Optimizing Nitrogen Dynamics in Upland and Lowland Agriculture

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ABSTRACT

Despite being the most prevalent atmospheric element, nitrogen presents a paradoxical challenge for agriculture. While plants require large quantities, only a small fraction is readily available for uptake. Most nitrogen exists as inert dinitrogen gas (N2), unusable by most organisms. However, transformations occur, converting it into more reactive forms like nitrate (NO3-) and ammonium (NH4+). These forms are highly mobile in water and air, leading to potential losses through leaching, runoff, volatilization, and denitrification in both upland (leaching, run-off) and lowland (denitrification, volatilization) soils. Effective nitrogen management is crucial for optimal crop growth and minimizing environmental losses. This necessitates implementing various strategies to enhance Nitrogen Use Efficiency (NUE).

INTRODUCTION

Data from the Food and Agriculture Organization (FAO) reveals a concerning trend: a growing global population outpacing available arable land. This escalating pressure on agricultural resources necessitates a paradigm shift. The Green Revolution's reliance on ever-increasing fertilizer application (especially nitrogenous), though initially successful, has proven unsustainable. The current challenge lies in managing agricultural inputs effectively to enhance Nutrient Use Efficiency (NUE). In plants, nitrogen builds proteins and enzymes for growth and fuels photosynthesis through chlorophyll and also forms the foundation of DNA and RNA. Nitrogen deficiency first shows as a **pale green or light yellowing (chlorosis)** in older leaves, especially at the tips. This progresses to **leaf death and/or dropping** in severe cases. This happens because nitrogen is **relocated from older to younger leaves** to prioritize new growth (Uchida, 2000). Excessive nitrogen can induce hypertrophy **(**excessive leaf growth) with **marginal chlorosis** (yellowing at the edges) and **necrosis** (tissue death) **progressing inwards.** This is accompanied by reduced stature and increased susceptibility to pathogen attack**.**

Uplands and lowlands present a dichotomy in terms of soil aeration, parent material, and particle size distribution. Lowland soils, derived from alluvial deposits, exhibit finer textures dominated by silt and clay fractions (<50% sand). This fine texture translates to superior water holding capacity (WHC) exceeding 40% by weight. However, it also restricts drainage, fostering reducing conditions (low redox potential, Eh < 300 mV) with limited oxygen availability for plant roots. Conversely, upland soils develop from weathered bedrock and possess coarser textures rich in sand (>50% sand). This coarseness facilitates superior drainage and oxidizing conditions (high Eh > 500 mV) with ample oxygen availability for aerobic organisms.

Nitrogen dynamics in upland soils involve microbial mineralization, immobilization, nitrification, denitrification, plant uptake, and leaching. Microbes break down organic nitrogen into ammonium, which can be temporarily immobilized. Nitrifying bacteria convert ammonium to nitrate, enhancing plant accessibility but increasing leaching risk. Under anaerobic conditions, denitrification converts nitrate to gaseous forms, leading to nitrogen loss. Plants absorb nitrogen, while leaching can cause nitrate loss through water movement.

Nitrogen dynamics in lowland soils: In flooded rice fields, oxygen (O2) is depleted due to limited diffusion through floodwater, creating a two-layered soil profile. The upper layer, oxygenated by atmospheric O2, supports oxidative compounds and mineralizes organic nitrogen to nitrate (NO3). When ammonium (NH4+) fertilizers are added, NH4+ may volatilize, move to the lower reduced layer, or undergo nitrification. In the reduced layer, organic nitrogen mineralization halts at NH4+ due to oxygen absence. NH4+ may accumulate, be taken up by plant roots, or undergo nitrification in oxidized root zones. Nitrate in the reduced layer serves as an electron acceptor for facultative anaerobes, undergoing denitrification to gaseous nitrogen forms.

Management:

1. **Split application**: It employs a targeted delivery method to optimize crop nutrition. This approach minimizes pre-plant volatile N losses (ammonia gas) and post-plant leaching or denitrification (conversion to unusable forms) by synchronizing nitrogen availability with periods of high crop demand during critical growth stages. It enhances nitrogen use efficiency by matching fertilizer availability with critical growth stages for maximum uptake.

2. **Deep placement**: Deep-point USG placement strategically reduces urea-N application (20-40%) in rice, maintaining yield. By placing 1-2 g USG granules at 5-10 cm depth (anaerobic zone), it minimizes floodwater and surface soil NH4+ concentration, curtailing ammonia volatilization, denitrification, and weed N uptake. This extends bioavailable N for rice and potentially stimulates BNF due

to lower floodwater NH4+. However, successful implementation necessitates meticulous attention to soil properties (low percolation rate, CEC > 10 cmol(+) kg^{-1}) and varietal selection (short- to medium-duration varieties preferred).

