55th Annual

NORTH CENTRAL EXTENSION-INDUSTRY SOIL FERTILITY CONFERENCE

November 19-20
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PROCEEDINGS

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ORAL PROCEEDINGS

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INVESTIGATING POTASSIUM FERTILITY IN INDIANA: K RATES AND NUTRIENT INTERACTIONS

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INTRODUCTION

Efficient nutrient management is essential for optimizing crop productivity and sustaining agricultural profitability. In Indiana, potassium (K) fertility has been a focal point of fertility management research in the state dating back to 1997. This paper presents a small subset of findings from these K plots, with more discussion planned for the presentation during the conference. New to fertility work in the state, nutrient interaction trials were established in 2025 to investigate the effects of nitrogen (N)xK interactions and NxSulfur (S) interactions on corn nutrition and yield. Preliminary results from one location of the NxK study will be discussed here, with additional results presented during this conference.

MATERIALS AND METHODS

Potassium Rate Study

Potassium fertility research has been ongoing in the state of Indiana at multiple sites since 1997. Potassium rates and management have changed over time at each location. Here, we will focus on results from the Davis Purdue Agricultural Center (DPAC; Farmland, IN) from 2020-2022, with additional site-years covered in the presentation. The majority of soils at DPAC are fine textured, heavy clay soils that are relatively poorly drained, with gently rolling topography. These plots are set up as a randomized complete block design with four replications and five K rate treatments (0, 45, 90, 135, and 180 lb K_2O/ac). All K_2O treatments were applied as potash in the spring. The site rotates between soybean (in even years) and corn (in odd years). Background fertility and other agronomic management (e.g., herbicides, fungicides, etc.) are managed at the discretion of farm management staff. Soil samples were collected in spring, prior to fertilization and planting. Soil samples were collected by plot, to a depth of 8” and analyzed for Mehlich-3 K. Soil test K can be found in Table 1.

Table 1. Pre-plant, pre-fertilization average soil test data by potassium rate treatment each year.

K Rate Treatment (lb K_2O/ac)	Spring 2020 (ppm)	Spring 2021 (ppm)	Spring 2022 (ppm)
0	88	78	67
45	85	80	71
90	71	71	78
135	72	83	77
180	88	97	85

Harvest data is collected from the center of each plot using a combine equipped with a calibrated yield monitor. Soybean yield is corrected to 13% and corn yield is corrected to 15%.

Nutrient Interaction Studies

Studies were established in the 2025 growing season to investigate interactive effects between nitrogen and potassium (NxK) and nitrogen and sulfur (NxS) for corn production. Both trials were established at two locations in the state including the Agronomy Center for Research and Education (ACRE; West Lafayette, IN) and Pinney Purdue Agricultural Center (PPAC; Wanatah, IN). Data collection included soil, tissue, and grain samples, as well as yield. Here, we will focus on the NxK trial at ACRE, but additional results will be discussed in the presentation.

The NxK trials involved four rates of K_2O (0, 60, 120, and 180 lb K_2O/ac) in a complete factorial design with six rates of N (0, 50, 100, 150, 200, and 250 lb N/ac) with four replications. The K_2O source was potash (0-0-60) and the N source was urea ammonium nitrate (UAN; 28-0-0). Potassium was broadcast and incorporated preplant, in the spring, and UAN was applied at V3. The site also received a blanket application of 20 lb S/ac as ammonium sulfate (AS; 21-0-0-24S). This provided an additional 18 lb N/ac for each NxK treatment combination. Prior to fertilization, soil samples were collected from each replicate and analyzed for the full suite of agronomic nutrients, including soil test K on a Mehlich-3 basis. Corn was planted and managed by ACRE staff (e.g., herbicide and fungicide applications, as needed). A total of 10 whole plant samples were collected from each plot at V6 and analyzed for K and N concentration. A total of 10 ear leaf samples were collected from each plot at R1. The center rows of each plot were harvested to determine grain yield using a Wintersteiger combine equipped with a HarvestMaster system. Yield data are corrected to 15% moisture content.

RESULTS AND DISCUSSION

Potassium Rate Studies

Soybean yield responded similarly to K rate in 2020 and 2022. The three highest K rate treatments (90, 135, and 180 lb K_2O/ac) significantly increased yield compared to the 0-K control (Figure 1). Yield of the 45 lb K_2O/ac treatment was similar to yield at both the higher K rates and the control.

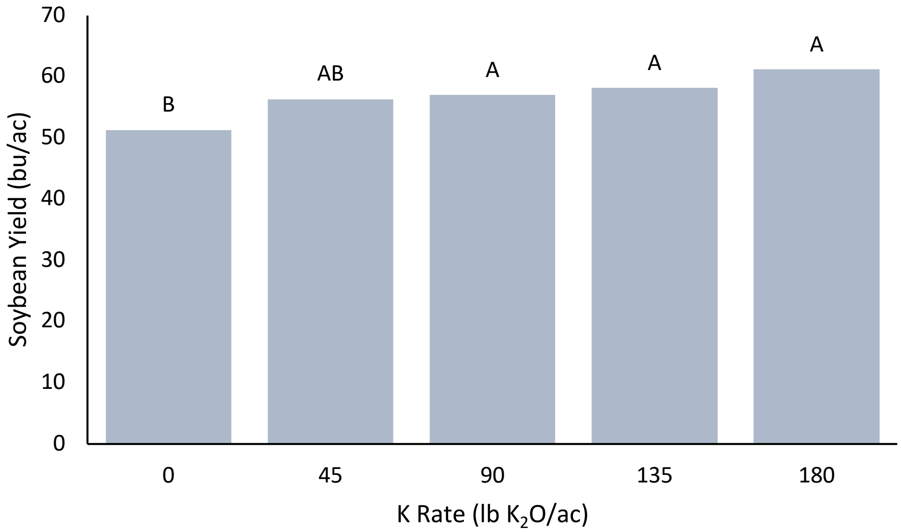

Figure 1. Soybean yield, averaged across 2020 and 2022, by potassium fertilizer rate.

In 2021, corn yield was significantly reduced in the 0-K control treatment, but was similar across all other rates (Figure 2). Based on the tri-state fertilizer recommendations (Culman et al., 2020) we would have expected to need the 135 or 180 lb K_2O/ac rate to maximize yield.

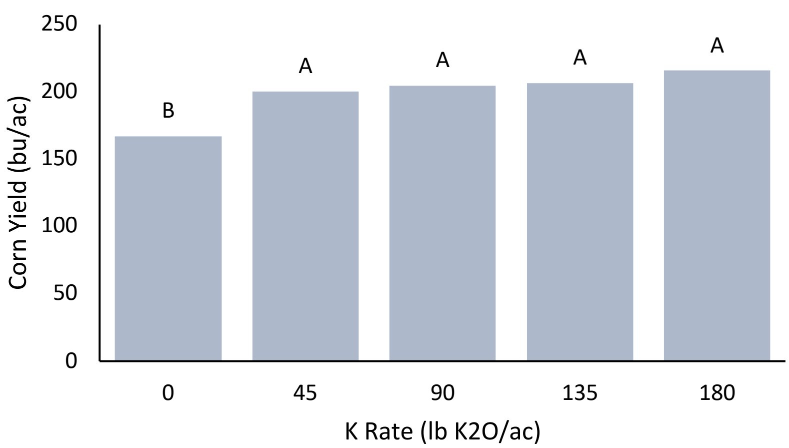

Figure 2. Corn yield across K rates in 2021.

Nutrient Interaction Studies

Whole plant K concentration at V6 was not affected by N rate, K rate, or their interaction at ACRE. However, N concentration in the whole plant at V6 was significantly affected by K rate (Table 2). Ear leaf samples did not show any response of N or K concentration from the treatments. Corn yield was significantly affected by N rate (Figure 3) but was not affected by K rate or the interaction between N and K rates.

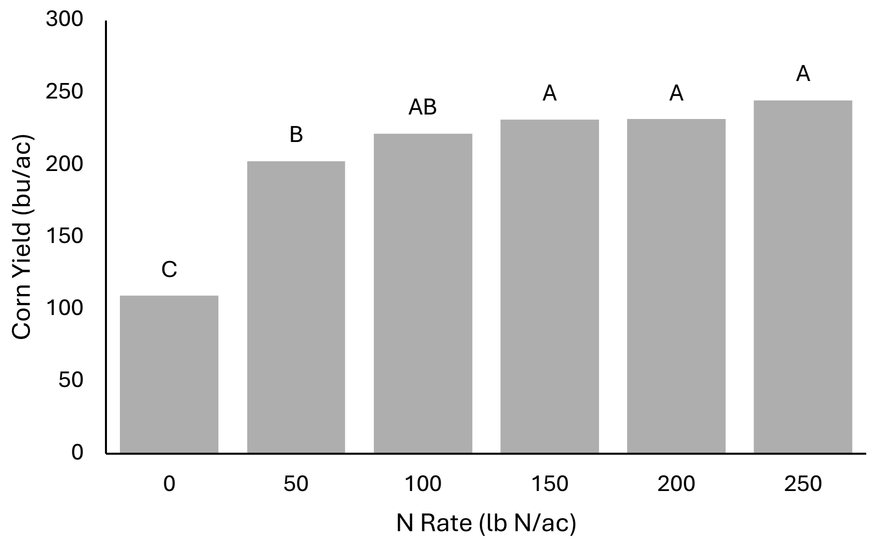

Figure 3. The effect of N rate on corn yield at ACRE, 2025.

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EVALUATING CLASSIFICATION METHODS FOR PHOSPHORUS RESPONSIVENESS FOR FERTILIZER RECOMMENDATIONS IN KANSAS WHEAT

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ABSTRACT

Field crop yield responses to fertilizer applications are often uncertain, and the likelihood of a response at a given site is typically determined using correlation-based soil test methods whose accuracy is not well established. The objective of this study was to evaluate three alternative approaches to clasify field sites as responsive or non-responsive to phosphorus (P) fertilization in wheat. The methods tested were: (i) a linear-plateau correlation model, (ii) a linear-plateau correlation model with ANOVA pre-classification, and (iii) a logistic regression model. A simulation framework using parameters from a historical Kansas wheat dataset (1970–2006) generated yield data with random noise based on known intercepts, slopes, and critical P rates across varying site numbers (10–100) and P rates (4–7 levels from 0 to 120 lb ac^{-1}). Each model was iterated 1,000 times, and performance was evaluated using accuracy and precision from confusion matrices. Logistic regression was the most accurate and stable, with average accuracy of 70 % and precision of 48 %, while linear-plateau approaches showed lower performance (≈ 40 % accuracy and 30 % precision). Increasing site numbers improved stability but not ranking among methods. Application to 21 Kansas wheat site-years confirmed these trends, indicating that probabilistic approaches such as logistic regression provide more reliable P responsiveness classification and support consistent fertilizer recommendations.

INTRODUCTION

The correlation method is the foundation for determining whether a site is responsive to P fertilization based on soil test P (STP) analysis.This approach establishes a critical soil test value (CSTV), which represents the STP concentration required to achieve maximum grain yield (Dahnke & Olson, 1990). The CSTV serves as a benchmark for predicting crop response to P fertilization, above this value, additional P inputs are not expected to increase yield. Grain yield is commonly expressed as relative yield (RY), a useful metric that standardizes yield data across sites and years, minimizing the influence of uncontrolled variables.

While several studies have compared the efficacy of different correlation-based methods for determining critical thresholds (Culman et al., 2023; Mallarino & Blackmer, 1992), few have evaluated how accurate these approaches are in identifying site responsiveness. This knowledge gap can be addressed using a simulation study, which is a statistical approach that allows controlled evaluation of estimator bias and accuracy under known conditions (Lacasa et al., 2023; Makowski & Wallach, 2001). Simulation frameworks can be generally divided into three steps: simulation, estimation, and comparison. First, “fake data” are simulated based on “true, baseline” parameter values. Then, the methods to be evaluated are applied to the data. Having a known “true” baseline state allows direct comparison between the true values and the estimates obtained from a given method.

This study aimed to assess the performance of different classification methods for P responsiveness in wheat and to determine how simulation-based validation can improve the reliability of fertilizer recommendations.

MATERIALS AND METHODS

The simulation study was based on parameters derived from a historical Kansas wheat dataset (1970–2006). Each simulation combined different numbers of sites (10, 20, 30, 40, 60, 100) and P rates (4–7 levels ranging from 0 to 120 lb ac^{-1}). For each site, yield data were generated using its estimated intercept, slope, and critical P rate, with random error added to represent environmental variability.For each scenario, three models were fitted:

a) Linear-plateau (LP) correlation model estimating CSTV.
b) LP + ANOVA model, where non-responsive sites ($p > 0.05$) were set to 100 % RY before refitting.
c) Logistic regression model, predicting the probability of response based on STP.

A single simulation framework was implemented in which yield data were repeatedly generated with random noise based on known and realistic site parameters. Figure 1 illustrates an example comparing observed and simulated relative yield (RY). Each classification method (linear-plateau, linear-plateau with ANOVA, and logistic regression) was iterated 1,000 times, producing 1,000 independent model fits per method and 3,000 in total. Site classifications (responsive or non-responsive) were compared with a gold-standard AIC-based classification, in which environments were labeled responsive when the slope model fits better than the intercept-only model ($\Delta AIC > 3$). Model performance was evaluated using accuracy and precision metrics derived from confusion matrices, where TP (true positives) and TN (true negatives) represent correctly classified sites, and FP (false positives) and FN (false negatives) represent misclassified sites. Accuracy was calculated as (TP + TN) / (TP + TN + FP + FN), and precision as TP / (TP + FP).

