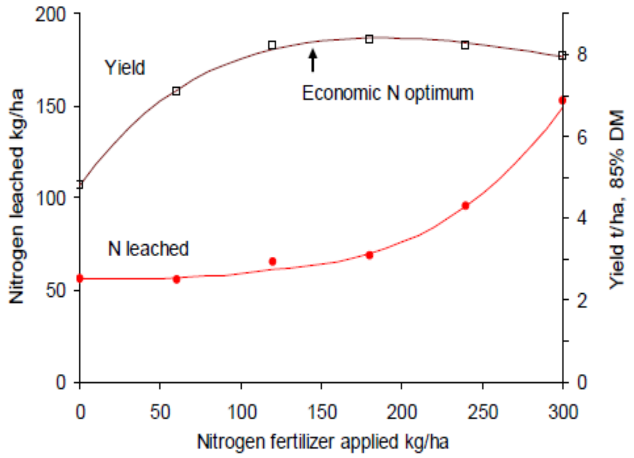
For manures high in readily available nitrogen (e.g., slurries, poultry manures, and digestates), applying organic materials when crops are actively growing increases nitrogen use efficiency and reduces nitrate leaching risk. Precision application techniques, such as band-spreaders and shallow injectors, can minimize ammonia emissions, odor, and crop contamination compared to conventional surface broadcast applicators [6].

Accounting for Manure Nutrients When Planning Manufactured Fertilizer Applications.

The nutrient supply from different manure application timings and methods can be calculated using the MANNER-NPK decision support tool or referenced in AHDB's Nutrient Management Guide. It is crucial to account for manure-supplied nutrients when determining manufactured fertilizer application rates to ensure crop nutrient requirements are met without exceeding them, thus minimizing environmental nutrient losses [1, 7].

2.3. Application of Nitrogen

Most agricultural soils require annual nitrogen applications from fertilizers and/or organic materials to ensure optimal crop growth. Mineral nitrogen in the soil mainly exists as nitrate, which is mobile. Nitrate present in the soil at the start of winter is unlikely to be taken up by crops as growth slows due to cold temperatures and reduced light. With typical excess winter rainfall, nitrate is at risk of leaching as water drains through the soil. Nitrogen applications that are below economic optimum result in sub-optimal crop yields and quality, while those exceeding crop requirements increase the risk of nitrate leaching (Figure 4) [23].



Adapted from: [23]

Figure 4. *Impact of fertilizer nitrogen applications on winter wheat yields and nitrate leaching losses.*

2.4. Application of Phosphorus

A significant portion of phosphorus (P) in soils is bound in forms that are not readily available to plants or at risk of leaching into water due to the strong affinity of certain soil substances (clays, iron-Fe, aluminum-Al, calcium-Ca) for P [13]. Therefore, managing crop-available P supply involves maintaining sufficient amounts in the soil for the needs of a crop rotation rather than focusing on individual crops.

3. The Role of Precision Nutrient Management in Climate-Smart Agriculture

Farmers' fields exhibit considerable variability in nutrient-supplying capacity and crop response to nutrients. Consequently, blanket fertilizer application recommendations may result in over-fertilizing some areas and under-fertilizing others, or applying an improper balance of nutrients for their soil or crop. As an alternative to blanket recommendations, agricultural producers are increasingly adopting precision agriculture technology due to its benefits in time management, efficiency, economics, and natural resource conservation. Soil test-based nutrient management recommendations have historically improved food grain production but have not significantly enhanced nutrient use efficiency. Researchers have shifted towards an approach of feeding the crops directly rather than feeding the soil. Assessing plant nutrient demand is a more efficient strategy since plant growth at any given time integrates the effect of nutrient supply from all sources, making it a reliable indicator of nutrient availability [3, 40].

Nitrate (NO^{3-}), a naturally occurring anion salt soluble in water, is a major concern for water quality. It can travel off-farm to surface and groundwater if the soil's water storage capacity is exceeded. Additionally, nitrous oxide (N_2O) is not only a greenhouse gas but also harmful to the ozone layer, which, when damaged, allows more ultraviolet light to reach Earth's surface, increasing health risks such as skin cancer. Fortunately, avoiding nitrogen loss as nitrate or nitrous oxide involves the same solution: matching nutrient use to crop needs using science-based methodologies to plan applications for optimal nitrogen use efficiency and production [39].

