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Precision Agronomy Strategies for Improving Nitrogen Use Efficiency and Soil Quality in Maize

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Abstract

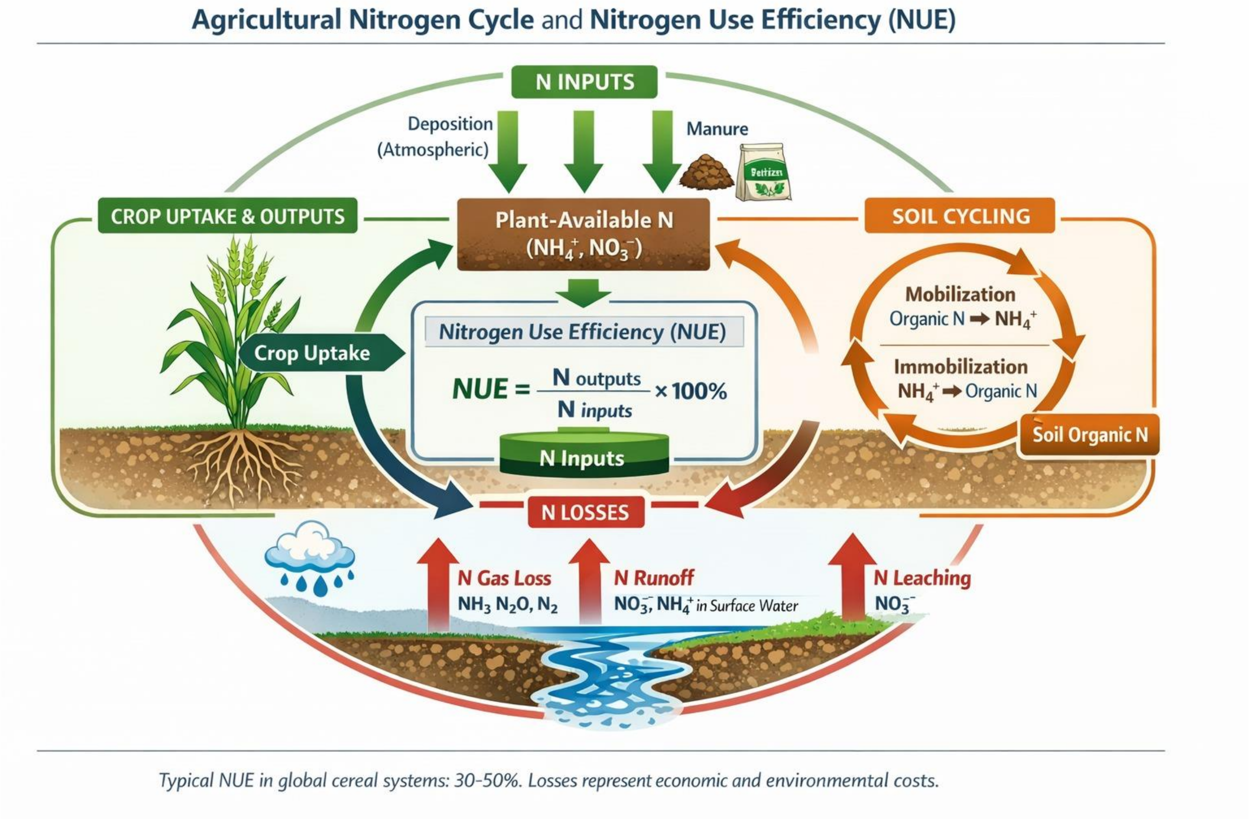
Maize production faces mounting pressure to achieve sustainable intensification amid rising global food demand, inefficient nitrogen (N) use, and environmental degradation. This review synthesizes recent advances in precision agronomy strategies aimed at improving nitrogen use efficiency (NUE) and soil quality in maize systems. Key approaches include site-specific nitrogen management through remote sensing (UAV–satellite data fusion, red-edge vegetation indices), machine learning predictive modeling, variable rate application (VRA), sensor-based fertigation (Holland-Schepers algorithm), controlled-release fertilizers, organic-inorganic blends, variable depth tillage, variable rate seeding, and hybrid switching. These technologies enable synchronization of N supply with crop demand, reducing losses via leaching, volatilization, and denitrification while maintaining or increasing grain yield. Precision practices also enhance soil health indicators, including soil organic carbon, microbial enzyme activity (urease, dehydrogenase, phosphatase), and structural stability. Integration with conservation agriculture and cover cropping further supports long-term soil resilience. Despite demonstrated economic and environmental benefits (N savings of 20–50 kg/ha, improved partial factor productivity, and alignment with SDGs), adoption remains limited by high costs, technical complexity, rural connectivity gaps, and data security concerns. The paper highlights the transformative potential of AI, robotics, and data fusion while emphasizing the need for accessible decision-support tools and robust cybersecurity frameworks to accelerate farmer adoption.