Following the simulation, the three methods were applied to field data from 21 Kansas wheat site-years (2019–2020). Phosphorus was applied as mono-ammonium phosphate (MAP) at 0, 40, 80, and 120 lb ac^{-1} with four replications per site. Each site-year was first classified using the AIC-based method as the reference. The LP and LP + ANOVA models were then fitted to estimate CSTV and corresponding confidence intervals, while the logistic regression model was fitted using AIC-derived labels as the response variable and STP as the predictor. This probabilistic framework provided a continuous likelihood of P responsiveness across the STP gradient rather than a fixed binary threshold.

RESULTS AND DISCUSSION

The logistic regression model achieved the highest median accuracy (70%) and precision (48%) across all P-rate groups and environment sizes (Figure 2). The linear-plateau (LP) model showed the lowest performance, with accuracy around 40 % and precision near 30 %, while adding the ANOVA pre-classification improved LP accuracy to about 50 % and precision to 35 %. Increasing the number of environments stabilized results rather than changing the relative ranking among methods. As site numbers increased from 10 to 100, the interquartile range of accuracy decreased by roughly 20 percentage points, suggesting that around 30 environments may be sufficient for correlation-based analyses if they cover a broad STP range. Varying the number of P-rates (4, 5, or 7) did not meaningfully affect model ranking (Figure 2).

Although the correlation-based approaches were less accurate overall, they tended to classify a higher proportion of sites as responsive, indicating a systematic bias toward over-prediction of fertilizer response. This tendency was also apparent in the case study, where both linear-plateau models identified nearly all responsive sites but slightly overestimated the number of environments showing a response. Such bias reinforces the advantage of probabilistic models like logistic regression, which better balance false and true classifications when predicting site responsiveness.

From the case study, we observed that all three methods produced CSTV estimates within a similar range of 25 to 30 ppm STP (Figure 3), indicating consistency across models. However, when the number of site was limited, the confidence intervals around the CSTV are wide. This pattern, consistent across all three approaches, points out that smaller datasets provide less information for parameter estimation, increasing uncertainty in identifying the true CSTV threshold. In the linear-plateau-based models, the upper confidence limit was undefined (NA) because data were sparse and limited.

The linear-plateau model resulted one false negative (a responsive site classified as non-responsive) and four false positives (non-responsive sites classified as responsive), resulting in an accuracy of 76%. The ANOVA plus linear-plateau model resulted one false negative and three false positives, with an accuracy of 80%. The very small number of false negatives in both models indicates that responsive sites were almost always correctly identified, which is favorable from a farmer's perspective because it minimizes the risk of missing potential yield gains. The few false positives suggest that the models had a limited tendency to recommend P fertilization where a response was unlikely.

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FIGURES

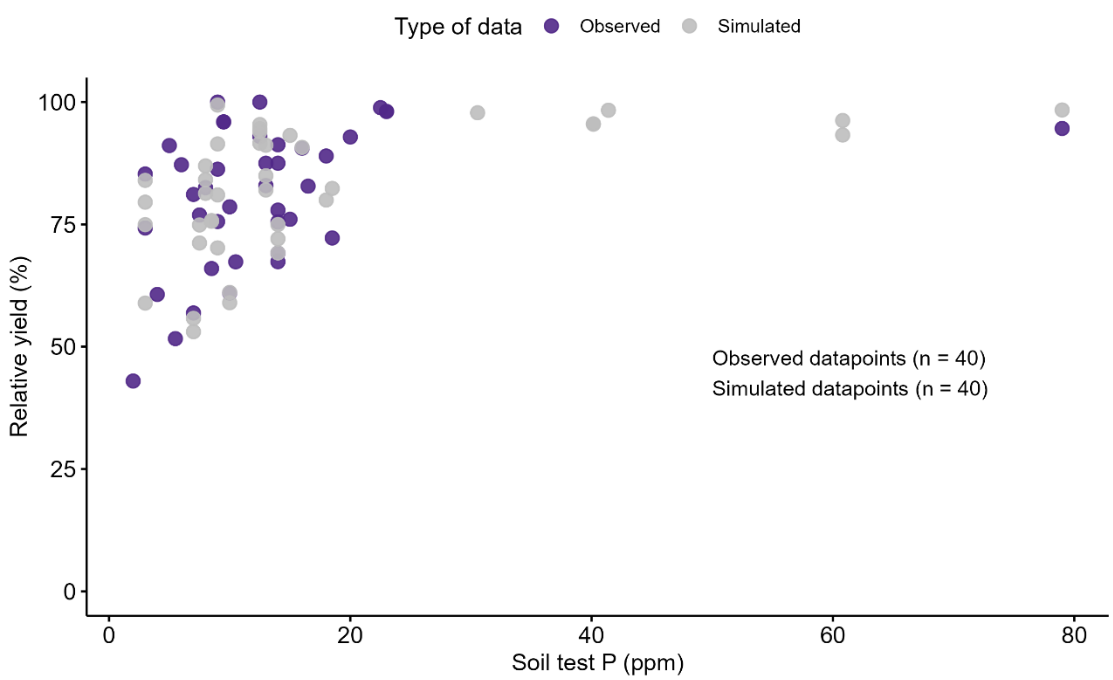

Figure 1 Comparison between relative yield (RY) from observed datapoints in the Kansas wheat dataset and simulated RY at the same soil test P (STP) levels. The example corresponds to a simulation with four P rates and 40 sites. Simulated datapoints were generated using the site-specific slope, intercept, STP, and added random error.

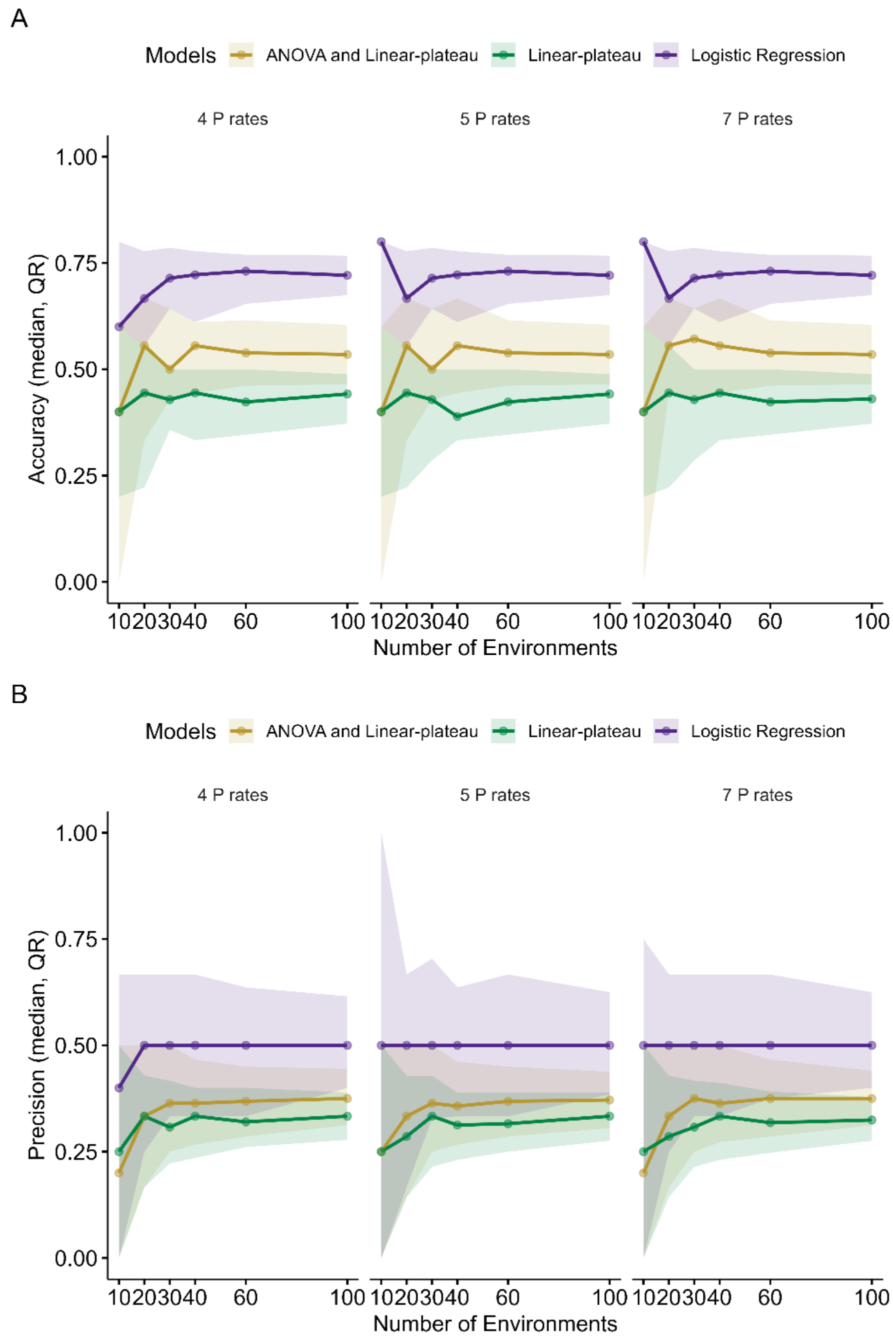

Figure 2 (A) Accuracy and (B) precision of three classification methods: Linear-plateau, ANOVA and linear-plateau and Logistic Regression. Lines represent the median values across 1,000 iterations for each simulation, and shaded areas indicate the interquartile range (25th–75th percentile).

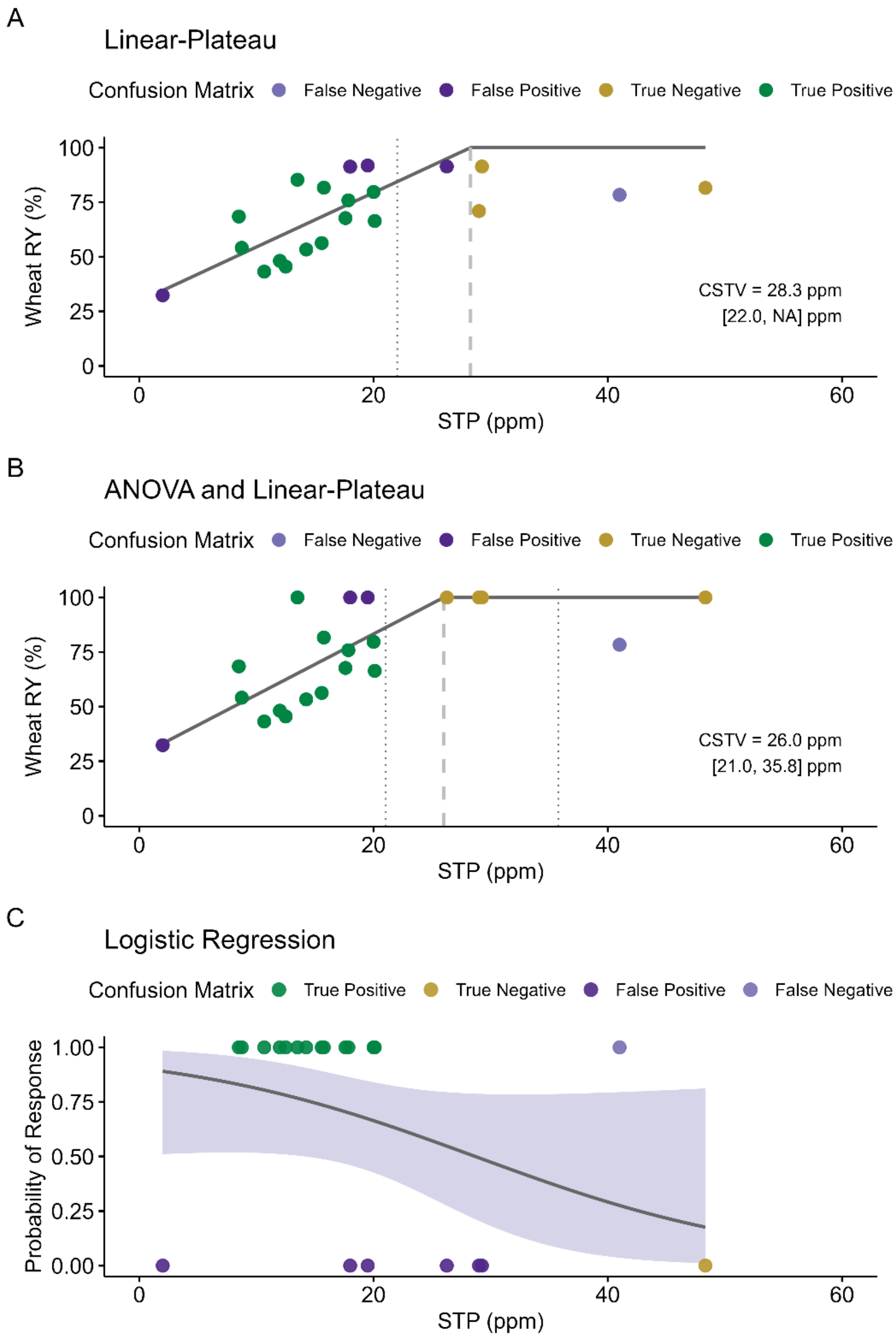

Figure 3 Case study results for the Kansas wheat data. (A) linear-plateau (B) Linear-plateau + ANOVA pre-classification (ANOVA and Linear-Plateau), where non-responsive sites were to 100% RY before refitting. (C) Logistic regression showing probability of response across STP gradient. Colored points denote the confusion matrix outcomes: true positive (green), true negative (tan), false positive (purple), false negative (lavander).