Efficient nutrient management, particularly nitrogen and phosphorus, is crucial for optimizing crop productivity and minimizing environmental impacts. Precision agriculture technologies and science-based methodologies, such as the 4R stewardship framework, help align nutrient applications with crop needs, thereby enhancing nutrient use efficiency and reducing environmental risks. Sustainable farming practices, including regular soil testing and tailored nutrient management plans, support climate-smart agriculture by promoting efficient food production and mitigating greenhouse gas emissions. Fortunately, avoiding the loss of nitrogen as nitrate or as nitrous oxide has the same solution: matching the use of nutrients to the needs of crops- in other words, using science-based methodologies to plan applications for optimal nitrogen use efficiency and production. It is for this reason that The Fertilizer Institute advocates 4R stewardship (Table 1) [3, 14, 18]. This is why The Fertilizer Institute advocates for 4R stewardship. The four R's are:

1) Right Source: Ensure a balanced supply of essential nutrients, considering both naturally available sources and the characteristics of specific products, in plant-available forms.
2) Right Rate: Assess and apply the proper amounts of nutrients to meet crop needs and minimize losses.
3) Right Time: Make nutrients available when crops need them most, reducing losses.
4) Right Place: Place nutrients where crops can easily access them, reducing losses to the environment.

Table 1. *Key scientific principles and associated practices of 4R nutrient stewardship.*

SSNM principle	Scientific basis	Associated practices
Product	Ensure balanced supply of nutrients Suit soil properties	Commercial fertilizer Livestock manure Compost Crop residue
Rate	Assess nutrient supply from all sources Assess plant demand	Test soil for nutrients Balance crop removal
Time	Assess dynamics of crop uptake and soil supply Determine timing of loss risk	Apply nutrients: Pre-planting At planting At flowering At fruiting
Place	Recognize crop rooting patterns Manage spatial variability	Broadcast Band/drill/inject Variable-rate application

Source: [18].

3.1. Improving Nutrient Use Efficiency

Analyzing manure nutrients is one way to assess its fertility. The impact of nitrogen fixed from previous legume crops and residual manure effects also influences rate recommendations. Other nutrient sources should be considered in the plan as well. Differences in climate, soil physical properties, and application rates generally result in minimal variations in nitrous oxide (N_2O) emissions between different nitrogen sources, and no single fertilizer type typically contributes significantly more N_2O than another [10, 19].

Slope, rainfall patterns, soil type, crop rotation and many other factors determine which method is best for optimizing nutrient efficiency (availability and loss) in farms. The combination that's right in one field may differ in another field even with the same crop. When fertilizer or manure is incorporated within 24 hours, the N loss can jump to 25 percent. For every additional day that fertilizer is not incorporated, approximately 5 percent N is lost. Up to 90 percent of applied broadcast fertilizer N can be lost within 5 days when environmental conditions are warm and dry. This is extremely inefficient nutrient management for the farmer and it releases N gases to the environment [4, 6].

3.2. Nitrogen Capture

Rotating with deep-rooted crops helps capture nitrates deeper in the soil profile. Cover crops capture residual nitrogen after harvest and recycle it as plant biomass. Eliminating restrictions to subsoil root development, such as subsoil compaction and acidity, prevents nitrate build-up and subsequent denitrification and leaching. Good agronomic practices, including proper plant populations, spacing, and effective weed and pest management, promote large root systems that optimize nitrogen capture and crop yield [4, 8].

3.3. Use of Slow-Release Nitrogen Fertilizers, Urease, and Nitrification Inhibitors

Slow-release fertilizers release nutrients gradually, matching crop needs and reducing the risk of nitrogen loss through denitrification and leaching by limiting soil nitrate concentrations. Nitrification inhibitors maintain applied nitrogen in ammonium form longer, reducing losses. Slow-release fertilizers are more expensive, which may limit their use to high-value crops. Urease inhibitors prevent volatilization of surface-applied urea or UAN solutions, while nitrification inhibitors slow the conversion of ammonia to nitrate, reducing N_2O emissions and other losses [27, 39].

3.4. 4R Nutrient Management Demonstration in Ethiopia

The International Fertilizer Association (IFA) supports IPNI's project in Ethiopia, where 85 demonstrations and learning sites dedicated to 4R nutrient management have already demonstrated significant potential for improving yields and profits for farmers (Table 2) [18].

Table 2. *Ethiopia Farmer Practice vs. 4Rs* demonstration and learning sites established in three regions*.