Keywords: Precision Agriculture; Nitrogen Use Efficiency; Maize; Variable Rate Application; Remote Sensing; Data Fusion; Fertigation; Soil Health; Controlled-Release Fertilizer; Variable Rate Seeding; Conservation Agriculture; Machine Learning; Cybersecurity In Agriculture

1. Introduction

The imperative for sustainable agricultural intensification has never been more pronounced as the global population approaches a projected nine billion by the year 2050 (Bhat & Huang, 2025). Maize (Zea mays L.), as one of the most critical staple crops globally, necessitates substantial nitrogen (N) inputs to reach its genetic yield potential; however, the traditional management of these inputs is fraught with inefficiencies that pose severe economic and environmental risks (Xiao et al., 2025). Nitrogen use efficiency (NUE) remains a primary metric for agricultural sustainability, yet in conventional systems, plants often utilize only 50% of the supplied nitrogenous fertilizers. The remaining fraction is lost through various pathways, including ammonia volatilization, nitrate leaching into groundwater, and the emission of nitrous oxide (N2O), a potent greenhouse gas (Sharma et al., 2023). Precision agronomy represents a paradigm shift from uniform, "blanket" applications to a data-driven, site-specific management (SSM) strategy that monitors, quantifies, and responds to the inherent spatial and temporal variability of fields (Wang et al., 2025). By integrating advanced sensors, satellite imagery, machine learning algorithms, and variable-rate application (VRA) technologies, precision agronomy offers a pathway to optimize nitrogen delivery, enhance soil quality, and ensure the long-term viability of maize production systems (Yang et al., 2023).

Figure 1. Conceptual Framework of Nitrogen Use Efficiency (NUE) and System-Level Nitrogen Cycling.

