FROM PREDICTION TO PRECISION: SELECTING THE RIGHT NITROGEN TOOL TO IMPROVE NITROGEN USE EFFICIECY AND WATER QUALITY

Javed Iqbal*, Arshdeep Singh

Department of Agronomy and Horticulture, University of Nebraska-Lincoln, NE, USA

*jiqbal2@unl.edu

ABSTRACT

The comparison of static versus dynamic nitrogen (N) recommendation tools has gained significant attention for enhancing N management in the U.S. Midwest maize production. However, both approaches have limitations in performance under variable field conditions. This two-year study (2021–2022) evaluated the agronomic, environmental, and economic outcomes of a static Nebraska Yield Goal (NE YG) tool against four dynamic N tools: Maize-N, canopy reflectance sensing, Granular, and Adapt-N. Six N rates (0, 60, 120, 180, 240, and 300 lb N ac^{-1}) were applied in a loamy sand soil highly susceptible to N loss to estimate the economic optimum N rate (EONR) and compare with tool-based recommendations. Despite similar EONR between years, seasonal precipitation and irrigation influenced N dynamics, with 2022 showing 3.8 times higher pore-water NO_3^--N concentrations and 2.3 times greater leaching than 2021. Maize yield followed a quadratic response to N rate, while NO_3^--N leaching exhibited linear and exponential increases in both years. Among N tools, the static Nebraska Yield Goal (NE YG) most closely aligned with EONR and consistently maintained yields, while dynamic tools (e.g., Granular, Adapt-N, Canopy Reflectance Sensing) tended to under-predict EONR but reduced NO_3^--N leaching in >80% of cases. The Excess-N scenario, an alternative to Maize-N in 2022, resulted in significantly higher NO_3^--N leaching and lower return to N with environmental cost (RTN_{Env}). No tool significantly improved all performance metrics, but findings highlight the trade-offs among agronomic, environmental, and economic outcomes. NE YG optimized yield but lacked environmental benefits, while dynamic tools showed potential to reduce NO_3^--N losses with modest yield penalties. These results underscore the importance of tailoring N management strategies to decision-making priorities and suggest that refined decision support tools may better reconcile productivity with environmental stewardship.

INTRODUCTION

Nitrogen (N) is maize's most limiting nutrient, so producers often apply high rates to avoid yield loss (Archontoulis et al., 2020). Yet decades of research have not delivered consistently accurate, site-specific economic optimum N rates (EONR) because N transformations and losses vary across space and time (Dobermann & Cassman, 2002; Thompson et al., 2023). This uncertainty drives two costly errors: under-application (yield and profit risk) and chronic over-application (unnecessary input cost and environmental damage). Nebraska illustrates the stakes: groundwater nitrate (NO_3-N) concentrations exceed the U.S. EPA limit (10 mg L^{-1}) across roughly one million hectares, and many rural communities, where >80% of residents depend on groundwater, incur substantial treatment costs and face health risks (Ouattara, 2022). Nebraska's Natural Resources Districts (NRDs) manage water quality at watershed scale through groundwater management areas and tiered "phase" rules that tighten practices as NO_3-N rises. The Bazile Groundwater Management Area (BGMA) ~1,958 km² of predominantly sandy soils, ranks among the most affected, supplying ~7,000 people with drinking water while frequently recording NO_3-N >10 mg L^{-1}. Shallow groundwater that reduces irrigation cost simultaneously heightens leaching risk. Regulations reflect that most leaching occurs during early vegetative growth (March–May) when precipitation coincides with early N availability; hence prohibitions on pre-March 1 N and emphasis on in-season splits to improve nitrogen use efficiency (NUE).

Within this context, producers rely on two broad classes of N tools. Static tools, exemplified by the Nebraska Yield Goal (NE YG) calculator, use a Stanford-style mass balance (Stanford, 1973) with expected yield plus credits for indigenous and residual N (soil profile, irrigation water, soil organic matter, manure, prior legumes), with timing and price adjustments. NE YG's breadth makes it widely usable, but like other static tools it does not explicitly incorporate current-season weather, a key driver of N need and loss. Dynamic tools integrate weather with soil and crop data to tailor recommendations in season: Maize-N (process-based modeling), Adapt-N and Granular (data-driven decision aids), and canopy reflectance sensing (e.g., red-edge/NDVI). In principle, dynamic tools better synchronize N supply with crop demand as weather unfolds and are valuable in sandy, irrigated systems. Yet, the evidence is mixed: some studies show limited or inconsistent gains in predicting EONR and N losses, while others report improved profits. Critically, many evaluations emphasize simulations or yield; few include field-measured leaching in high-risk landscapes.