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

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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 km^2 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.

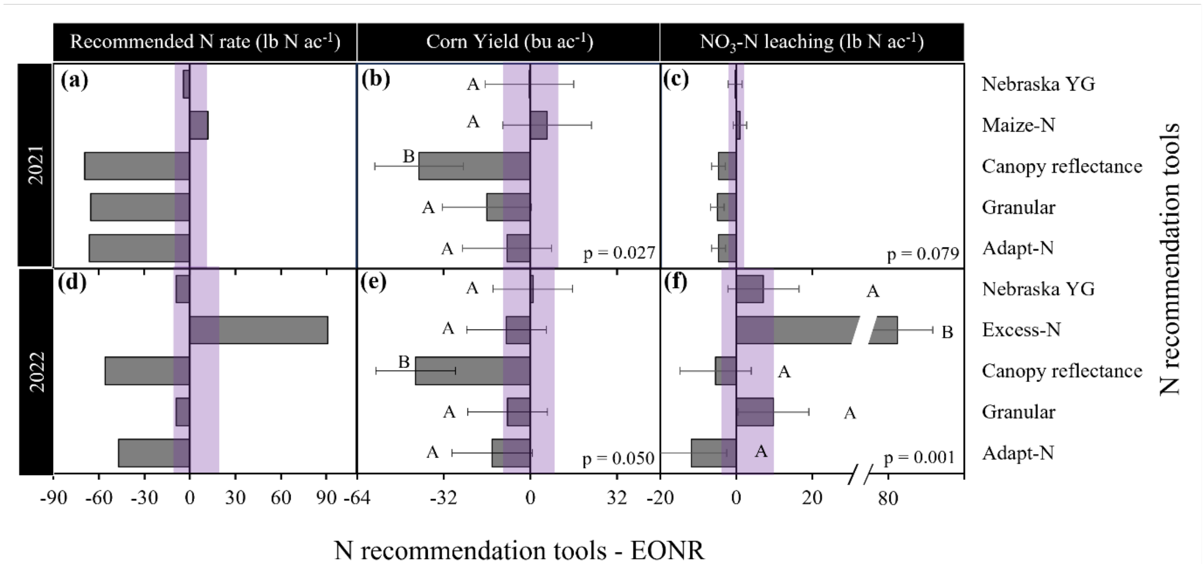

Figure 1. Comparison of N recommendation tools to EONR for N recommendation rate (a, d), maize yield (b, e), and NO_3-N leaching (c, f) during the study years (2021, 2022).

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.

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PHOSPHORUS FERTILIZER MANAGEMENT: IMPLICATIONS ON CROP YIELDS AND SOIL P BUDGETS

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ABSTRACT

Recent volatility in fertilizer prices, declining commodity values, and increasing water quality concerns have intensified scrutiny around phosphorus (P) management decisions in Ohio. In response, we initiated a field trial to evaluate crop yield response and soil phosphorus budgets under various P application strategies within a corn–soybean rotation during the 2024 and 2025 growing seasons. The study investigated two P application timings (fall and spring), two fertilizer sources (triple superphosphate and diammonium phosphate), and five application rates (0, 30, 60, 90, and 120 lb P_2O_5/acre), with each treatment replicated four times. Soil samples were collected in fall 2023, 2024, and 2025 to determine Mehlich-3 extractable P. Corn and soybean yields were measured using a plot combine. In addition, corn tissue samples were analyzed to assess P uptake under different management scenarios. Results from 2024 indicate that fall-applied P significantly increased corn tissue P concentrations at the V4 growth stage compared to both the control and spring-applied P treatments. At the VT stage, spring-applied P and DAP treatments showed lower tissue P concentrations relative to other treatments. Despite these differences in tissue P content, corn yields were not significantly affected by P timing, source, or rate. However, P application rate had a significant impact on the soil P budget in 2024. Treatments receiving 0, 30, and 60 lb P_2O_5/acre resulted in negative P budgets. Soil P data collected in fall 2025 showed no influence of P rate. Like corn yield, soybean yield was similar across the treatments. Overall, these findings suggest that while P management practices can influence soil P budgets and plant P uptake, yield responses are minimal. These results highlight the need to further explore factors such as sub-surface soil P reserves and contributions from other P pools in meeting crop nutrient demands.

INTRODUCTION

Recent volatility in fertilizer prices, declining commodity values, and increasing water quality concerns have intensified scrutiny around phosphorus (P) management decisions in Ohio. Phosphorus management guidelines in Ohio are based on the Tri-State Fertilizer Recommendations (Culman et al.,2020), which uses soil test P level and crop removal rate to calculate P amount for the crops. While these recommendations are effective, limited guidance is present around how P rate could change based on the fertilizer source and application timings.

Different phosphorus fertilizer sources, rates, and application timings can have implications on crop yields and environment. Barcos (2007) and Nakayama et al (2024) showed no crop response to P applied in fall versus spring in Iowa and Illinios, respectively. However, fall P application has been observed to increase water quality concerns by increasing the dissolved reactive phosphorus by 33% and total P by 19%

compared to spring injected P scenarios. Similarly, while Diammonium Phosphate (DAP) and Triple Superphosphate (TSP) has been reported to produce similar crop yields, there is potential that nitrogen input from DAP can increase nitrate leaching to water bodies (Nakayama et al. 2024). Furthermore, rate of P application can alter the soil P budgets with minimal effect on crop yields (Rakkar et al. 2024). Therefore, it is important to evaluate the significance of soil P management strategies on soil and crop yields to further improve P recommendations while maintaining the environmental quality. Our objective of this study was to evaluate the crop and soil response to two different P sources (DAP and TSP), two application timings (Fall and Spring) and five different P fertilizer rates. We hypothesized that crop yields will improve with P application with potentially more benefit on crops from Spring applied P than Fall while minimal differences will be observed on soil and crops based on the P source.

MATERIAL AND METHODS

An experiment was established in 2023 at Wooster Research and Development center in Ohio (40.75944444, -81.90111111). Baseline soil sample analysis showed 22 ppm soil P, silt loam texture, 2.1% organic matter and pH of 6.9. The previous crop at the site was wheat and followed corn-soybean rotation during the study period (2024-2025). The study had 17 fertilizer treatments: two P sources (DAP and TSP); two P application timings (Fall and Spring) and five P application rates (0, 30, 60, 90, and 120 lb P_2O_5/acre) arranged in a factorial randomized complete block design with four replications. Plot width was 10 ft by 40 ft. The fall treatments were broadcasted on Feb 1, 2024 while spring applications occurred on May 7, 2024. Corn was planted with 30-inch row spacing on May, 2024. Other agronomic inputs such as herbicide and fertilizers were uniform across the study area. For 2025, no P fertilizer was applied to track the legacy of 2024 P application treatments. The crop for 2025 was soybean.

Soil samples were collected from each plot in fall of 2023 (baseline), 2024, and 2025 from 0 to 6 inches. The samples were air-dried, ground, and analyzed for available P using Mehlich-3 extraction procedure (NCERA-13, 2015). Soil budget was calculated by subtracting Baseline soil P and fall P values of 2024 and 2025 season. Leaf tissue samples were collected at V4-V5 stage and VT stage to determine the P content in corn plants. At harvest, grain yield data was collected by harvesting the two center rows of corn plots and center six rows of soybean plots. Grain yield is reported at 15.5% moisture content for corn and 13% for soybeans.

A three-way analysis of variance was conducted by year using R 4.5.1 version to determine the effect of P source, timing and rate on soil P budget, %P tissue content, and crop yields. The significance level was set at $P \leq 0.05$ for all statistical analysis.

RESULTS AND DISCUSSION

In 2024, phosphorus fertilizer treatments affected %P in corn tissue at V4 and VT stage (Table 1; Fig. 1). At V4, %P in corn was significantly higher in fall treated plots compared to spring and control treatments. At VT, the %P in corn was significantly lower in spring treatments compared to the control and fall treatments. During VT, source of P also affected %P, with DAP treatments showing the least %P in corn tissue. Despite differences in %P during the growing season, corn yield was similar across all the treatments. Similar to 2024 yield outcomes, soybean yield in 2025 was similar across the treatments.

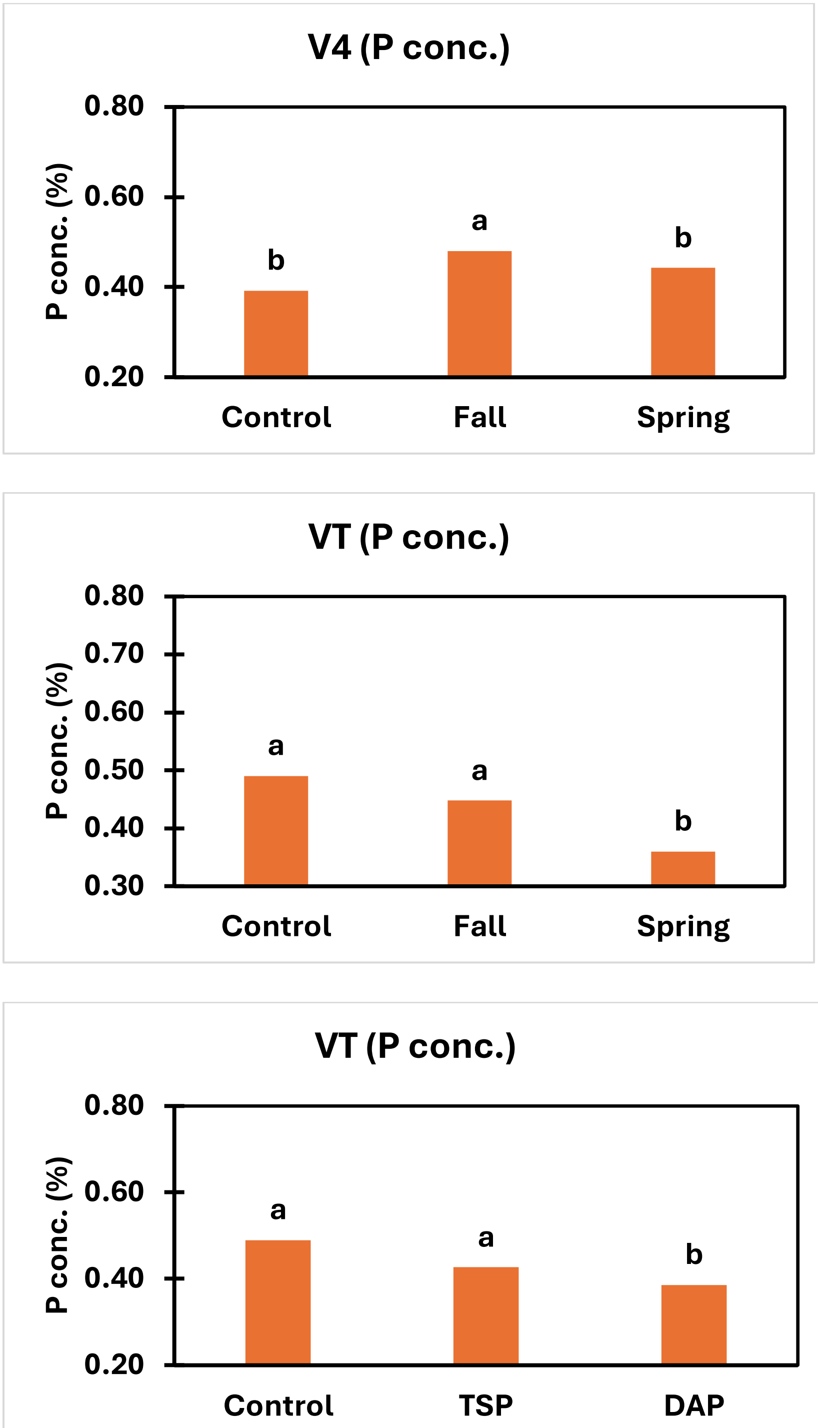

Fig. 1. Phosphorus concentration (%) in corn tissue during V4 and VT stage in 2024 at Wooster, OH.

Table 1. Analysis of variance (p-values) to detect the impact of P source, P timing, and P rate on %P at V4 and VT stage, corn and soybean yields, and soil P budget.