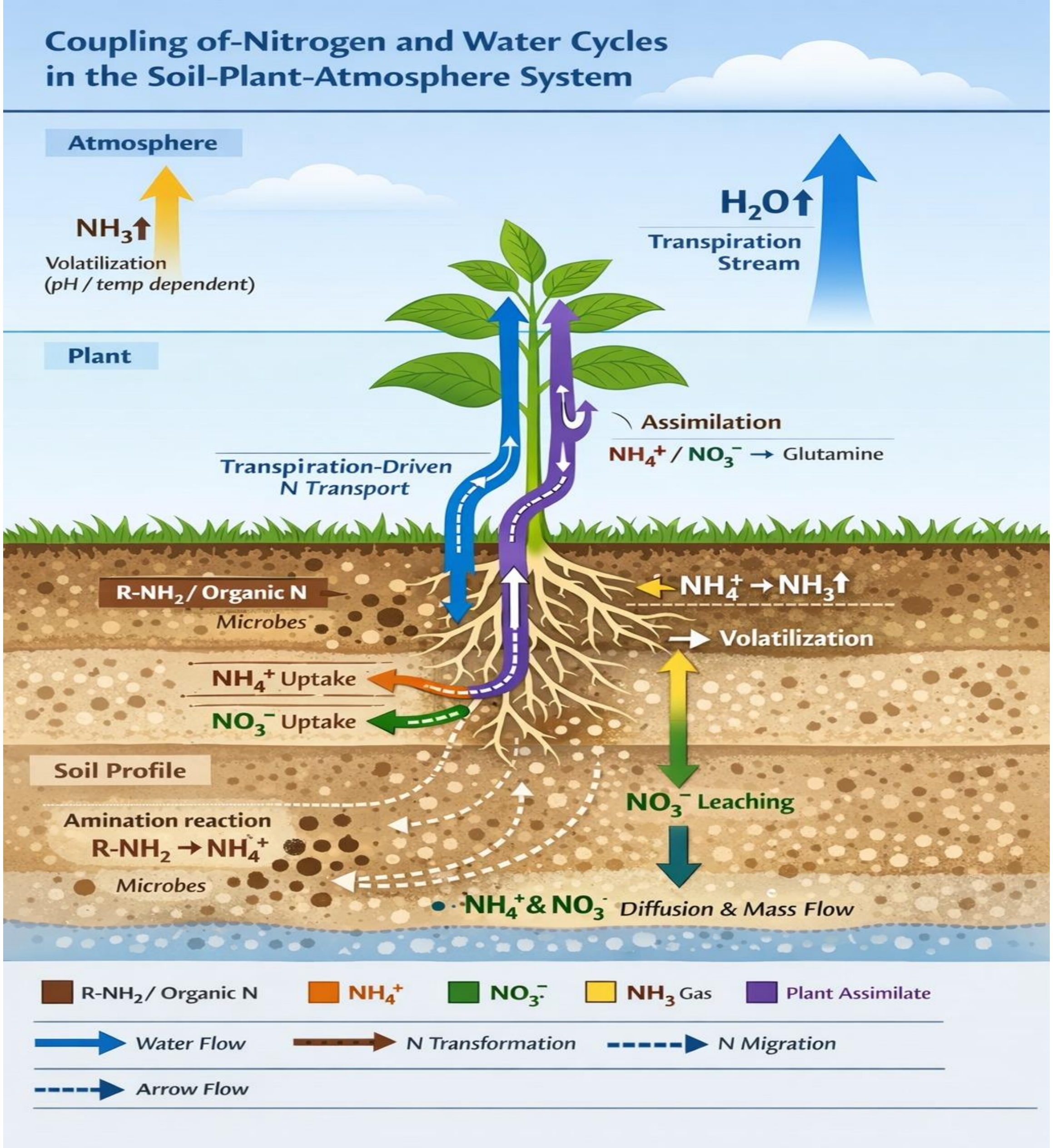


Typical NUE in global cereal systems: 30-50%. Losses represent economic and environmemtal costs.

2. The Biogeochemical Context of Nitrogen Management in Maize

Maize is a nitrogen-demanding crop that exhibits a highly non-linear uptake pattern throughout its growth cycle. The peak of nitrogen uptake generally occurs during the spathe stage (V10 to VT), where the rapid expansion of leaf area and the initiation of reproductive structures create a surge in nutrient demand (Nebraska Extension, 2025). In conventional agriculture, the practice of applying the majority of nitrogen at or before planting creates a significant temporal mismatch between supply and demand (Stamp, 2023). During the early vegetative stages (VE to V6), the maize root system is insufficiently developed to capture high concentrations of soil nitrogen, leaving the surplus vulnerable to leaching, particularly in sandy soils or regions with high early-season rainfall. Precision nitrogen management seeks to mitigate these losses by adopting a "monitor and respond" approach rather than the traditional "predict and apply" framework (Parenti , 2020).

Figure 1. Biogeochemical Pathways of Nitrogen Transformation and Transport in the Soil-Plant-Atmosphere Continuum.



The efficiency of nitrogen utilization is not solely a function of fertilizer timing but is deeply influenced by soil physical and chemical properties. Factors such as soil texture, organic matter content, and moisture levels dictate the rate of nitrogen mineralization and immobilization (Kumar et al., 2021). For instance, high organic matter content provides a natural reservoir of nitrogen that is slowly released through microbial activity, whereas sandy soils with low water-holding capacity are prone to rapid nitrate movement through the profile (Bingham et al., 2016). Precision strategies utilize apparent soil electrical conductivity (ECa) mapping to delineate management zones based on these soil attributes, allowing agronomists to tailor nitrogen rates to the specific buffering capacity and productivity potential of different areas within a single field (Udvardi et al., 2021).

Table 1. Pathways of Nitrogen Loss and Precision Mitigation Strategies

Pathway of Nitrogen Loss	Mechanism	Environmental Impact	Precision Mitigation Strategy
Leaching	Downward movement of NO3- with water	Groundwater contamination; eutrophication	VRA fertigation; soil ECa mapping
Volatilization	Gaseous loss of NH3 from surface urea	Air pollution; acid rain precursor	Targeted sub-surface placement (VRT)
Denitrification	Microbial conversion of NO3- to N2O or N2	Greenhouse gas emissions; ozone depletion	Real-time N-sensing; drainage management
Surface Runoff	Lateral movement of nutrients during rain	Surface water pollution	Site-specific tillage; cover cropping

3. Evolution of Precision Fertilizer Application Technologies

The trajectory of precision fertilization has evolved through three distinct technological epochs, reflecting advancements in computational power and sensor accuracy. The initial phase, arising in the 1990s, was characterized by "prescription agriculture," which utilized Geographic Information Systems (GIS) to create static application maps based on historical soil samples and yield data (Aarif et al., 2025). While this era successfully broke the mold of uniform application, it was limited by the high cost of manual grid sampling and its inability to respond to in-season weather variability (Tey et al., 2024).