To address this gap, we compare a static tool (NE YG) with dynamic tools (Maize-N, Adapt-N, Granular, canopy sensing) under BGMA conditions, evaluating agronomic, environmental, and economic performance. Objectives were to (1) quantify differences in prescribed N rates and (2) assess, side-by-side, yield and NUE, field-measured NO_3-N leaching (suction-cup lysimeters), and net returns with and without environmental costs. The goal is not to crown a universal "winner," but to identify BGMA conditions under which each approach reliably delivers yield, higher NUE, lower leaching, and stronger returns, while evidence producers, advisors, and water managers can use to align profitability with groundwater protection.

MATERIALS AND METHODS

Experimental Site

A two-year on-farm experiment (2021–2022) was conducted near Creighton, Nebraska (42°25′02.3″N, 98°02′52.3″W; elevation 568 m) in Phase III of the Bazile Groundwater Management Area (Upper Elkhorn NRD). The humid climate averages 714 mm precipitation and 9.6 °C mean annual temperature. Soils are excessively drained Thurman loamy sand (82.3% sand, 9.7% silt, 8.0% clay). Baseline soil properties are in Table 1.

Experimental Design and Treatments

A center-pivot system with variable-rate irrigation (outer two spans; Valley VRI) over continuous maize was used. In addition to N-model recommendation rates, treatments had six N rates (0, 60, 120, 180, 240, and 300 lb N ac^{-1}) organized in a randomized complete block design to calculate EONR. Plots were 24 m × 36 m. Nitrogen was applied in five splits: pre-plant urea (AGROTAIN-coated; 2.1 L ton^{-1}), sidedress UAN-32% at V4 (furrow-applied; 19 mm irrigation within 24 h to limit volatilization), and three fertigations (UAN-28%) at V8, V12, and VT via VRI using GPS-loaded application maps.

Yield, N Use Efficiencies, and Economic Return

At physiological maturity each year, hand harvests were taken from the middle two rows (3 m each) per plot. Grain and stover (stalks, leaves, cobs) were separated; stover was shredded, subsampled, dried at 71 °C, milled, and analyzed for total N (dry combustion; Ward Lab). Grain was shelled, dried to 15.5% moisture for yield. Plant population, grain/stover N concentrations, and moisture were used to estimate above-ground N uptake.

Lysimeter Installation, Water Sampling, and Analysis

Two suction-cup lysimeters (Irrometer SSAT; 100-kPa ceramic cups) were installed per plot at 1.2 m depth (~30 m apart) using a silica slurry, native backfill, and a surface bentonite seal. Pore water was sampled 1–3× weekly after rain/irrigation (May–Oct 2021; May–Sep 2022) by applying ~80 kPa vacuum, retrieving after ~4 h with 20 mL syringes, acidifying (0.1 N HCl), and chilling. Deep percolation (DP) was estimated by $DP = P + I - R - ET \pm \Delta S$; P (HPRCC), I (producer), ET (Penman–Monteith with NDVI-derived Kcr), R (NRCS curve numbers). Daily NO_3-N (and NH_4-N) leaching equaled DP×concentration×0.01; sub-seasonal means spanned planting–V8, V8–VT, VT–physiological maturity. >70% NH_4-N was < detection, so omitted.

Statistical Analysis

Quadratic-plateau models (PROC NLIN) estimated EONR; tools differing beyond ±$2.47 ha^{-1} were distinct. One-/two-way GLIMMIX ANOVA and repeated-measures tested yields, leaching, economics, efficiencies, residual N, and lysimeter NO_3^- responses (α=0.05).

RESULTS

Lysimeter NO_3–N

Across 23 (2021) and 26 (2022) leaching events, pore-water NO_3–N ranged 0–20 mg L^{-1} (2021) and 0–257 mg L^{-1} (2022). NO_3–N increased with N rate in all stages. In 2021, responses were linear in early and late vegetative phases and exponential in reproductive; mean stage concentrations were 7.8 (early), 4.7 (late), and 1.0 mg L^{-1} (reproductive). In 2022, NO_3–N rose exponentially across all stages; means were 27 (early), 17 (late), and 16 mg L^{-1} (reproductive). Season-average NO_3–N in 2022 was 3.8× higher than 2021. N-tool treatments showed similar temporal trends.