	2024				2025	
Factor	**V4**	**VT**	**Corn Yield**	**Change in fall soil P**	**Soy Yield**	**Change in fall soil P**
P_source	0.07	**0.01**	0.07	0.07	0.91	**0.03**
P2O5_Rate_lb_ac	0.83	0.58	0.28	**0.03**	0.33	0.38
Application_Timing	**0.01**	**0.00**	0.24	0.56	0.77	0.10
P_source:P2O5_Rate_lb_ac	0.06	0.53	0.35	0.61	0.11	0.59
P_source:Application_Timing	0.33	0.24	0.07	0.26	0.17	0.92
P2O5_Rate_lb_ac:Application_Timing	0.20	0.70	0.54	0.50	0.96	0.53
P_source:P2O5_Rate_lb_ac:Application_Timing	0.22	0.77	0.27	0.36	0.79	0.76

Phosphorus treatments significantly affected the soil P budget measured by subtracting P values at the end of each season from baseline P values (Fig 2). In 2024, P rate significantly changed the soil P reserve. The control, 30 and 60 lb P rate showed negative P budgets whereas P values were similar to baseline in other treatments. Statistically significant soil P reduction was observed in control compared to 90-and 120-lb P rates. In contrast, in 2025, P rates had no influence on the soil P measured at the end of soybean growing season compared to baseline soil P. However, P sources showed significant effect on soil P budget with TSP showing the least change in P reserve.

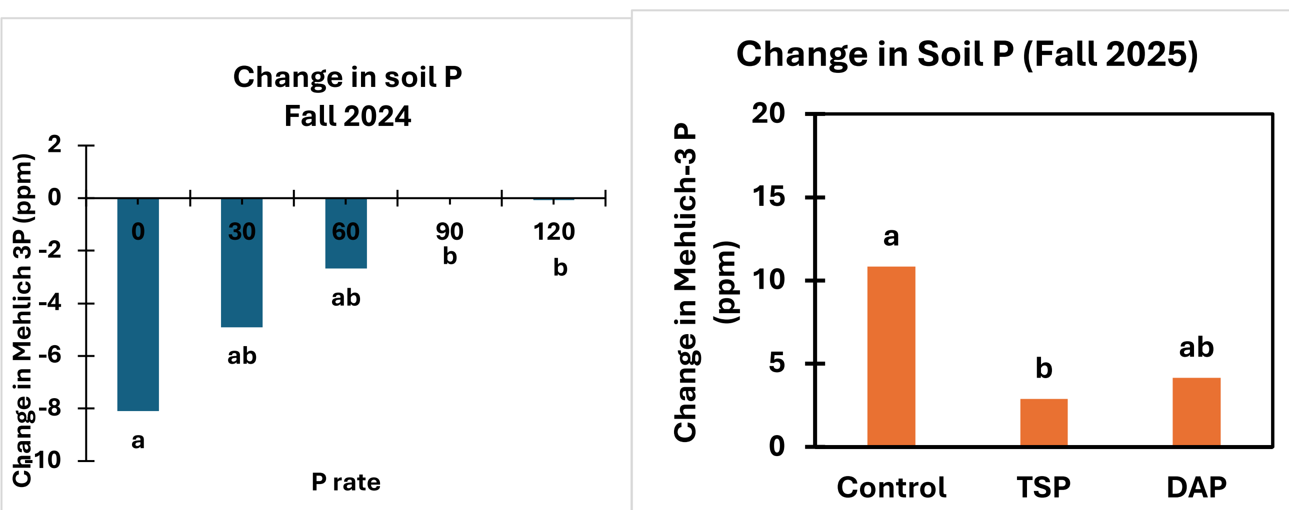

Fig 2. Changes in soil P (End of growing season P -baseline P) as impacted by P source, rate, and timings in 2024-2025 at Wooster, OH.

Overall, these findings suggest that while P management practices can influence soil P budgets and plant P uptake, yield responses in Ohio are minimal, especially when soil P is above the critical level of 20 ppm.

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UPDATING OAT NITROGEN FERTILIZER RATE GUIDELINES

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ABSTRACT

The current yield-goal based system for calculating oat N rate recommendations in SD has not been evaluated for accuracy recently. There are two main N rate recommendation systems used in the U.S.–Yield goal and maximum return to N (MRTN). Therefore, the objective of this project was to 1) evaluate the accuracy of the current yield goal-based equation and 2) evaluate the accuracy of using the MRTN approach for predicting N rate requirements. Twenty-eight oat N rate response trials were conducted at field locations across central and eastern SD from 2017-2022. Nitrogen fertilizer was applied before planting at rates from 0 to 150 lbs N/ac. Soil samples were collected before planting and fertilizer application from the 0-6 and 6-24 in. depth increments and analyzed for nitrate-N. Accuracy of the N recommendation for the yield goal and MRTN approaches were calculated by subtracting the actual EONR from the predicted EONR. The lbs N/bu oat multiplier (coefficient) used in the yield goal approach ranged between 0.4 and 2.4 lbs N/bu oats with an average of 0.9 lbs N/bu oats, indicating that the average amount of N to produce a bushel of oats has decreased from the previous 1.3 value. Across all locations, the median accuracy was +37, +20, +3, -16, -38, and -57 lbs N/ac using a multiplier of 1.3, 1.1, 0.9, 0.7, 0.5, and 0.3, respectively. Therefore, the multiplier (coefficient) of 0.9 instead of 1.3 provides the most accurate yield-goal based N fertilizer rate recommendation. The MRTN for the state of SD at a N price to oats price ratio of 0.12 was 54 lbs N/ac. In comparing the MRTN and yield goal results, the median accuracy for the MRTN approach was +48 lbs N/ac compared to +3 for the 0.9 yield goal approach. Subtracting the soil nitrate-N from the top two feet from the MRTN recommendation improved the median accuracy to 0.5 lbs N/ac. This result indicates that the MRTN approach is most accurate when subtracting soil test N (2 ft.) from the initial 54 lbs N/ac recommendation. Overall, once soil test N is subtracted from the initial MRTN recommendation both the yield goal approach and MRTN approaches had similar accuracies and both methods can be used with confidence.

INTRODUCTION

Nitrogen (N) is an essential plant nutrient commonly applied to South Dakota (SD) oat crops and is critical for optimizing yield. The correct fertilizer-N rate is important as too low of a rate reduces economic return while too high of a rate can lead to N loss, potential negative environmental effects, and reduced economic return. Therefore, it is important to always work on improving the accuracy of oat N rate recommendations. Common N rate recommendation approaches at this time include the yield goal approach and the maximum return to N (MRTN) approach (Morris et al., 2018).

The yield goal approach was developed in the 1970s and was the main system for creating crop N recommendations until the maximum return to N approach was developed in 2005 (Morris et al., 2018; Sawyer et al., 2006). South Dakota currently uses a yield goal-based system to determine N fertilizer recommendations. However, it is unknown when these recommendations were last evaluated. Therefore, the objective of this project was to 1) evaluate the accuracy of the current yield goal-based equation used in SD, which includes yield potential (goal), 1.3 lbs N/bu oats multiplier (coefficient), pre-plant soil test N (0 to 24 inches), and previous crop and 2) evaluate the accuracy of using the MRTN approach for predicting N requirements.

MATERIALS AND METHODS

Twenty-eight oat N rate response trials were conducted at field locations across central and eastern SD from 2017-2022. Site locations varied in tillage practice, crop rotation, and soil type. Specifically, 9 were in conventional till and 19 in no-till fields. The previous crop was soybean at 25 locations, and corn at 3 locations. Nitrogen fertilizer was applied before planting at rates from 0 to 150 lbs N ac^{-1}. Nitrogen fertilizer as urea (46-0-0) was broadcast on the soil surface. Fertilizer was incorporated if conventional tillage practices were used or remained on the soil surface when no tillage was used. Soil samples were collected before planting and fertilizer application from the 0-6 and 6-24 in. depth increments and analyzed for nitrate-N (Nathan et al., 2015). Oat grain yield was determined by harvesting the center five feet of each plot and adjusting grain weight to 13% moisture.

Economic optimal N rates were determined by modeling the relationship between oat yield and N fertilizer rate by averaging the results from both the linear-plateau and quadratic-plateau models using a N fertilizer price to oat price ratio of 0.12 (Miguez & Poffenbarger, 2022). If no plateau was reached within the N rates used in the study, the economic optimal N rate was set to the maximum N rate used at that location. The lbs N/bu oats multiplier (coefficient) was calculated for each site by adding the amount of N fertilizer needed to optimize oat yield and the nitrate-N in the soil from 0 to 24 in. and dividing it by the optimal oat yield (e.g., (soil test N + economic optimal N fertilizer rate) / optimal grain yield). For the yield goal approach, the N rate recommendation was calculated using 1.3 (current value), 1.1, 0.9, 0.8, 0.7, 0.5, and 0.3) as the coefficient. The 28 site-years of response trials were input into a database developed by John Sawyer at Iowa State University (Sawyer et al., 2006). This spreadsheet was used to calculate a maximum return to N (MRTN) rate. The accuracy of the N recommendation for the yield goal and MRTN approaches was calculated by subtracting the actual EONR from the predicted EONR. The closer these numbers were to 0, the more accurate the recommendation. If numbers were positive, it meant an over application of N was recommended while negative numbers meant an under application of N was recommended. The mean, median, lower 25^{th} quartile, upper 75^{th} quartile and RMSE values were calculated to help in comparing the accuracy of each N recommendation approach.

RESULTS AND DISCUSSION

Yield Goal Approach

Across the 28 locations, maximum oat yields ranged from 65 to 162 bu/ac with an average of 100 bu/ac while the optimal fertilizer-N rate ranged from 0 to 125 lbs N/ac with an average of 27 lbs N/ac (Figure 1). The optimal fertilizer-N + Soil nitrate-N amount ranged from 28 to 172 lbs N/ac with an average of 64 lbs N/ac. The lbs N/bu oats multiplier (coefficient) ranged between 0.4 and 2.4 lbs N/bu oats with an average of 0.9 lbs N/bu oats (Figure 2). These results demonstrate that the average amount of N to produce a bushel of oats has decreased from the previous 1.3 value.

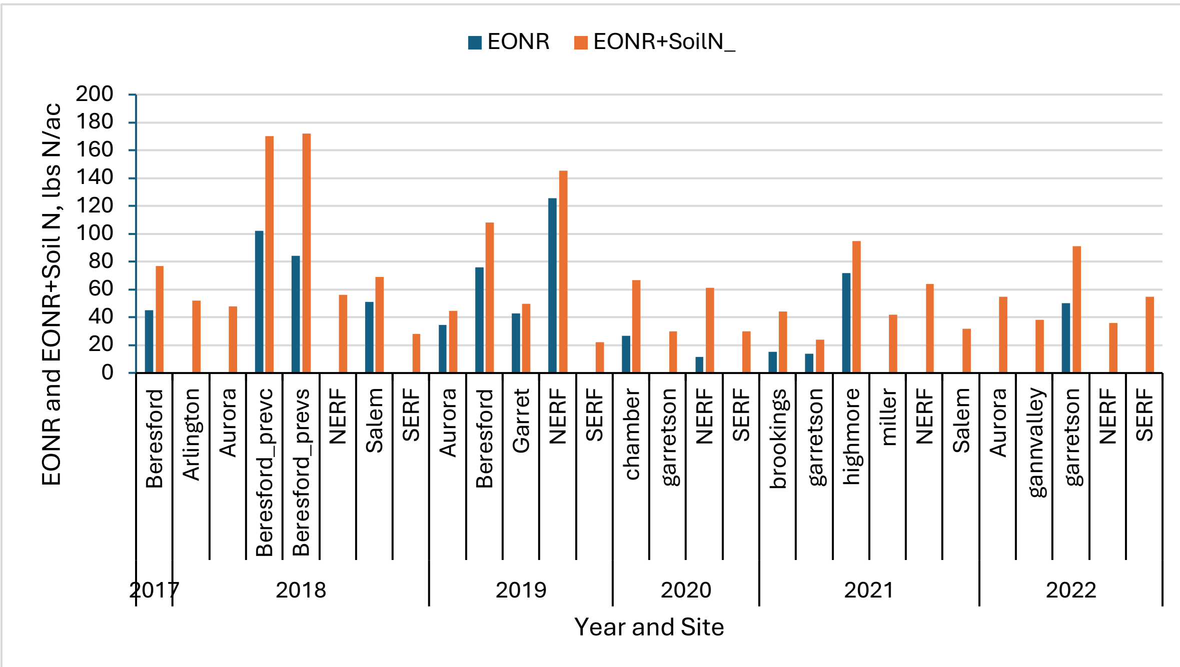

Figure 1. The oats economic optimal N rate (EONR) and EONR + soil nitrate-N from the top two feet at research sites across South Dakota from 2017 to 2022.