Crop	Farmer Practice		4R Demonstration	
	Yield, t/ha	Ave. Gross Margin, $	Yield, t/ha	Ave. Gross Margin, $
Maize	2.0 - 4.0	560	7.0	>1,000
Beans	0.5 - 1.0	240	2.3	980
Groundnuts	0.5 - 1.5	320	3.0	850

Source: [18].

4. Precision Nutrient Management Tools and Techniques

Nutrient Use Efficiency (NUE) gauges the increase in crop yield achieved per unit of fertilizer nutrient applied. It can be assessed from agronomic, physiological, and economic perspectives. NUE is crucial for evaluating crop production systems and is significantly influenced by nutrient management and soil-plant-water interactions. Precision nutrient management involves a dynamic, field-specific approach tailored to a particular cropping system or season, optimizing nutrient supply and demand based on their unique cycling through soil-plant systems [49].

The evergreen revolution aims to maximize yields from available resources such as land and water while avoiding ecological and social harm. Precision agricultural techniques and technologies play a vital role in achieving this goal. While precision agriculture has seen remarkable growth in developed countries, its adoption in developing nations has been slower. There is a common misconception that precision agriculture is complex and suitable only for large fields in developed regions. However, there is no specific scale requirement for precision farming [36].

Traditionally, assessing the spatial and temporal variability of soil nutrients involves labor-intensive field sampling and testing. These methods are often destructive. Nowadays, tools such as chlorophyll meters, leaf color charts, and optical sensors offer alternatives for making immediate nutrient management decisions. Advances in geo-spatial technologies, including GPS, GIS, remote sensing, and variable rate applications (VRA), facilitate need-based nutrient management. These technologies can significantly enhance fertilizer use efficiency by addressing over- and under-fertilization issues [34, 45].

4.1. Optical Sensors

Farmers and extension agents can use optical sensors to develop site-specific nutrient management (SSNM) recommendations, particularly for nitrogen. Optical sensors measure light reflectance from leaves to create a vegetative index known as NDVI (Normalized Difference Vegetation Index), which assesses the nutrient status of plants based on leaf size and color. Originally designed for large farms, a smaller, more affordable handheld version (approximately USD 500) is now available commercially [32, 33].

These sensors detect nitrogen stress by measuring visible and near-infrared (NIR) spectral responses from plant canopies [24]. Chlorophyll in the leaf's palisade layer affects visible light reflectance (400-720 nm), while NIR reflectance (720-1300 nm) depends on mesophyll tissue structure. Spectral indices like NDVI, calculated as (FNIR – FRed) / (FNIR + FRed) where FNIR and FRed are fractions of emitted NIR and red radiation, provide insights into photosynthetic efficiency, productivity potential, and yield [20]. NDVI measurements at different growth stages help develop algorithms for determining fertilizer-N rates based on expected yields and leaf greenness [32, 33].

4.2. Chlorophyll Meters

Chlorophyll meters are reliable tools for diagnosing plant nitrogen status, serving as alternatives to traditional tissue analysis. The hand-held Minolta SPAD-502 is the most widely used chlorophyll meter. Developed by Minolta, Osaka, Japan, the SPAD-502 provides quick, non-destructive estimates of leaf nitrogen status by measuring chlorophyll content with red (650 nm) and infrared (940 nm) LEDs [24, 26, 9, 2].

Fertilizer-N is applied when chlorophyll meter readings fall below a predetermined threshold. This threshold, representing the point below which yield reduction occurs, must be established in advance. Comparisons between fixed and dynamic sufficiency index approaches for need-based fertilizer-N management showed that using 32 to 65 kg N ha-1 less fertilizer yielded comparable or better results than soil test-based recommendations, with agronomic efficiency increases ranging from 2.6 to 42.2 kg grain per kg N applied [15, 16].

4.3. Leaf Color Chart (LCC)

The Leaf Color Chart (LCC) helps farmers make informed decisions about nitrogen fertilizer applications. Traditionally, farmers relied on visual observations of crop nutrient status. The LCC, a cost-effective and easy-to-use tool, measures leaf greenness, which correlates with chlorophyll content. The LCC consists of a plastic strip with various shades of green, from light yellowish-green to dark green, and adjusts nitrogen application based on leaf color reflectance. While not as precise as the SPAD meter, the LCC is a practical tool for real-time nitrogen management [45].