The second phase, commencing around 2010, integrated real-time monitoring systems powered by the Internet of Things (IoT) and proximal sensors. This allowed for mu-level precision by adjusting inputs based on the instantaneous status of soil nutrients and crop growth (Karunathilake et al., 2023). The current epoch, from 2020 toward 2026, is defined by the fusion of Artificial Intelligence (AI), robotics, and high-resolution remote sensing. This "individual precision" paradigm enables the management of single plants through autonomous drones and robotic micro-Babar et al., 2024).

In addition to timing, the physical method of application has seen significant innovation. While broadcast application of nitrogen yields a typical efficiency of approximately 36.6%, side-dressing the targeted placement of nitrogen alongside the crop row can increase this efficiency to between 43% and 54% (Sharma et al., 2023). Modern precision applicators utilize intelligent control systems, such as the PSO-RBF-PID algorithm (Particle Swarm Optimization-Radial Basis Function-Proportional-Integral-Derivative), to reduce flow control errors and ensure millimeter-level tracking of fertilizer placement relative to the root zone (Lu et al., 2024).

4. Remote Sensing and Data Fusion for Nitrogen Monitoring

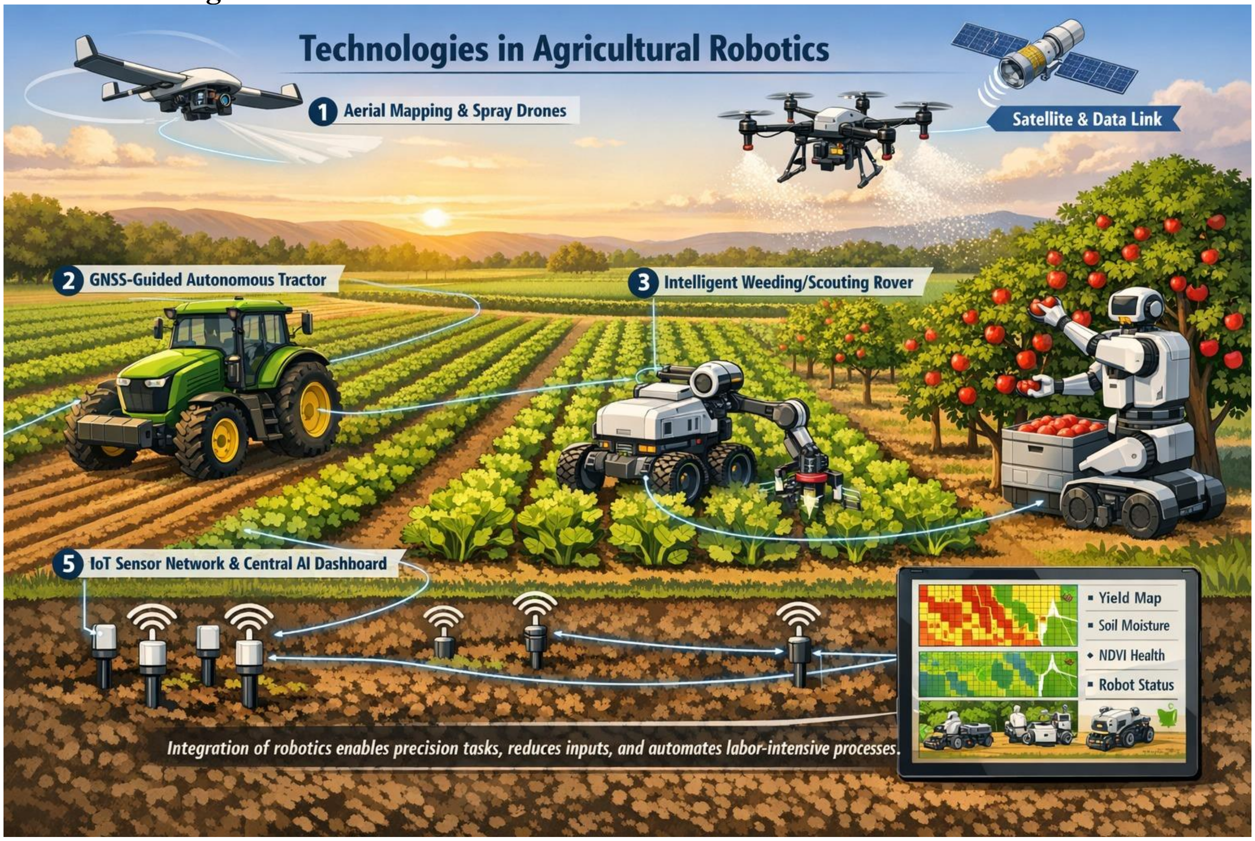
The ability to detect nitrogen stress before it becomes visible to the human eye is a cornerstone of modern precision agronomy. This is primarily achieved through multispectral and hyperspectral remote sensing, which measures the reflectance of the crop canopy across various wavelengths (Billah et al., 2024). Nitrogen is a vital component of chlorophyll; thus, leaf reflectance in the visible green and "red edge" (700-740 nm) regions serves as a proxy for the nitrogen status of the plant (Laveglia et al., 2024).