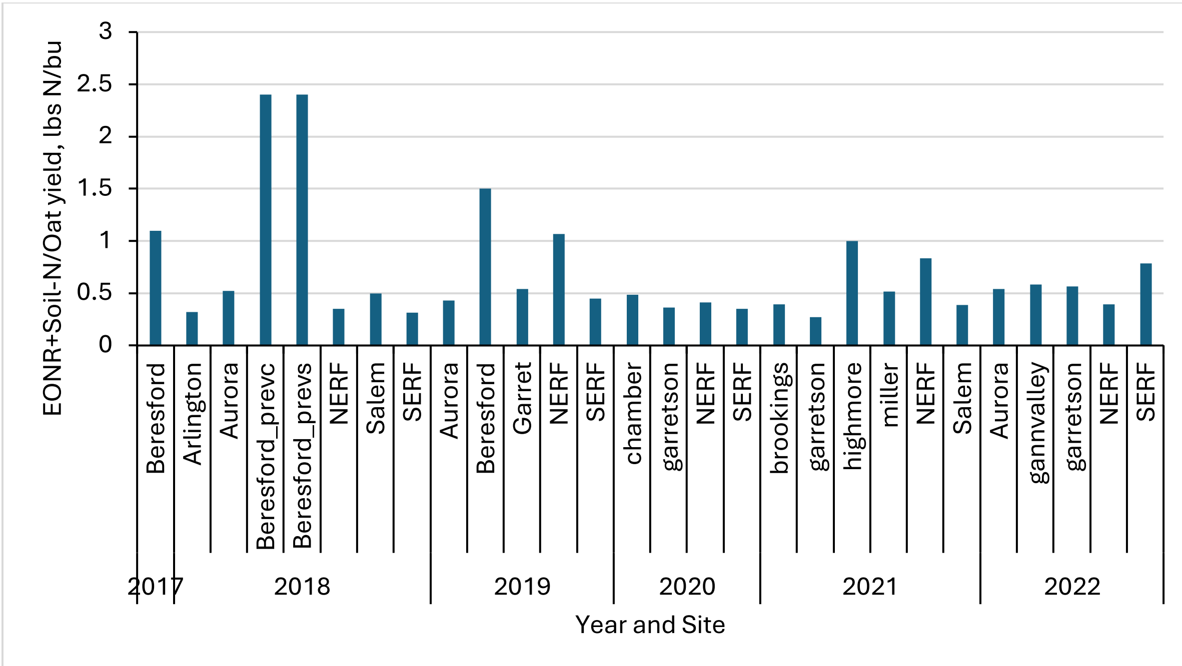

Figure 2. The amount of N fertilizer + soil nitrate-N before planting needed to produce one bushel of oats at research sites across South Dakota from 2017 to 2022.

The N fertilizer rate equation accuracy was assessed using six different multipliers (0.3, 0.5, 0.7, 0.9, 1.1, and 1.3) with the 1.3 value being the currently used multiplier. The N rate recommendation for each of the 28 locations was calculated using all six multipliers. The recommended N rate was then subtracted from the actual rate needed at each location. The closer these numbers were to 0, the more accurate the recommendation. If numbers were positive, it meant an over application of N was recommended while negative numbers meant an under application of N was recommended. Across all locations, using a multiplier of 1.3 the median accuracy was +37 lbs N/ac (Figure 3; Table 1). Reducing the multiplier led to median accuracies of +20, +3, -16, -38, and -57 lbs N/ac using a multiplier of 1.1, 0.9, 0.7, 0.5, and 0.3, respectively. These results demonstrate that reducing the multiplier from 1.3 to 0.9 improved the accuracy of the N rate recommendations the most. Reducing the multiplier from 1.3 to 0.9 improved the N rate accuracy by 34 lbs N/ac and resulted in the closest distribution around zero difference between the predicted and actual N requirements. Therefore, the multiplier (coefficient) of 0.9 instead of 1.3 provided the most accurate N fertilizer rate recommendations. Economically, the 34 lbs N/ac improvement in N rate recommendations by changing from a multiplier of 1.3 to 0.9 can save SD farmers $15/ac ($0.43/lb N).

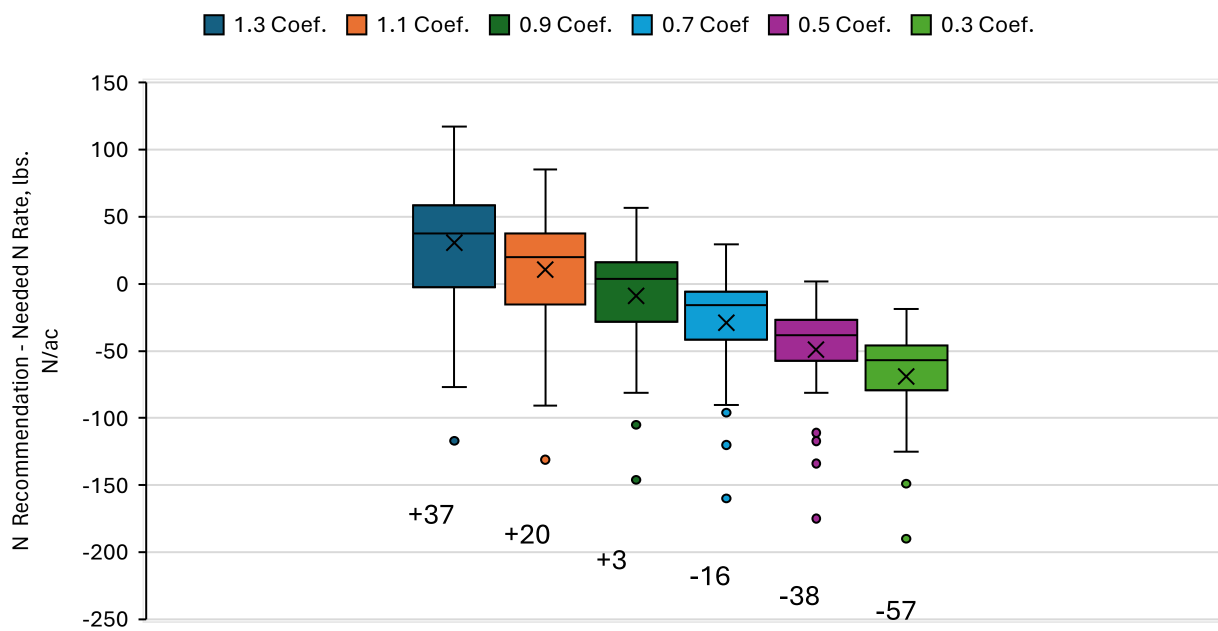

Figure 3. The accuracy of N fertilizer recommendations using six different lbs N/bu oats multipliers (1.3, 1.1, 0.9, 0.7, 0.5, and 0.3) across 28 locations from 2017 to 2022. Accuracy as shown by the Y axis is determined by taking the N recommendation calculated using each of the multipliers and subtracting it from the N fertilizer rate needed at each location. Values closest to 0 are most accurate. Values above 0 are over applications and values below 0 are under applications. The box midline represents the median, the 'x' marks the mean, the upper and lower edges of the box represent the 25^{th} to 75^{th} percentiles, the whiskers represent the range of data within 1.5 times the middle 50% of data, and points beyond the whiskers represent points beyond that.

MRTN Approach

The MRTN for the state of SD at a N price to oats price ratio of 0.12 was 54 lbs. N/ac. Using the MRTN across all locations led to a median accuracy of +48 lbs N/ac, demonstrating that using the MRTN would normally lead to over applying N fertilizer (Figure 4 and Table 1). However, subtracting soil nitrate-N in the top two feet improved the accuracy of the MRTN method. For example, subtracting 1/2 of the N led to a median accuracy of +25 lbs N/ac, subtracting 2/3 of the N had an accuracy of +17 lbs N/ac, and subtracting the full soil test value had an accuracy of +0.5 lbs N/ac. These results indicate that the MRTN approach is most accurate when subtracting soil test N (full 2 ft.) from the initial 54 lbs N/ac recommendation, demonstrating that accounting for soil test N is an important step in making recommendations for N fertilizer rates for oats.

Compared to the yield goal approach using a multiplier of 0.9, the MRTN method alone was less accurate by 45 lbs N/ac. However, once soil test N was subtracted from the initial MRTN recommendation both the yield goal approach and MRTN approaches had similar accuracy. Therefore, both methods can be used reliably when soil test N is incorporated into the recommended rate value.

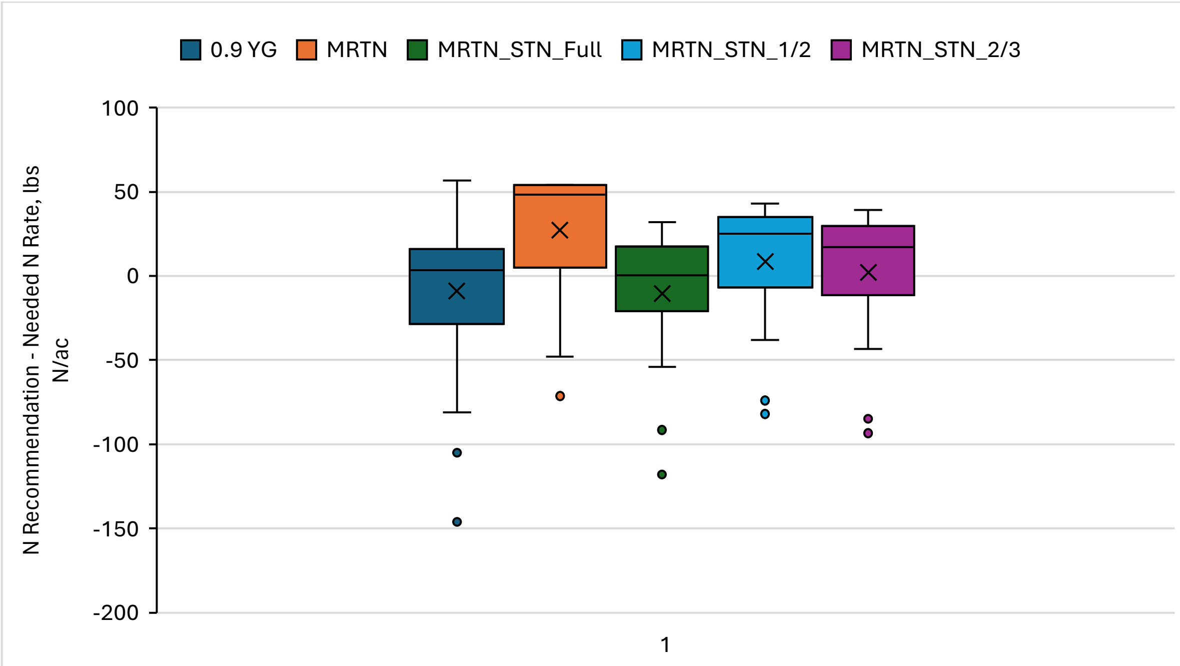

Figure 4. The accuracy of N fertilizer recommendations across all sites using yield goal approach with the 0.9 lbs N/bu oats multiplier (0.9 YG) and three maximum return to N (MRTN) methods where MRTN alone was used or the full (MRTN_STN_Full), 2/3 (MRTN_STN_2/3), or 1/2 (MRTN_STN_1/2) amount of the soil test N (2 ft. depth) was subtracted from the initial MRTN value. Accuracy as shown by the Y axis is determined by taking the N recommendation calculated using each method and subtracting it from the N fertilizer rate needed at each location. Values closest to 0 are most accurate. Values above 0 are over applications and values below 0 are under applications. The box midline represents the median, the 'x' marks the mean, the upper and lower edges of the box represent the 25th to 75th percentiles, the whiskers represent the range of data within 1.5 times the middle 50% of data, and points beyond the whiskers represent points beyond that.

Table 1. Descriptive statistics regarding the accuracy of N rate recommendations using yield goal (YG) approaches with six different lbs N/bu oats multipliers (1.3, 1.1, 0.9, 0.7, 0.5, and 0.3) and three maximum return to N (MRTN) methods where MRTN alone was used or the full (MRTN_STN_Full), 2/3 (MRTN_STN_2/3), or 1/2 (MRTN_STN_1/2) amount of the soil test N from the top 2 ft. was subtracted from the initial MRTN value.

Statistic	YG @ 1.3	YG @ 1.1	YG @ 0.9	YG @ 0.7	YG @ 0.5	YG @ 0.3	MRTN	MRTN STN Full	MRTN STN 2/3	MRTN STN 1/2
Min	-117	-131	-146	-160	-175	-190	-71	-91	-93	-81
Max	117	85	57	29	2	-25	54	30	39	43
Mean	51	40	31	34	49	69	41	-10	2	8
Median	37	20	3	-16	-39	-57	48	1	17	25
75th quartile	58	37	16	-6	-27	-45	54	18	30	35
25th quartile	-3	-16	-28	-42	-58	-79	5	-21	-11	-7

RMSE	51	40	31	34	49	69	41	27	30	32

ACKNOWLEDGEMENT

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HOW DO COVER CROPS, NITROGEN RATE, AND CROPPING SYSTEM AFFECT NITRATE LOSS IN TILE DRAINAGE WATER?

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ABSTRACT

A field research study was conducted on clay loam soil in Waseca Minnesota. The objectives were to quantify the effects and interactions of cover crops, nitrogen (N) fertilizer rates and cropping system on corn production and nitrate-N concentration and loss in tile drainage water. Cover crop treatments [cereal rye and a blend of annuals (oat, forage pea and radish)] were drilled soon after corn silage harvest each fall. Nitrogen treatments were split-applied at planting and V3 growth stage. Corn silage yields were not affected by cover crop treatments. Silage yield and quality were optimized at 180 lb N ac^{-1}. However, corn grain yields required more N, 220 or 260 lb ac^{-1}, to optimize production. Total annual tile drainage ranged from 7.3 inches in 2022 to 19.9 inches in 2024. Nearly all tile drainage occurred in spring months. Annual flow-weighted (FW) NO_3-N concentrations and losses were reduced by the cereal rye cover crop in 2 of 3 years. The reduction during those two years averaged 33%. The annual blend reduced FW NO_3-N concentrations in 1 of 3 years. Flow-weighted NO_3-N concentrations in tile water were 20% greater with 220 lb N ac^{-1} than with 180 lb N ac^{-1}, when averaged across cropping system and cover crop treatments. In 2 of 3 years FW NO_3-N concentrations were less with the corn grain cropping system than with corn silage systems. In all 3 years FW NO_3-N concentrations were numerically greatest with the corn silage no cover crop system. Nitrate-N concentrations in the control treatment, which received only 5 lb N ac^{-1} ranged from 1.9 and 3.6 mg L^{-1} among years, whereas the corn silage no cover crop treatment ranged from 10.7 to 25.8 mg L^{-1}. Seeding a cereal rye cover crop after silage harvest and applying 180 lb N ac^{-1} reduced nitrate loss in tile drainage water and optimized corn silage production in this study.