Yield and Leaching vs. N Rate

Grain yield followed a quadratic-plateau in both years. In 2021, yields were 207–271 bu ac^{-1} with EONR ≈ 230 lb N ac^{-1} (range 220–242) and a plateau of ~259 bu ac^{-1}. In 2022, yields were 199–244 bu ac^{-1} with EONR ≈ 225 lb N ac^{-1} (range 215–241) and a plateau of ~242 bu ac^{-1}. Seasonal NO_3–N leaching increased linearly with N in 2021 (~15.5 lb NO_3–N ac^{-1} at EONR) but exponentially in 2022 (~36.6 lb NO_3–N ac^{-1} at EONR). At the 2022 EONR, yield was ~21 bu ac^{-1} lower and leaching 2.3× higher than at the 2021 EONR.

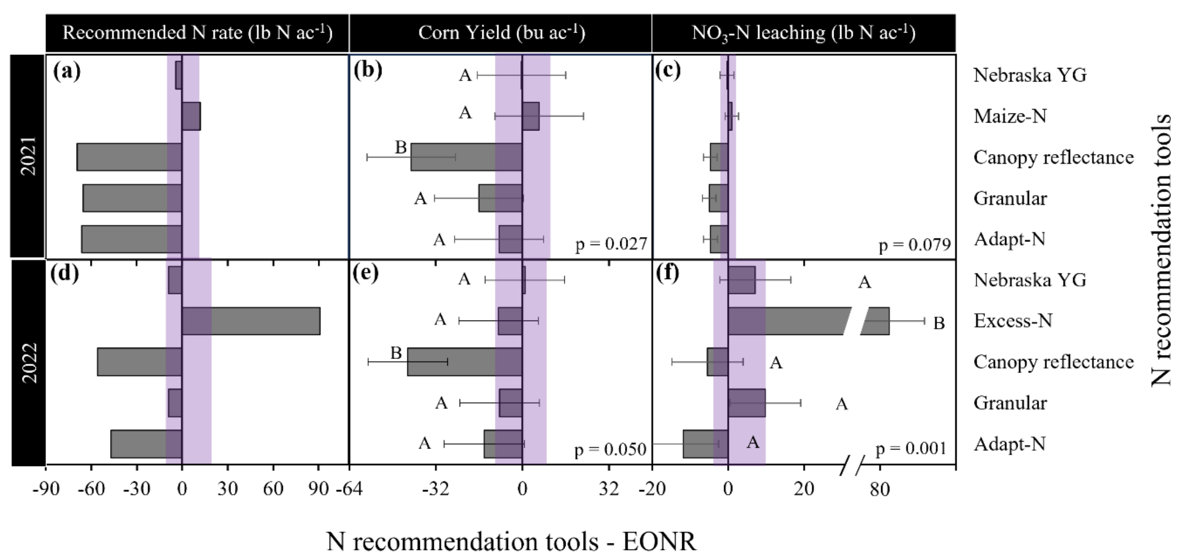

Figure 1. Comparison of N recommendation tools to EONR for N recommendation rate (a, d), maize yield (b, e), and NO_3-N leaching (c, f) during the study years (2021, 2022).

Tools Closest to EONR

Differences from EONR (dEONR) ranged −69 to +12 lb N ac^{-1}. The static Nebraska Yield Goal was closest (−4 to −9 lb N ac^{-1}) both years. Among dynamic tools, canopy sensing and Adapt-N under-recommended (−47 to −69); Granular under-recommended in 2021 (−65) but was close in 2022 (−9). Maize-N over-recommended (+12 to +91).

Agronomic, Environmental, Economic Performance

Using dEONR and ANOVA, grain yields were generally similar among tools except canopy sensing, which was lower both years. NO_3–N leaching tracked N input in 7/10 cases: NE YG was near or slightly above EONR leaching; Maize-N and Excess-N were consistently above; canopy sensing, Granular, and Adapt-N were below in 5/6 cases. All tools had negative RTN/RTNEnv; NE YG was closest to EONR, while Excess-N was lowest.