4.3.1. Real-Time N Management Approach

Precision nitrogen management experiments have shown that traditional soil test-based or farmer practices often fall short of achieving high NUE while maintaining crop yields. Using threshold LCC shade 5, it is possible to save 25-50% of fertilizer-N compared to blanket recommendations of 120 kg N ha-1. Precision N management using LCC was evaluated at 23 locations in Punjab, where applying a basal dose of 30 kg N ha-1 at planting followed by additional top-dressing based on LCC readings resulted in comparable or higher yields with 20 kg N ha-1 less fertilizer. This approach highlights the effectiveness of precision N management in enhancing productivity and NUE [18, 21].

4.3.2. Fixed-Time Variable Rate Dose Approach

The fixed-time variable rate approach adjusts fertilizer-N application based on leaf color intensity. If the leaf color is higher (e.g., >LCC4), less fertilizer-N is applied; if it is lower (e.g., <LCC4), more fertilizer-N is applied. Adjustments during active tillering and panicle initiation stages ensure appropriate N application according to plant demand. [9] suggested using nutrient omission plot techniques and four-panel IRRI-LCC to estimate and adjust pre-determined fertilizer-N rates. A single large application of >45 kg N ha-1 can be made under favorable weather conditions if the crop response to N is high [8, 9].

4.4. Omission Plot Technique

The omission plot technique estimates fertilizer requirements to achieve a yield target by applying all major nutrients except the nutrient of interest. This method estimates the soil's indigenous nutrient supply, and the yield gap between the maximum achievable yield and the omission plot yield indicates the fertilizer requirement. This technique is mainly used for major nutrients like NPK. Limitations include the potential impact of climate, agronomic practices, and pest damage on native nutrient supply (Table 3) [10].

Table 3. *Design of Nutrient Omission Technique.*

Treatment	N-Omission	P-Omission	K-Omission	Targeted Yield plot
N	Nil	Full Dose	Full Dose	
P	Full Dose	Nil	Full Dose	Full dose of NPK
K	Full Dose	Full Dose	Nil	

Source: [10]

Precision Nutrient Management: Tools and Techniques

Precision nutrient management has significantly improved nutrient recovery efficiency, increasing it from 0.17 kg per kg in traditional practices to 0.27 kg per kg in precision-managed plots, marking a 63% increase in agronomic nutrient use efficiency. Witt et al. (2006) conducted experiments on hybrid maize using omission plots and farmers' practices as benchmarks. Farmers typically applied 107 kg N, 30 kg P_2O_5, and 63 kg K_2O per hectare. Nutrient limitations followed the sequence N > P > K, with average yield responses of 0.9, 0.7, and 0.6 tons per hectare for N, P, and K applications, respectively. According to Pasuquin et al. (2014), the response to fertilizers in Southeast Asia also followed N > P > K, with irrigated sites showing higher yield responses to N than rain-fed sites (6 tons per hectare vs. 2 tons per hectare). Responses to P and K were similar across different production systems (<2 tons per hectare). Precision nutrient management increased average grain yield from 5.9 to 6.4 Mg per hectare, improved nutrient uptake by 8 to 14%, and enhanced N recovery efficiency from 0.18 kg per kg to 0.29 kg per kg, with agronomic N use efficiency improving by 80%. Indigenous nutrient supply estimates from omission plots on individual farms were used to model field-specific fertilizer requirements for rice and wheat crops [2, 21, 24].

Nutrient Management Models

Modern tools, including computer and mobile phone-based applications, are increasingly utilized to enhance nutrient management practices, especially where blanket fertilizer recommendations are common. These tools provide tailored crop and nutrient management advice for small-scale maize, rice, and wheat farmers based on specific conditions and needs. Examples of such tools include Nutrient Expert® and Crop Manager. Nutrient Expert (NE) and QUEFTS are computer-based systems designed for precision nutrient management, accounting for spatial and temporal variability in nutrient supply to optimize nutrient applications. NE generates fertilizer recommendations based on historical yield data, fertilizer applications, soil fertility indicators, and environmental factors, taking available resources into account [12, 36].

Nutrient Expert and GreenSeeker-based management strategies have been shown to yield higher grain productivity and net economic returns while reducing greenhouse gas (GHG) emissions compared to conventional practices. This was observed in no-till wheat as well [37].