INTRODUCTION

Research has shown subsurface tile drainage systems deliver nitrate (NO_3^-) to surface waters and thereby degrade water quality (Randall and Mulla, 2001, Dinnes et al., 2002). The use of cover crops and applying appropriate rates of nitrogen (N) for corn are potential management strategies to reduce nitrate loads in tile drainage water. Research in Minnesota has shown cover crop establishment can be difficult (Strock et al., 2004), often producing minimal cover crop growth which results in less or inconsistent NO_3^- reduction in tile drainage water compared to other areas in the Midwest (Kaspar et al., 2007). Cover crop establishment after corn silage harvest in early September would allow more time for cover crop growth in the fall before soils freeze in Minnesota. Furthermore, a cover crop could protect the soil from erosion and potentially replenish carbon lost during the silage harvest which could improve soil health.

MATERIALS AND METHODS

A research experiment was initiated in 2021 on the drainage research facility at the Southern Research and Outreach Center. This facility has 36 tile drainage plots. Each plot measures 20 ft. by 30 ft. and has a separate drain outlet that is automated for flow measurement and sample collection. Eight treatments were comprised from a partial factorial combination of three management factors: corn crop system (corn for grain and corn for silage), cover crop use and N rate. Cover crop treatments included no cover crop, cereal rye with spring termination, and a blend of annuals (oat, forage pea and radish) with winter termination. Cover crops were only seeded in the corn silage system. Therefore, the four crop system treatments were corn for grain no cover crop (Gnc), corn for silage no cover crop (Snc), corn for silage with cereal rye cover (Srye) and corn for silage with annual blend cover (Sblend). Cover crop treatments were drilled soon after silage harvest at 60 lb ac^{-1} for cereal rye and 18, 8, and 1 lb ac^{-1} for oat, forage pea, and radish, respectively. Strip tillage was performed in the late fall each year with P, K and S fertilizer application in the strip. Corn was planted into the strips the following spring.

Nitrogen rates of 180 and 220 lb N ac^{-1} for continuous corn were compared across the four crop systems (Gnc, Snc, Srye and Sblend). Three additional N rate treatments were included in the corn grain system. A control, which received only 4.6 lb N ac^{-1} from starter fertilizer and 140 and 260 lb N ac^{-1}. These additional rates for corn grain production were used to determine the optimum N rate for corn each year. Nitrogen fertilizer was split-applied with 20 lb N ac^{-1} at planting and the remainder applied at V2 as urea ammonium nitrate (32-0-0) which was stream-injected between the rows.

Corn silage yields were measured from all treatments by hand harvesting, while corn grain yields from select treatments were harvested with a plot combine. Cover crop biomass yields were measured in the fall and prior to termination in spring. Treatments were arranged in split-plot design within a randomized complete block with four replications. All data were statistically analyzed using ANOVA with Proc mixed in SAS® (SAS 9.4, SAS Institute Inc., 2014. Cary, North Carolina) after examination of residuals, outliers and normality assumptions using Proc univariate in SAS.

RESULTS AND DISCUSSION

Cover Crop

Cover crop species significantly affected biomass production in 1 of 2 fall harvests (Table 1). The annual blend had 230 lb dry matter (DM) ac^{-1} while cereal rye had only 92 lb DM ac^{-1} in the fall of 2023. The lack of a difference in rye biomass from fall of 2021 to spring of 2022 was not related to poor spring growth as rye height in the spring was about 2X greater than in the fall. It was due to stand loss in wheel tracts and strip-till zones. Rye growth increased dramatically from fall of 2023 to spring of 2024. A very dry fall in 2022 limited establishment and growth, so no fall data was collected. The C:N ratio was greater with rye than blend in the fall of 2021.

Table 1. Cover crop dry matter yield and C:N ratio as affected by cover crop species.

Cover	Timing of cover crop biomass harvest					
Crop	Fall ‘21	Spring ‘22	Fall ‘22	Spring ‘23	Fall ‘23	Spring ‘24
	----------------------- Biomass yield, lb of dry matter ac^{-1} -----------------------					
Cereal rye	296	296	ND	28	92 b	676
Blend	255	ND	ND	ND	230 a	ND
	-------------------------------- C:N ratio of biomass --------------------------------					
Cereal rye	11.4 a	12.4	ND	9.8	9.6	10.4
Blend	10.2 b	ND	ND	ND	9.1	ND

ND, no data collected

Corn Grain Yield

In all three years corn grain yields increased numerically as N rate increased (Table 2). In 2023 and 2024 grain yields were statistically similar with 220 and 260 lb N ac^{-1}. A wet spring delayed planting, and was followed by a dry summer which reduced corn yields in 2023. However, weather, delayed planting and N loss likely contributed to reduced yields in 2023.

Table 2. Corn grain yields as affected by nitrogen rate.

	Corn grain yield		
Nitrogen rate	2022	2023	2024
lb ac^{-1}	-------------------- bu ac^{-1} ------------------		
4.6	60 c	48 d	84 d
140	189 b	137 c	180 c
180	194 b	150 b	204 b
220	201 b	158 ab	223 a
260	218 a	163 a	227 a

Corn Silage Yield

In all three years corn silage yields were not affected by main effect of N rate (Table 3). In 2024 silage yields were greater with silage crop systems than with the corn grain system. However, a significant interaction between crop system and N rate showed in the corn grain system, silage yields were less with 180 lb N ac^{-1}. These data show regardless of cover crops 180 lb N ac^{-1} was sufficient to optimize corn silage yield in silage crop systems. Whereas in the corn grain system, grain yields required 220 lb N ac^{-1} or more in all three years and corn silage yield required 220 lb N ac^{-1} in 1 of 3 years. Like corn grain yields, silage yields were reduced in 2023.

Table 3. Slage yields as affected by crop system, cover crops and N rates.

Crop system treatments			Silage yield		
Corn for	Cover crop	N rate	2022	2023	2024
			Tons dry matter ac^{-1}		
Grain	None	180	8.17	6.85	8.22 c†
Grain	None	220	8.45	6.73	9.13 b
Silage	None	180	9.03	7.13	9.59 ab
Silage	None	220	8.89	6.74	9.19 b
Silage	Cereal rye	180	9.11	7.29	9.84 a
Silage	Cereal rye	220	8.95	7.30	9.48 ab
Silage	Blend	180	9.09	6.92	9.25 ab
Silage	Blend	220	9.07	7.30	9.17 b
Crop system effects					
Grain, no cover			8.31	6.79	8.68 B
Silage, no cover			8.96	6.93	9.39 A
Silage, rye			9.03	7.29	9.66 A
Silage, blend			9.08	7.11	9.21 A
Nitrogen rate effects					
180 lb N ac^{-1}			8.85	7.05	9.23
220 lb N ac^{-1}			8.84	7.02	9.24
Interaction effects					
Pr. > F			0.751	0.385	0.052

† Yields followed by different letters within a column are significantly different.

Nitrate Concentration in Tile Drainage Water

When averaged across N rates in 2022, annual flow-weighted (FW) NO_3-N concentrations were greater with Snc than with Srye and Sblend (Table 4). Srye had 36% lower NO_3-N concentrations than did Snc. In 2023 annual FW NO_3-N concentrations were less with the corn grain system (Gnc) than with silage systems (Snc, Srye and Sblend). The rye cover crop was not effective at sequestering N from the soil in 2023, likely due to poor rye growth. In 2024 annual FW NO_3-N concentrations were less with the Gnc and Srye systems than with Snc and Sblend. Rye reduced NO_3-N concentration in 2024, especially during the high tile flow interval of April-June. However, rye was less effective at reducing NO_3-N concentrations later in the growing season (Figure 1). When averaged across crop systems, 220 lb N ac^{-1} had greater annual FW NO_3-N concentrations than 180 lb N ac^{-1} in all three years of the study.

Nitrate-N concentrations in the control were much less than in N fertilized treatments in 2024 (Table 1), which was like previous years (previous years not shown). The Gnc and Srye systems had similar NO_3-N concentrations in April but Srye was greater during other months. These seasonal differences could result from N being released from the cereal rye during the growing season or greater mineralization and less immobilization of N in the silage system than with the corn grain system. The Snc and Sblend systems had similar NO_3-N concentrations in April and June but Snc was greater in May while Sblend was greater in July.

Table 4. Annual nitrate-N concentrations as affected by crop systems, cover crops and N rates.

	Nitrate-N concentration		
Treatment main effects	2022	2023	2024
	------------	mg L^{-1}	-----------
Crop system effects			
Grain, no cover	8.9 ab	8.1 b	13.9 b†
Silage, no cover	10.7 a	13.0 a	25.8 a
Silage, rye	6.8 c	12.1 a	17.7 b
Silage, blend	8.5 bc	12.2 a	25.1 a
Nitrogen rate effects			
180 lb N ac^{-1}	7.8 b	10.5 b	19.0 b
220 lb N ac^{-1}	9.7 a	12.2 a	22.3 a
Interaction effects			
Pr. > F	0.485	0.608	0.541

† Yields followed by different letters within a column are significantly different.

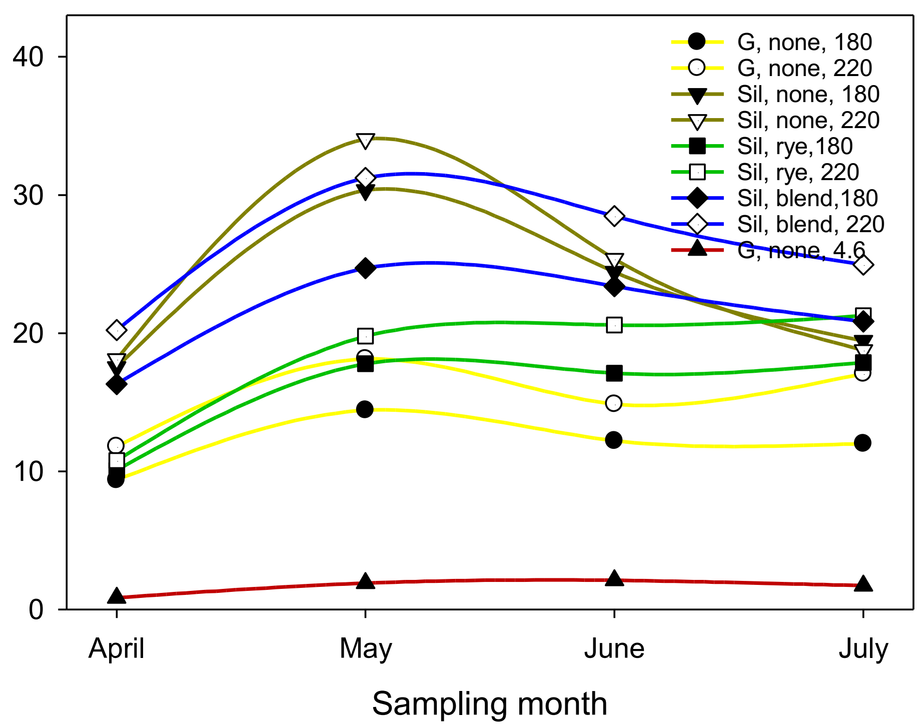

Figure 1. Effects of crop system, cover crops and N rates on monthly nitrate-N concentrations in tile drainage water in 2024.

The rapid increase in NO_3-N concentration from April to May is very interesting since most of the N fertilizer was applied at the V2 growth stage on 7 June 2024 (Figure 1). This suggests the increase in NO_3-N concentration in tile drainage water in May resulted from NO_3-N remaining in the soil from the previous year (2023 had a summer drought) or a flush of N from mineralization in May.

CONCLUSION

Greater N rates were needed to optimize corn grain yield than corn silage yield in this 3-year study. Seeding cover crops after corn silage harvest in September had no effect on corn silage yields. The corn grain and silage yield responses to N rate observed in this study may the result of cooler soils due to greater residue cover in the corn grain system which could reduce N mineralization of SOM and increase N immobilization of fertilizer and soil derived N. Nitrate concentrations in tile drainage water can be reduced in corn silage systems by applying an MRTN rate of N fertilizer (180 lb N ac^{-1}) and seeding a cereal rye cover crop after harvest. These data suggest nitrate concentrations and losses in tile drainage water may be greater in corn silage systems than in corn grain systems.

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THE MANITOBA AGRICULTURAL GREENHOUSE GAS ASSESSMENT TOOL

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Manitoba Agriculture

ABSTRACT

Manitoba Agriculture has developed an educational greenhouse gas (GHG) assessment tool that allows farmers to evaluate annual emissions from their practices and explore the impact of changing practices. Methane (CH_4) and nitrous oxide (N_2O) are potent greenhouse gases emitted by agriculture (Agriculture and Agri-Food Canada, 2025). The first phase of the GHG assessment tool provides annual estimates of N_2O and CH_4 emissions from soil and crop management practices, livestock and livestock manure. These contributions are converted to CO_2 equivalents so that their relative contributions can be compared.