4.1 UAV and Satellite Synergy

A critical challenge in remote sensing has been the trade-off between spatial resolution and temporal frequency. Unmanned Aerial Vehicles (UAVs) offer centimeter-level resolution and high flexibility but are limited in the area they can cover. Conversely, satellites like Sentinel-2A or PlanetScope provide regional-scale coverage but are often plagued by "mixed-pixel" effects where soil or shadow reflectance interferes with the crop signal (Alvarez-Vanhard et al., 201). Recent research has established a data fusion framework that uses UAV data as a "medium-scale bridge" to calibrate and correct satellite imagery (Linan et al., 2025).

This band correction method harmonizes the multispectral responses between sensors, significantly improving modeling performance. For example, the coefficient of determination (R2) for predicting plant nitrogen content (PNC) in maize was found to increase from a range of 0.35-0.45 to approximately 0.70-0.80 after UAV-based calibration (Xiao et al., 2025). This allows for regional-scale nitrogen management that maintains the accuracy of field-level proximal sensing (Yan et al., 2025).

Figure 3. The Digital Ecosystem of Precision Agronomy: Integrating IoT, Robotics, and Remote Sensing.



4.2 Vegetation Indices and Predictive Modeling

Various vegetation indices (VIs) have been developed to isolate the nitrogen signal from other environmental variables. While the Normalized Difference Vegetation Index (NDVI) is widely used for biomass estimation, it often saturates in dense maize canopies during reproductive stages (Vidican et al., 2023). The Normalized Difference Red Edge (NDRE) index has emerged as a more robust alternative for late-season nitrogen monitoring because it utilizes the red-edge band, which penetrates deeper into the canopy and is more sensitive to chlorophyll concentrations (Amori et al., 2024).

The integration of these spectral inputs into machine learning models has further refined the accuracy of nitrogen demand prediction. Random Forest (RF) and Gradient Boosting models have demonstrated a high capacity for estimating leaf nitrogen percentage and plant height, with RF algorithms achieving a Pearson correlation (r) of up to 0.91 for leaf nitrogen concentration (LNC) (Dong et al., 2025). For more complex datasets involving multi-source data fusion, Convolutional Neural Networks (CNN) have outperformed traditional models by more than 10%, as they can automatically learn multi-level spatial features and nonlinear relationships (Jain et al., 2025).

Table 2. Sensor Platforms for In-Season Nitrogen and Crop Monitoring

Sensor Platform	Spatial Resolution	Temporal Resolution	Primary Use Case
UAV (Multispectral)	1-5 cm	On-demand	Precision scouting; model calibration
PlanetScope	3 m	Daily	In-season VRA fertigation guidance
Sentinel-2	10-20 m	5 days	Regional monitoring; residue detection
Proximal (Tractor-mounted)	Plant-level	Real-time	On-the-go variable rate application

5. Variable Rate Application (VRA) and Automated Fertigation

Precision application hardware translates data insights into actual field interventions. Variable Rate Application (VRA) systems utilize two primary approaches: map-based and sensor-based (Saleem et al., 2023). Map-based systems follow an electronic prescription map generated from historical data or soil attributes, whereas sensor-based systems measure crop reflectance in real-time as the tractor traverses the field, calculating the necessary nitrogen dose instantaneously (Mishra et al., 2025).

5.1 The Holland-Schepers Algorithm and Fertigation

A prominent framework for sensor-based management is the Holland-Schepers sufficiency index (SI) algorithm. This algorithm benchmarks the reflectance of the target crop against a well-fertilized "reference strip" within the same field (Krienke et al., 2022).

If the SI falls below a certain threshold (0.95), nitrogen stress is identified, and the system triggers an application. Field trials in Nebraska have shown that satellite-guided fertigation using this framework can reduce total nitrogen inputs by 23% while maintaining yields comparable to full-rate conventional fertilization (Thompson et al., 2020). This targeted delivery improved agronomic efficiency by 12% and partial factor productivity by 26% (Kalra et al., 2025).

Furthermore, the integration of VRA with center-pivot irrigation systems a process known as precision fertigation allows for the splitting of nitrogen applications into multiple, small-dose events throughout the V8 to R2 growth stages (Sood et al., 2025). This approach ensures that nitrogen is available exactly when the crop's uptake capacity is at its peak, minimizing the window for atmospheric loss and leaching (Nguyen et al., 2023).