3. **Fertigation:** Fertigation, the application of fertilizers via irrigation systems, offers a precise approach to nutrient management, enhancing NUE by up to 30% compared to traditional methods. This targeted delivery minimizes nutrient losses from volatilization (ammonia gas escape), leaching (washout by precipitation), and fixation (reactions with soil particles). Additionally, fertigation facilitates controlled nutrient release throughout the growing season, matching application with crop demand at specific stages.

4. **Foliar application:** Foliar application offers a strategic approach for delivering nitrogen (N) directly to plant leaves, bypassing soil and associated losses from volatilization, leaching, and denitrification. This targeted approach enhances N uptake efficiency through direct foliar absorption. Foliar N can directly boost photosynthesis and enzyme activity within the plant, but it remains a supplement, not a replacement, for a balanced fertilization program during active growth stages.

5. **Speciality fertilizers:**

a. **Slow release**: They offer controlled nitrogen delivery through two main approaches: synthetic and natural. Synthetic options (e.g., coated urea, IBDU) employ physical barriers or controlled chemical reactions for gradual release. Natural options (e.g., blood meal, compost) rely on slower microbial decomposition in the soil, minimizing nutrient loss and optimizing plant uptake throughout the season.

b. **Nitrification inhibitors:** Nitrification inhibitors employ targeted strategies to optimize nitrogen use efficiency. Synthetic options like Dicyandiamide (DCD) and 3,4-Dimethylpyrazole phosphate (DMPP) directly impede the activity of Nitrosomonas bacteria, thus restricting ammonium (NH4+) conversion to nitrate (NO3-). This minimizes leaching and denitrification losses. Natural alternatives like neem cake or brassicaceous green manures may exert a more indirect influence on nitrification through their impact on soil microbial communities or broader environmental conditions.

c. **Urease inhibitors**: **Urease inhibitors strategically prolong the efficacy of urea-based fertilizers.** Synthetic options like N-(n-butyl) thiophosphoric triamide (NBPT) and N-phenylphosphoric triamide (NPPT) directly neutralize the urease enzyme, impeding the conversion of urea to ammonia gas and subsequent dissipation. While no natural equivalents exist, evidence suggests neem cake (a nitrification inhibitor) and humic acids (found in compost) might exhibit weak inhibitory effects on the urease enzyme.

6. **Efficient genotypes: Targeted breeding programs have yielded rice cultivars** with demonstrably enhanced Nitrogen Use Efficiency (NUE). These include high-yielding **indica** varieties like Swarna and **progeny** from the NERICA project, known for their **concomitant** drought tolerance (often indica/japonica hybrids). Similarly, maize breeding has produced **elite** hybrids like DKC 6085, showcasing superior NUE alongside other desirable characteristics. Notably, specific Quality Protein Maize (QPM)

varieties from Agronomic BioTech exhibit **concurrent** improvements in NUE and grain protein content.

7. **Site-Specific Nutrient Management: (SSNM)** fosters a data-driven approach to fertilizer application, optimizing nutrient delivery to crops. This technique surpasses traditional uniform application by considering field-specific parameters like soil fertility (through analysis) and targeted crop yield. The basic principles of SSNM approach entail components like indigenous nutrient supply (INS) from the soil and crop nutrient requirement for attaining targeted yield. The nutrient gap i.e. the difference between the crop nutrient requirement and INS is managed through application of manures and fertilizers as and when required by the crop during its growth (Gorai *et al.*, 2021). SSNM employs two primary methods:

   1. **Plant-based analysis:** This method estimates crop nutrient demand based on a desired yield and factors in the inherent nutrient supply (INS) of the soil. Fertilizer application is then dynamically adjusted throughout the growth cycle based on plant response.

   2. **Soil-cum-plant analysis:** This method leverages scientific analysis of both soil and plant samples to generate site-specific fertilizer recommendations.

   These recommendations, often derived from fertilizer adjustment equations or soil test crop response (STCR) equations, ensure precise fertilizer dosing to achieve the targeted yield.

Tools: The Leaf Colour Chart (LCC) offers a cost-effective and user-friendly alternative to expensive chlorophyll meters for evaluating crop nitrogen (N) status. This simple tool, usually a plastic strip featuring coloured panels from yellowish-green to dark green, enables farmers to visually assess the relative greenness of rice, maize, and wheat leaves. By comparing leaf color to the critical LCC panel for their crop and variety at regular intervals (7-10 days), farmers can decide if nitrogen fertilizer application is needed to prevent N deficiency in crops.