Carbon dioxide (CO_2) is a GHG that is also absorbed (or sequestered) by agriculture over a long period of time (Agriculture and Agri-Food Canada, 2025). Because the GHG assessment tool provides annual estimates of N_2O and CH_4, and carbon (C) sequestration occurs on a different time scale, the GHG tool does not include C sequestration.

The annual emissions of N_2O and CH_4 generated by the tool are ballpark estimates. The calculations are based primarily on coefficients provided in Canada's National Inventory Report, which estimates GHG emissions from various activities or practices within different sectors (Environment and Climate Change Canada, 2022). Additional GHG emissions coefficients, for which there are Manitoba data, have also been included.

When using the tool, management changes should not be made based solely on the potential GHG estimates that are generated. Other important factors, such as economics, animal welfare and soil, air and water quality, should also be considered. For this paper, GHG estimates will focus on the use of synthetic nitrogen (N) fertilizer and the inclusion of enhanced efficiency fertilizers (EEFs) that are specific to Manitoba.

DATA ENTRY

The user must enter their data for:

- Crop types and yields
- Residue management
- Use of synthetic N fertilizer
- Use of manure and/or compost N
- Soil type, tillage practice and irrigation

Crop Types and Yields

This tool organizes GHG emissions by crop; therefore, when entering crop type, it is possible to create more than one entry per crop if soil type or management practice varies for a particular crop. For example, if the soil type varies, those crop acres and yields can be identified by a distinct 'description' which enables the user to make management changes more specific to the soil type.

Crop Type	Description	Crop Area (acres)	Typical Yield
Cereal - Whea	clay soil	500 Acres	65 (bu/acre)
Cereal - Whea	clay loam soil	500 Acres	70 (bu/acre)

Total: **1000 acres**

+ Add a crop

Residue Management

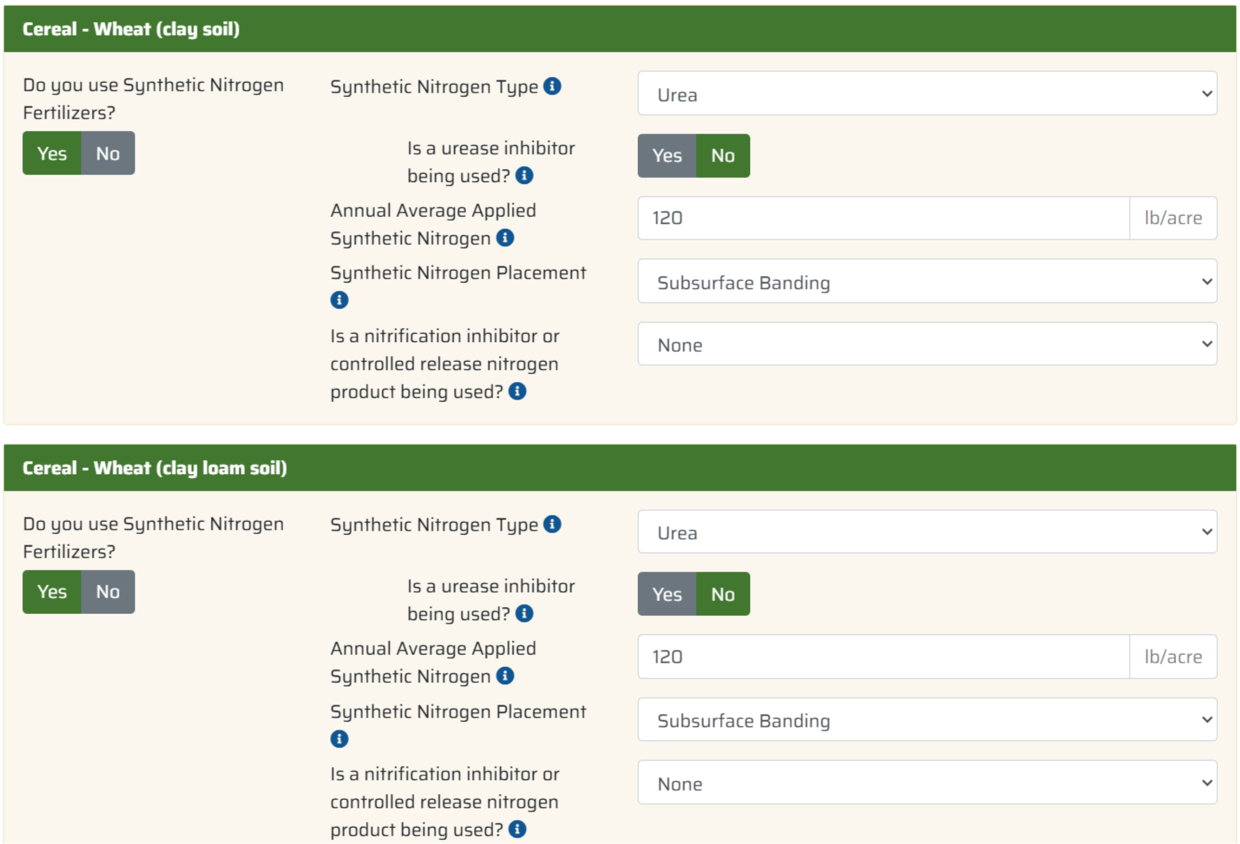
Residue management options include no removal, baling (either a straight cut or swathed crop), and burning. For this example, the wheat residue on the clay soil type has been baled and removed from the field. The residue on the clay loam soil has been left behind.

Crop Type	Description	Residue Management Type	Crop Area (acres)	Acres Under Residue Management
Cereal - Wheat	clay soil	Straight cut, drop and bale	**500 acres**	500 acres
Cereal - Wheat	clay loam soil	No removal	**500 acres**	500 acres

Synthetic Nitrogen Fertilizer

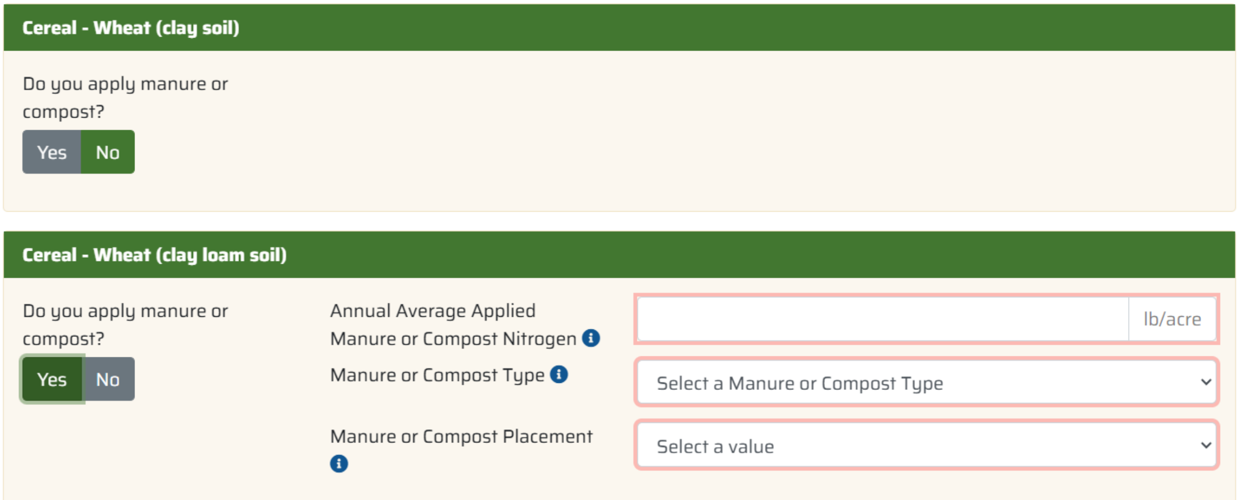
Synthetic N fertilizer options include the use of anhydrous ammonia, urea, UAN solution, or 'other'. The fertilizer rate chosen will be applied to all the acres identified under the crop type selected. If N rate for each crop type is similar, then an average rate should be entered, since this tool gives a general estimate of GHG emissions. However, if the rate of N applied varies widely, then the user may wish to go back and enter an additional crop under the ‘crop types and yields’ screen to allow for a more focused N rate to be applied at this stage.

Fertilizer placement and the use of urease inhibitors, nitrification inhibitors, or a controlled release N product (such as a polymer coated urea) are entered on this screen. For this example, no inhibitor has been used so it can be added as a practice change later in the assessment.



Manure/Compost Use

The use of manure or compost on cropped fields can offset the requirements for N fertilizer. For this example, no manure or compost has been identified.



Soil Properties and Practices

Finally, soil type, tillage practice and whether irrigation is used are entered for the different crop types. If soil type varies across farmed fields, such that different crops are grown on different soil textures, then this should be identified on the 'crop type and yields' screen (as was done for this example). It is possible to go back and adjust the crop types and descriptions at any point in the process. For this example, the tillage practices are conventional and the crops are not irrigated.

Crop Type	Description	Dominant Soil Texture	Tillage Practice	Irrigation
Cereal - Wheat	clay soil	Fine (Clay)	Conventional	No
Cereal - Wheat	clay loam soil	Medium (All loams)	Conventional	No

BASELINE EMISSIONS REPORT

Once all data has been entered, a baseline emissions report will be generated. The report is primarily based on the emissions factors identified in the National Inventory Report (Environment and Climate Change Canada, 2022) for:

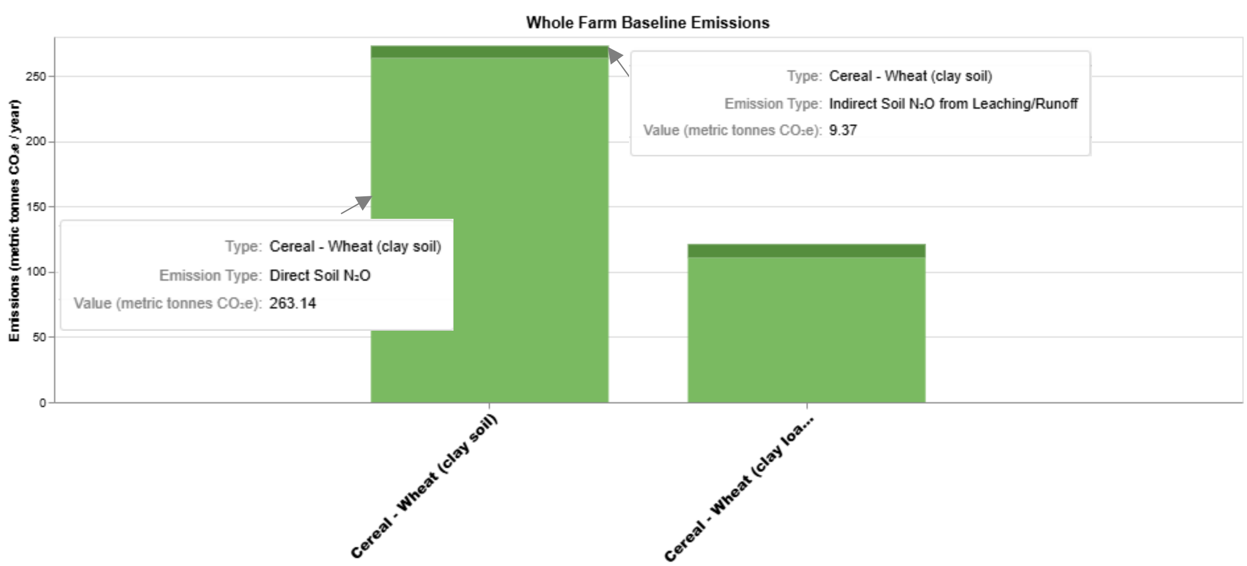
- Soil texture
- Cropping system (annual vs perennial)
- Crop type and total crop biomass
- Nitrogen source (synthetic, manure/compost, crop residue)
- Tillage (conventional vs reduced/no-till)

- Residue management (burning, baling, no removal)
- Irrigation
- Use of EEFs *(data used for nitrification inhibitors, polymer coated urea and urease inhibitors is unique to Manitoba)*

Emissions are reported in metric tonnes of CO_2 equivalent per year. They are separated into 'direct' and 'indirect' emissions:

- Direct soil N_2O – result of synthetic N fertilizer or manure/compost application, manure deposition by grazing animals, crop residue management
- Direct soil CH_4 – result of crop residue burning
- Indirect N_2O from volatilization – result of deposition and then nitrification/denitrification of volatilized ammonia-N from synthetic fertilizer or manure
- Indirect soil N_2O from leaching/runoff – result of nitrification/denitrification of N lost from field due to leaching or runoff

Emissions are displayed in a bar graph highlighting the direct and indirect emissions for all crop types identified. The data can also be viewed in a downloadable chart.