5.2 Hardware Innovations in Application Units

The effectiveness of VRA is also contingent upon the mechanical precision of the applicators. Recent innovations between 2020 and 2025 have focused on structural optimizations of fertilizer discharge units. For instance, the multi-stage arc trajectory applicator uses segmented PID control to track the groove opener's path with millimeter accuracy, maximizing fertilizer-to-root contact while minimizing root damage (Andrade et al., 2020). Similarly, pneumatic variable-diameter systems allow for high-precision discharge even in complex terrains by combining variable speed control with pneumatic conveying (Jesmer, 2025).

6. Soil Quality and Microbiological Impacts of Precision Management

Beyond the immediate goal of nutrient efficiency, precision agronomy significantly impacts soil health and biological productivity. Conventional over-fertilization can lead to soil acidification, reduced microbial diversity, and the degradation of soil structure (Wasay et al., 2024). In contrast, precision nitrogen management (PNM) has been shown to stabilize fundamental soil properties like pH and electrical conductivity while enhancing the activity of key soil enzymes (Raza et al., 2023).

6.1 Enzymatic Activity and Microbial Resilience

Studies in the Trans-Gangetic Plains have revealed that synchronizing nitrogen supply with crop demand through real-time sensors significantly enhances the activity of urease, dehydrogenase, and alkaline phosphatase enzymes (Dinesh, 2022). Urease is critical for the conversion of urea into plant-available ammonia, while dehydrogenase acts as a proxy for the overall oxidative metabolism and vitality of the soil microbial community (Ullah et al., 2023). Alkaline phosphatase is essential for the mineralization of organic phosphorus, suggesting that precision nitrogen management facilitates a more comprehensive nutrient cycling (Xiaomei et al., 2024).

Moreover, the use of threshold-based nitrogen applications such as those guided by a Chlorophyll Content Meter (CCM-50) or a Leaf Color Chart (LCC-5) has been linked to a significant increase in soil organic carbon (SOC). Higher SOC levels improve soil aggregate stability and water-holding capacity, creating a positive feedback loop that enhances crop resilience against climate-induced stressors such as drought (Baliyan et al., 2025).

Table 3. Impacts of Precision Nitrogen Management on Soil Quality Attributes

Soil Attribute	**Effect of Precision Nitrogen Management**	**Primary Driver**
Organic Carbon	Significant increase in SOC content	Synchronized N supply; high biomass
Urease Activity	Enhanced conversion of N inputs	Optimized microbial substrate
Dehydrogenase	Increased microbial oxidative capacity	Reduced chemical stress/acidification
Aggregation	Improved soil structural stability	Higher microbial exudates and SOC

(Baliyan et al., 2025; Bhat & Huang, 2025)

7. Integrative Strategies: Organic Blends and Controlled Release

Optimizing NUE often requires combining precision technology with advanced fertilizer formulations. Traditional mineral fertilizers are rapidly soluble, making them vulnerable to leaching. Precision strategies increasingly incorporate controlled-release nitrogen (CN) fertilizers and organic-inorganic blends (ON) to extend the nutrient availability window (Singh et al., 2025).

7.1 Controlled-Release Urea (CN)

Controlled-release formulations use specialized coatings to regulate the release of nitrogen according to soil temperature and moisture, mirroring the plant's uptake curve. In maize field trials in Northwest China, the CN treatment achieved the highest grain yields (15,672 kg/ha), which was 8.92% higher than conventional farmer practices while using less total nitrogen (Ibrahim et al., 2022). Furthermore, the apparent utilization rate of nitrogen in CN systems was up to 23% higher than in conventional systems, largely due to the reduction in residual inorganic nitrogen in the soil post-harvest (Alghamdi et al., 2022).

7.2 Organic-Inorganic Combinations

The partial replacement of chemical nitrogen with organic fertilizers (e.g., ON strategies where organic sources replace 50% of inorganic N) has been shown to maintain high maize yields while significantly reducing NH3 volatilization and N2O emissions (Geng et al., 2019). Organic matter not only provides a slow-release nitrogen source but also improves the physical and chemical properties of the soil, such as porosity and cation exchange capacity (CEC), which further supports nutrient retention and maize growth (Haider et al., 2025).

8. Precision Soil Management: Tillage and Compaction Control

A critical but often overlooked aspect of precision agronomy is the management of soil physical structure. Repeated uniform-depth tillage over decades often results in the formation of a "plough pan" a compacted soil layer that restricts root penetration and reduces water infiltration (Fox, 2018). Precision soil management addresses this through Variable Depth Tillage (VDT), which adjusts the depth of the tillage tool based on real-time sensor measurements of soil resistance or pre-existing compaction maps (Šarauskis et al., 2024).