The SPAD chlorophyll meter scientifically assesses nitrogen levels by analyzing leaf N status through light transmission measurements at specific wavelengths. Chlorophyll, essential for photosynthesis and containing nitrogen, influences SPAD readings. By comparing transmitted light at red and infrared wavelengths with and without a leaf sample, SPAD values reflect chlorophyll content. However, critical SPAD readings for fertilizer application vary based on crop type, variety, growth stage, and environmental factors.

Canopy reflectance sensors, like GreenSeeker, utilize spectral reflectance to evaluate crop nitrogen levels. These tools measure reflected light across visible and near-infrared (NIR) bands. Healthy, nitrogen-rich crops display elevated NIR reflectance, forming the basis for NDVI, a pivotal indicator of crop health and nitrogen status. By comparing readings with optimally fertilized reference areas, these sensors suggest site-specific nitrogen application for effective crop growth while mitigating environmental impact. Normalized Difference Vegetation Index (NDVI) is:

$$\mathbf{NDVI = (NIR - Red) / (NIR + Red)}$$

Soil test crop response (STCR) based management is a method for fertilizer recommendation that considers both the inherent soil fertility and the targeted crop yield. It utilizes mathematical equations established for specific crops and soil conditions to determine the fertilizer application rates required to achieve a desired yield goal.

8. **Precision agriculture**: Three essential steps comprise the map-based SSNM techniques: assessing crop and soil variability, managing the variability, and evaluating it. Based on the site-specific management zone and nutrient variability map, site-specific fertilization was recommended. The sensing system takes measurements of the required crop attributes or soil parameters. Measured data are then used, via an algorithm, to calculate fertilizer rates, which in turn control the variable rate applicator.

Tools: Global positioning (GPS): Users can perform georeferenced sampling, data collection, and agricultural operations in precision farming with the use of GPS receivers. GPS enables precision farming by georeferencing tasks like sowing and fertilizing across different locations within fields. Farmers utilize GPS receivers to collect data on factors such as soil quality and crop health, optimizing nitrogen use for enhanced agricultural efficiency.

GIS Software in precision agriculture surpasses mapping, serving as a robust geospatial database and decision support system. It stores and analyzes diverse data layers including detailed soil surveys, satellite imagery, and agronomic records. This facilitates the creation of nutrient variability maps, directing focused fertilizer application to optimize crop nutrition while reducing environmental impact.

Remote sensing Advanced techniques enable precision nitrogen management through spectral and thermal data captured by sensors on drones, airplanes, or satellites across fields. Scientists analyze this data, identifying nitrogen deficiencies using indices like NDVI, which correlates nitrogen content with chlorophyll reflectance. This guides targeted nitrogen application for optimized crop growth.

Yield monitoring systems, integrated into harvesters, leverage GPS and sensors to generate geo-referenced yield maps. These maps reveal spatial variations in crop productivity, informing decisions on nutrient uptake, profitability, management zones, and the impact of practices and environmental factors.

Variable Rate Technology (VRT) addresses field variability in fertilizer application by relying on three essential components: understanding spatial variations, reliable crop response prediction models, and cost-effective technology. VRT utilizes Differential Global Positioning System (DGPS) for precise location, pre-made maps or real-time sensors for identification of fertilizer needs, and variable-rate applicators to adjust application rates accordingly.

9. Integrated Nitrogen Management (INM): optimizes crop N use via

1. **Diversified Sources:** Organic amendments improve soil health and retention, while strategic fertilizer use based on testing minimizes waste (CEC, N mineralization). Biological nitrogen fixation also supplements soil nitrogen.
2. **Enhanced Soil Health:** Reduced tillage, cover crops, intercrops (legumes) and organic amendments promote beneficial microbes for efficient N cycling.
3. **Precise Application:** Splitting fertilizer application and band placement ensure efficient plant uptake and minimize losses (leaching, denitrification).

Many strategies have been developed to increase the efficiency of urea-N through proper timing, rate, placement, modified forms of fertilizer, and use of nitrification and urease inhibitors (Shukla et al., 2004; Shan et al., 2008).

- **5 R's stewardship:** N use efficiency depends upon potential of cultivars, time, method, rate and source of N fertilization (Shukla et al., 2012). Implementing the **5 R's** - Right Source, Right Rate, Right Time, Right Placement, and Right Method—optimizes fertilizer application for enhanced agricultural productivity and sustainability.

CONCLUSION:

Effective N management is crucial for both uplands (leaching) and lowlands (denitrification/volatilization). Uplands benefit from cover crops and split application, while lowlands need controlled drainage and urease inhibitors. The 5Rs (Right source, rate, time, placement, review) guide practice, with advancements like yield monitors and remote sensing enabling precise N application. Future research on N cycling, crop breeding, and real-time sensors promise further optimization. Responsible management ensures a sustainable agricultural future for uplands and lowlands alike.

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