Nutrient Expert®

Nutrient Expert® is an interactive, computer-based tool that helps smallholder farmers apply SSNM efficiently, with or without soil test data. It estimates attainable yield based on growing conditions and calculates the nutrient balance using data from previous crops and current fertilizer or manure applications. It generates location-specific nutrient recommendations and performs a simple cost-benefit analysis comparing current practices with recommended alternatives. The algorithm used for fertilizer calculations was validated over five years of research and is currently available for free for wheat and maize systems in South Asia [12, 36, 37].

Crop Manager

Crop Manager is a mobile and computer application that provides site- and season-specific fertilizer recommendations for rice, rice-wheat, and maize systems. It allows farmers to adjust nutrient applications based on their soil, water management, and crop variety. Recommendations are based on information input by users, which can be collected by extension workers or advisors [43, 46]. The software is available for free download at http://cropmanager.irri.org/home.

Green Seeker

Green Seeker is an optical sensor technology that measures crop input variability and helps apply the correct amount of fertilizer at the right time and place. It reduces nutrient input costs by preventing overuse and provides precise NDVI and RED/NIR values for plants. These values are used alongside other agronomic practices to monitor field variability and the effects of input doses on crop growth [36, 37, 43].

Use of Simulation Models

Short-term changes in plant-available N make it challenging to predict crop N requirements accurately. However, models like NLEAP and Adapt-N, which use data on soil, weather, crops, and field management, can provide more accurate predictions by updating with daily changes. These models help farmers make adaptive decisions that improve N-use efficiency, minimize N losses, and enhance profitability [38].

Aerial Imagery and Site Maps

Aerial imagery and site maps, along with soil survey data, are used for precision nutrient management. These tools help make decisions based on previous land use and other factors. However, imagery alone may not explain within-field variations caused by management decisions, climate, geology, or other factors. Some studies have shown that aerial data correlates with phosphorus and organic matter content but not with soil fertility indicators [25, 29, 40, 46].

Precision Agriculture Technologies for Nutrient Management

Precision agriculture for nutrient management involves using data collection technologies (e.g., sensors, GPS) and analytics to guide nutrient application practices. This approach aims to enhance nutrient use efficiency and farm productivity by minimizing nutrient leaching and accumulation (Singh et al., 2015).

Nutrient Monitoring

Technologies that use GPS, GIS, and various sensors (optical, electrochemical, mechanical, etc.) capture data on soil and crop attributes. Geo-location technologies are crucial for overlaying collected data with geographical information, while sensors monitor variables such as climatic conditions, soil characteristics, and nutrient levels.

Nutrient Planning

Technologies for nutrient planning use raw data from monitoring tools to create precise field maps for nutrient application. This includes using photogrammetry and spatio-temporal technologies for topography and crop monitoring. APIs facilitate data sharing between applications, while data analytics helps in real-time decision-making and nutrient planning [40].

Nutrient Application

Technologies for nutrient application include variable rate technologies (VRT) that allow site-specific control of inputs, and GPS guidance systems that automate vehicle steering. Agbots, such as Rowbot, are used for precise fertilizer application between crop rows. These technologies are often used in combination to optimize nutrient management (Figure 5) [32, 33, 41].

The Technology-Driven Future for Precision Nutrient Management

Future technological advances are expected to transform precision farming. Upcoming innovations include:

1) High-precision soil testing with real-time fiber optic spectrometers.
2) Micro-ecology testing alongside water runoff and air sample analysis.
3) Weather monitors on sprayers that adjust droplet size and spray patterns based on real-time data.
4) Enhanced guidance systems for straight rows and optimized inputs.
5) Advanced crop models for better economic and environmental decision-making, including direct insurance purchases and risk modeling based on remote sensing.