8.1 Variable Depth Tillage (VDT)

VDT systems utilize ultrasonic sensors or soil electrical conductivity data to identify areas where deep subsoiling is necessary to break the hardpan and areas where shallower, less energy-intensive tillage is sufficient (Lou et al., 2021). Research in the Southeastern Coastal Plain found that only 20% of a typical test field actually required the commonly recommended tillage depth of 15 inches (Fox, 2018). By applying tillage only where needed, VDT reduced fuel consumption by 45% compared to conventional, constant-depth tillage (Tahmasebi et al., 2023).

Beyond energy savings, VDT improves maize root architecture. Cotton and maize taproots in VDT plots have been observed to be nearly twice as long as those in no-till plots, allowing plants to access deeper water reserves during periods of drought stress (Qin et al., 2018). This precision approach ensures that the soil profile is managed according to its specific mechanical needs, promoting a healthier rhizosphere for nitrogen uptake (AL-Halfi, 2021).

9. Seeding and Genetic Integration in Precision Agronomy

The intersection of precision agronomy and crop genetics is most evident in Variable Rate Seeding (VRS) and hybrid switching technologies. Maize yield is highly sensitive to plant density, and the optimal population varies significantly across a field based on soil water-holding capacity and nutrient availability (Šarauskis et al., 2022).

9.1 Variable Rate Seeding (VRS)

VRS adjusts the number of seeds planted per acre based on management zones derived from topography, yield history, and soil maps. In high-productivity zones with high available water capacity, increasing plant density maximizes yield. Conversely, in drought-prone or low-fertility zones, reducing seeding rates minimizes intra-plant competition and reduces the risk of crop failure (Agyei, 2025).

9.2 Hybrid Switching

Advanced precision planters now allow for "hybrid switching," where two different maize hybrids can be alternated in real-time. For example, a drought-tolerant hybrid might be planted on elevated, sandy ridges, while a high-yield potential hybrid is used in lower, moisture-rich areas of the same field (Bűdi et al., 2025). This strategy uses machine learning and computer vision to identify field zones and automatically switch hybrids, ensuring that the genetic potential of the seed is perfectly matched to the micro-environment (Kassem, 2025).

Table 4. Differentiated Management Strategies for Maize Production Zones

Management Zone Factor	High Productivity Zone	Low Productivity Zone
Soil Texture	Silt loam / Clay loam	Sand / Sandy loam
Water Capacity	High	Low (Drought prone)
Seeding Rate	High (35,000+ seeds/acre)	Low (24,000-28,000 seeds/acre)
N Requirement	High (Targeted top-dress)	Moderate (Risk mitigation)
Hybrid Choice	High-Yield potential	Stress-tolerant / Drought-ready

10. Conservation Agriculture and Cover Crop Integration

Integrating precision nitrogen management with conservation agriculture practices, such as cover cropping and residue management, represents a holistic approach to soil health. Cover crops are essential for maintaining soil coverage during fallow periods, reducing erosion, and sequestering carbon (Quintarelli et al., 2022).

10.1 Remote Sensing of Conservation Practices

The adoption of these practices can be monitored at a regional scale using satellite-derived indices and environmental drivers. Using a CatBoost classifier trained on Sentinel-2 and Sentinel-1 (radar) data, researchers achieved over 80% accuracy in detecting cover crops and tillage intensity (Jain et al., 2024). These tools are vital for policymakers to assess the impact of conservation programs and for agronomists to understand the spatial distribution of soil residue, which influences nitrogen mineralization rates (Bhat & Huang, 2025).

10.2 Challenges and Precision Solutions

While cover crops offer long-term benefits, they can complicate nitrogen management. Legume cover crops (clover) add nitrogen to the soil, while grass-based cover crops (e.g., rye) can temporarily immobilize soil nitrogen due to their high carbon-to-nitrogen (C:N) ratio (Nebraska Extension, 2025). Precision agronomy mitigates these challenges through "banding" fertilizer and using strip-tillage, which places nutrients directly in the crop row while leaving the cover crop residue in the inter-row space. This minimizes nutrient competition and allows for the successful integration of cover crops without a yield penalty (Tuğrul, 2022).

11. Cybersecurity and Data Security in Smart Farming

As maize production transitions into the digital age, the security and privacy of agricultural data have become critical concerns. Precision agriculture relies on a constant stream of data from IoT sensors, drones, and GPS-guided machinery, much of which is stored on cloud platforms (Kumari et al., 2024).