DISCUSSION

Maize Yield and NO_3–N Leaching vs. N Rate

Although EONR was similar between 2021 and 2022, grain yield, NO_3–N leaching, RTN, and RTNEnv at EONR differed markedly, underscoring strong year effects from weather and management. The quadratic-plateau yield response agrees with prior work. By contrast, leaching responses diverged by year: linear in 2021 (with relatively low losses) and exponential in 2022 (substantially higher losses), consistent with studies linking exponential leaching to reduced yield and efficiency. Lower yield, PFP, and NUEcrop in 2022 aligned with greater leaching. Potential contributors include producer tillage in 2022 (vs. no-till in 2021), which can elevate leaching under intense rainfall, and slightly greater early-season N in 2022; however, companion evidence suggested split timing differences had limited effect under below-normal precipitation.

Agronomic Performance of N Tools

Tool performance is context-dependent and shaped by inputs each model uses. Both static and dynamic tools spanned wide outcomes for EONR proximity, leaching, RTN/RTNEnv, and N-use metrics on the same sandy, irrigated site. Surprisingly, the static Nebraska Yield Goal (NE YG)—despite not using current-season weather—consistently recommended rates closest to EONR across years. Its broad accounting (soil/irrigation NO_3–N, manure/legume credits, timing and price adjustments) likely fits Nebraska systems well. Dynamic tools, designed for wide geographies and data universes, may misalign with local processes when coefficients or loss pathways (e.g., denitrification) are simplified.

Maize-N. Over-recommended (+12 to +91 lb N ac^{-1}), echoing prior findings. Likely causes include conservative mineralization estimates and simplified parameters; adding explicit denitrification and refining coefficients could improve alignment.

Canopy reflectance sensing. Under-recommended (−56 to −69 lb N ac^{-1}), with ~41–43 bu ac^{-1} yield penalties. Skipping a V4 sidedress (used by other tools) likely induced early N stress, exacerbated by higher early-season leaching risk in sand; multiple early splits may be needed when relying on sensing.

Granular and Adapt-N. Typically under-recommended by 9–66 lb N ac^{-1} with modest yield reductions. Sensitivity to weather, SSURGO soils, and sizable irrigation-water N credits at this site may explain underestimation; better accounting for NO_3–N in irrigation water could enhance performance.

Environmental and Economic Performance

Despite varied N recommendations, NO_3–N leaching differed significantly only for Excess-N (highest losses). In 7 of 10 comparisons, leaching direction followed N input. Residual soil NO_3–N mirrored this pattern: little difference among tools unless rates exceeded EONR. Three dynamic tools (sensing, Granular, Adapt-N) reduced leaching ~18% in most cases, suggesting environmental potential even when yield gains were absent. RTN/RTNEnv differences were generally small; NE YG was closest to EONR, canopy sensing was lower (due to yield loss), and Excess-N had the worst RTNEnv. Overall, NE YG best matched EONR and yield; dynamic tools showed environmental advantages in several cases. Prioritization should reflect stakeholder goals (profit vs. leaching), while future work should integrate strengths across tools and improve local calibration (e.g., irrigation NO_3–N, denitrification) to enhance both ROI and groundwater protection.

REFERENCES

Archontoulis, S. V, Castellano, M. J., Licht, M. A., Nichols, V., Baum, M., Huber, I., Martinez-Feria, R., Puntel, L., Ordóñez, R. A., Iqbal, J., 2020. Predicting crop yields and soil-plant nitrogen dynamics in the US Corn Belt. Crop Sci. 60(2), 721–738.

Dobermann, A., Cassman, K. G., 2002. Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. Plant Soil 247, 153–175.

Ouattara, B. S., 2022. Agrichemicals (Nitrate and Atrazine) In Drinking Water and Adverse Health Outcomes in Children in Nebraska. Theses & Dissertations. 668. https://digitalcommons.unmc.edu/etd/668.

Stanford, G., 1973. Rationale for optimum nitrogen fertilization in corn production. J. Environ. Qual. *2*(2), 159–166.

Thompson, L. J., Archontoulis, S., Puntel, L. A. (2023). Determining site-specific corn nitrogen rate over time with APSIM model. In Precision agriculture’23. Wageningen Academic. pp. 1099–1105.