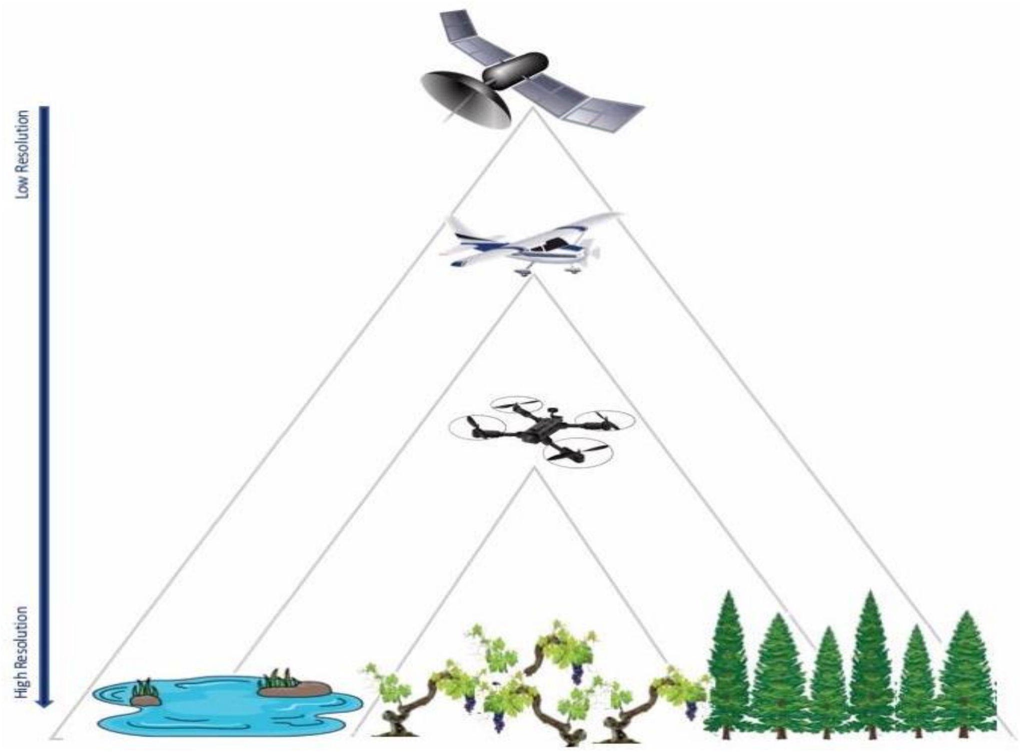


Image adapted from: [35].

Figure 5. *Geographic capacity and resolution of geospatial technologies.*

5. Summary and Conclusion

1) The primary microbial pathway for N_2O production is denitrification. This process involves the reduction of nitrate to molecular nitrogen through N_2O under anaerobic or micro-aerobic conditions [5]. To minimize N_2O production, it's beneficial to keep synthetic fertilizers in their reduced ammonium form, using inhibitors like urease or nitrification inhibitors. These inhibitors reduce microbial nitrification, which produces nitrate and N_2O, and decrease nitrate losses through leaching or volatilization as N_2 and N_2O due to denitrification [30].
2) Agricultural lands face increasing demands to produce enough food for the expanding global population. This pressure is compounded by changing weather patterns, including fluctuations in rainfall and temperature, which adversely affect soil fertility.
3) To boost crop yields under these conditions, it is crucial to use chemical fertilizers wisely, enhance the use of natural nutrient sources, recycle available plant nutrients, and exploit the genetic potential of crop species. Efficient nutrient management will be essential for adapting to global climate changes and achieving smart plant nutrition.
4) Effective use of on-farm nutrient sources, such as crop residues, and selecting the most efficient and economical fertilizer combinations are key. Integrating these practices with other crop management techniques—like quality seed selection, optimal plant density, integrated pest management (IPM), and efficient water management—can enhance overall productivity.
5) Although precision farming has not yet been widely adopted, it holds significant potential to improve economic returns by reducing costs and increasing yields while mitigating environmental risks associated with fertilizers, pesticides, and erosion.
6) Nutrient overuse is prevalent in North America, Europe, and parts of South and East Asia, especially China. Conversely, in Africa, Latin America, and some parts of Asia, many areas suffer from nutrient deficiencies. In these regions, limited access to affordable mineral fertilizers, coupled with inadequate local supplies and poor infrastructure, results in high prices and reduced agricultural yields. Biological nitrogen fixation, manure, and sewage recycling are critical local nutrient sources but are often insufficient, of low quality, or poorly managed.

Abbreviations

AHDB	Agricultural & Horticultural Development Board
CSA	Climate Smart Agriculture
GHG	Green House Gas
GIS	Geographic Information System
GPS	Global-Positioning System
IFA	International Fertilizer Association
IPCC	Intergovernmental Panel on Climate Change.
IPNI	International Plant Nutrition Institute's
IRRI	International Rice Research Institute
NDVI	Normalized Difference Vegetation Index
NUE	Nitrogen Use Efficiency
4R's	Right Source, Right Rate, Right Time, Right Place

Conflicts of Interest

The authors declare no conflicts of interest.

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