11.1 Threat Landscape

The agricultural sector faces growing cybersecurity threats, including data breaches, ransomware, and physical tampering with field devices. Vulnerabilities in unencrypted data flows from drones or sensors could allow malicious actors to intercept proprietary yield patterns or soil health maps Adewusi et al., 2022). More severely, unauthorized access to farm management platforms could lead to data manipulation, where an attacker alters fertilization or irrigation schedules, causing substantial economic loss or crop failure (Alahmadi et al., 2022).

11.2 Privacy and Data Sovereignty

Data privacy is equally significant, as farmers generate sensitive operational data that could be misused if disclosed without consent. There is a growing need for robust legal and ethical frameworks to define data sovereignty ensuring that farmers retain control over their data while still benefiting from third-party analytics (Kaur et al., 2022). Innovative solutions like blockchain and decentralized access control are being explored to create tamper-proof records of field data, enhancing trust across the food supply chain (Barton et al., 2025).

Table 5. Cybersecurity Risks and Mitigation Strategies in Precision Agriculture

Cybersecurity Risk	Impact on Precision Agronomy	Mitigation Strategy
Ransomware	Lockout from critical systems; operation halt	Network segmentation; regular backups
Data Manipulation	Skewed N-recommendations; crop failure	Multi-factor authentication; security audits
Data Interception	Loss of competitive trade secrets/yield maps	Advanced encryption (VPN, DLT)
Physical Tampering	Device hijacking; corrupted sensor data	Integrated cyber-physical security

(Kumari et al., 2024)

12. Socio-Economic Impact and Adoption Barriers

The transition to precision agronomy is not merely a technical challenge but a socio-economic one. While the benefits of improved NUE and soil quality are well-documented, the adoption of these technologies remains relatively low. In Nebraska, for instance, only 11% of producers currently use sensor-based nitrogen management (Nebraska Extension, 2025).

12.1 Barriers to Adoption

The primary barriers to the widespread adoption of precision agronomy include high initial investment costs for sensors and VRT hardware, a lack of technical expertise among farmers and agronomists, and infrastructure limitations such as inadequate rural internet connectivity (Bhat & Huang, 2025). Furthermore, the complexity of data integration where farmers must harmonize data from multiple sources like soil sensors, drones, and yield monitors can be overwhelming without simplified decision-support tools (Amori et al., 2024).

12.2 The Economic Value Proposition

Despite these barriers, the economic potential is substantial. Precision nitrogen management can save an average of 33 to 56 lb of nitrogen per acre (Kalra et al., 2025). At a commercial scale, a 10% saving on fertilizer and a 5% increase in yield can translate to an additional profit of $30 to $90 per acre, depending on market prices and field variability (Krienke et al., 2022). Precision agriculture also contributes directly to United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 9 (Innovation and Infrastructure), by improving food security and fostering technological advancement in rural areas (Saleem et al., 2023).

13. Conclusions

Precision agronomy has evolved from static prescription mapping to dynamic, AI-driven, plant-level management systems capable of substantially improving nitrogen use efficiency and soil quality in maize production. By leveraging multispectral/hyperspectral remote sensing, UAV–satellite data fusion, real-time proximal sensors, machine learning algorithms, and advanced application hardware (VRA, precision fertigation, variable depth tillage), and growers can better match nitrogen supply to spatially and temporally variable crop demand. This synchronization minimizes major loss pathways (leaching, volatilization, denitrification), reduces total N inputs by 20–30% in many cases, maintains or increases grain yield, and delivers measurable improvements in soil biological (enzyme activity, microbial resilience) and physical (organic carbon, aggregation, water-holding capacity) attributes. Complementary strategies controlled-release and organic-inorganic blended fertilizers, variable rate seeding, hybrid switching, and integration with cover crops and conservation tillage further amplify agronomic, economic, and environmental outcomes. Nevertheless, widespread adoption continues to face significant socio-economic and technical barriers, including high upfront investment, limited digital literacy, unreliable rural internet infrastructure, and emerging cybersecurity risks to sensitive farm data. Addressing these challenges through simplified decision-support platforms, cost-shared technology programs, and farmer training initiatives, clear data ownership policies, and blockchain-based security solutions will be essential to scaling precision nitrogen management. Ultimately, the transition toward data-driven, site-specific maize systems represents a critical pathway to reconcile the dual imperatives of feeding a growing population and safeguarding natural resources under intensifying climate and resource constraints. Continued interdisciplinary research and public private collaboration are needed to realize the full sustainability potential of these technologies by 2030 and beyond.

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