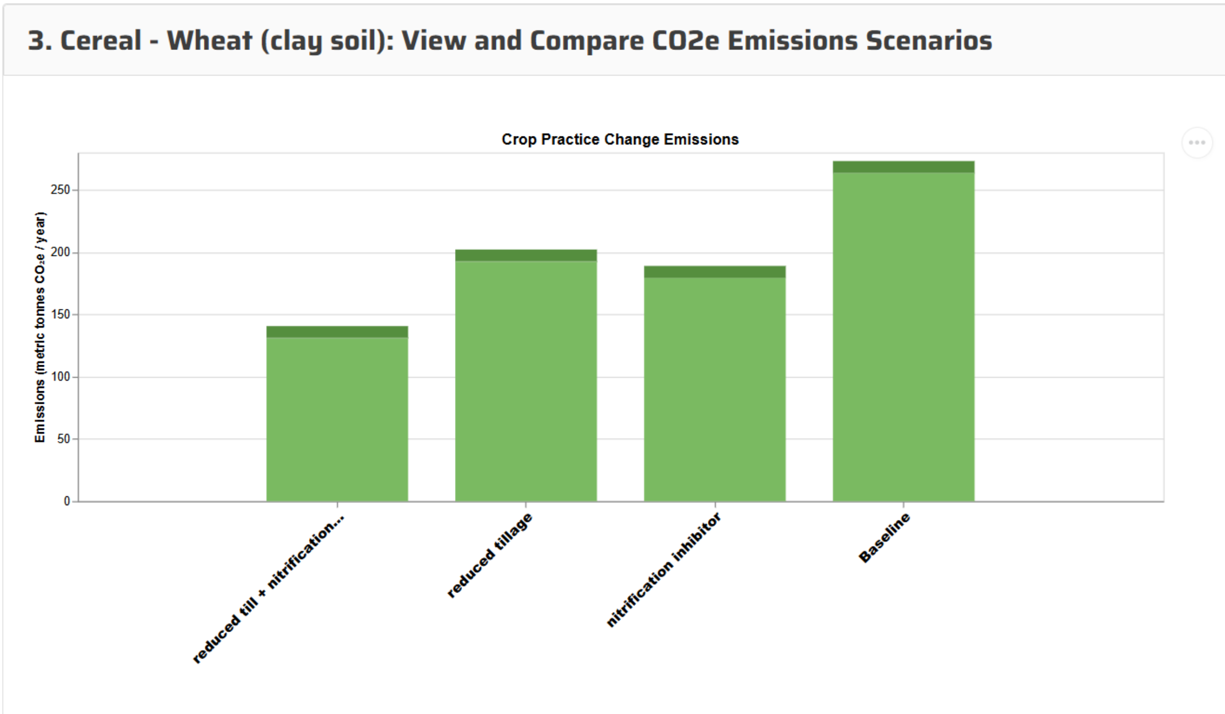


Search grid... Clear Filters

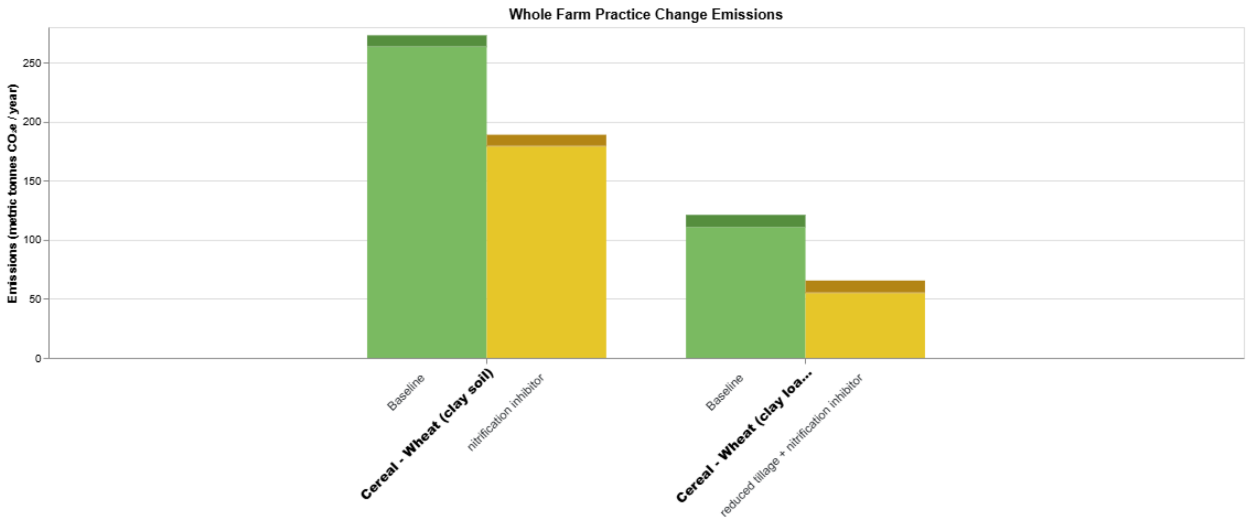
Crop Type	Description	Crop Area (acres)	Typical Yield	Yield Units	Baseline Em
Cereal - Wheat	clay soil	500	65	(bu/acre)	
Cereal - Wheat	clay loam soil	500	70	(bu/acre)	

PRACTICE CHANGE EXPLORATION

Once the baseline report has been created, practice changes can be explored for each crop type by creating practice change scenarios. Multiple practice changes can be created within a scenario or with multiple scenarios which allows the user to compare the impact of these practice changes on the potential for GHG emissions reductions.



Only one practice change scenario per crop type can be selected for the final ‘practice change report’. For this example, a combination of reduced tillage and the use of a nitrification inhibitor was chosen for the wheat grown on the clay loam soil; however, reduced tillage may not be as feasible on a heavy clay soil, so only the use of a nitrification inhibitor was chosen. Other options could be to adjust how crop residue is managed, lower the N application rate, or apply compost of manure, if possible. Users can include simple or more complex management changes when creating these scenarios to see how the resulting emissions might differ.



As with the baseline emissions report, the practice change report can also be downloaded in a CSV format:

Crop Type	Crop Description	Chosen Alternative	Crop Area (acres)	Typical Yield (bu/ac)	Baseline Emission (MT CO2e/yr)	Alternative Emission (MT CO2e/yr)
Cereal - Wheat	clay soil	nitrification inhibitor	500	65	273	189
Cereal - Wheat	clay loam soil	reduced tillage + nitrification inhibitor	500	70	121	66

SUMMARY

The GHG assessment tool has been designed for general extension and education purposes. The numbers that are generated are based on national GHG emissions factors (and Manitoba-specific emissions factors where available) but may not give an accurate reflection of the actual emissions by field or crop type on a specific farm. As a result, the tool is not intended for regulatory use. Instead, users may engage with this tool to understand the relative differences in GHG emissions between current and alternative management practices.

Currently, the GHG assessment tool includes both crop and livestock components, with the livestock module covering feeding and manure storage practices. An additional component focused on on-farm energy use is under development.

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POSTER PROCEEDINGS

ROLE OF WINTER RYE CULTIVAR AND SEEDING RATE IN MANAGING RESIDUE AND NITROGEN AVAILABILITY IN CORN CROPPING SYSTEMS

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ABSTRACT

Winter cereal rye (*Secale cereale* L.) (WCR) is the most widely used cover crop in Illinois and is recognized as one of the most effective in-field practices to reduce nitrate-N and phosphorus (P) losses to the Mississippi River Basin (MRB). However, adoption of WCR prior to corn (*Zea mays* L.) remains limited due to challenges such as stand establishment and nitrogen immobilization. Management strategies, such as selecting appropriate cultivars and optimizing seeding rates, may help mitigate these issues by improving N capture and release. Two experiments were conducted to evaluate the effects of WCR seeding rate (Study A) and cultivar × seeding rate interactions (Study B) on biomass production, tissue composition, decomposition, N release, and soil N dynamics. In Study A, a no-cover crop control and four seeding rates (30, 50, 75, and 100 lb ac^{-1}) were arranged in a randomized complete block design (RCBD) with six replicates. In Study B, two WCR cultivars (normal vs. hybrid) were factorially combined with two seeding rates (60 and 90 lb ac^{-1}) in an RCBD with four replicates. Study A showed that increasing seeding rate did not significantly affect WCR biomass, N, C, or C:N ratio, but did result in a positive linear increase in the lignin:N ratio. Decomposition rates were similar across seeding rates, but not for changes in C:N ratio over the corn growing period. Estimated N release at 30 lb ac^{-1} was greater than other rates in 2021 but not in 2022. In Study B, hybrid rye produced higher biomass than normal rye at the higher seeding rate, yet tissue composition (N, C, C:N, and lignin:N) and decomposition/N release were unaffected by treatment. Overall, our results suggest that reducing WCR seeding rates to as low as 30 lb ac^{-1} can enhance nutrient cycling benefits, lower cover crop costs, and potentially improve adoption. Moreover, N release dynamics differed between hybrid and normal rye, indicating that cultivar choice may further influence nutrient cycling outcomes. Future research should investigate low seeding rates in relation to water quality benefits.

Key words: Cover crop biomass; skipping the corn row; winter cereal rye, ecosystem services

TERRACE CONSTRUCTION EFFECTS ON SOIL FERTILITY, TEXTURE AND APPARENT ELECTRICAL CONDUCTIVITY

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ABSTRACT

The Midwestern United States is dominated by sloping terrains, where terraces are recognized as a tool to minimize soil erosion. The process of terrace construction involves heavy machinery and extensive soil profile manipulation, which may alter soil fertility and texture. This study evaluated the changes in soil fertility, texture, and apparent electrical conductivity (ECa) following the construction of eight broad-based terraces in northern Missouri. Geo-referenced soil samples were collected before and after terrace construction from three topographic positions (shoulder, backslope, and footslope) at four depths (0-15, 15-30, 30-45, and 45-60 cm). Averaged over depth and topographic positions, total exchange capacity, sulfur, magnesium, potassium, sodium, and iron significantly increased, whereas soil pH and boron decreased by 0.17 units and 45%, respectively, post-terracing. Similarly, averaged over depths, Mehlich-3 extractable nutrients were significantly higher at depositional position of the terrace compared to the shoulder position following terrace construction. A significant soil textural shift was also observed with sand and clay content increasing by 32 and 29 g kg-1, respectively, and silt decreasing by 60 g kg-1 for the whole soil profile, post terracing. About 19-36% reductions were observed in four ECa readings (ECa-H0.5, ECa-H1, ECa-V0.5, and ECa-V1) recorded with an EM38-MK2. These findings suggest that terracing substantially alters soil fertility, texture, and ECa through soil mixing and redistribution. Long-term monitoring is recommended under better management systems to determine whether these alterations persist or change further, compared to pre-terraced conditions.

FIELD CORRELATION AND CALIBRATION OF SOIL-TEST PHOSPHORUS AND POTASSIUM FOR CORN AND SOYBEAN IN ILLINOIS

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ABSTRACT

Effective phosphorus (P) and potassium (K) soil-test interpretation and fertilizer guidelines require each soil test to be field correlated with crop yield response to fertilization and calibrated to provide expected response probabilities. University of Illinois P and K guidelines require updates to reflect routinely used soil-test methods and current cropping systems. Field studies were established at eighteen sites across Illinois and Wisconsin to correlate soil-test P and K with corn and soybean response to fertilization and calibrate rate guidelines for both build and maintain and hybrid build and maintain systems. Soil P was measured using the Bray-1 (BP), Mehlich-3 colorimetric (M3P-COL), and Mehlich-3 ICP (M3P-ICP) tests. The ammonium acetate (AAK) and Mehlich-3 (M3K) tests were used to measure soil K. Soil-test P and K were analyzed as both oven-dried and field-moist using the Mehlich-3 test. Soil samples were collected from the 0 to 7-inch depth in the fall after crop harvest and spring prior to planting. Sites included sixteen soil series with silty clay loam to loamy fine sand textures, pH slightly acidic to slightly alkaline, and managed with either no-till or conventional tillage. Corn and soybean were grown each year at every site and were managed in corn-soybean rotations. Initial fall STP and STK ranged from 10 to 16 ppm M3P and 109 to 183 ppm M3K, respectively. Relationships between relative yield response and soil-test by each test and nutrient were described by fitting quadratic-plateau (QP), linear-plateau (LP), and exponential rise-to-maximum (EXP) models. Soil-test CC ranges for both corn and soybean were identified using all models that had significant fit to the data ($P \leq 0.01$). Preliminary critical concentrations for M3P in the fall and spring were 13 ppm P and 20 ppm P, respectively. Critical STK concentrations for the M3K test were 146 ppm K when sampling in the fall and 226 ppm K with spring soil samples. Results are initial phases in providing updated soil-test interpretations and rate guidelines to inform P and K fertilization decisions in Illinois.

INTRODUCTION

Phosphorus (P) and potassium (K) fertilization guidelines that support profitable crop production and avoid nutrient losses require consistent and robust soil-test recommendations. Initial steps to refine Illinois P and K guidelines include field correlation of crop yield response to fertilization and soil-tests to identify critical soil-test concentrations (CC), and calibration to rate responses. Critical soil-test concentrations for P and K are generally defined as the soil-test values or ranges below, and above which crop responses to P and K fertilization are expected or not expected. Determining an appropriate critical soil-test concentration for a specific extractant, soil–plant category, and region is a fundamental step in using soil testing to develop reliable fertilizer recommendations (Mallarino & Blackmer, 1992). Current Illinois guidelines are solely based on Bray-1 and Mehlich-3 colorimetric determination methods for P, while K interpretation for ammonium acetate and Mehlich-3 tests are used. Field and laboratory research supporting current recommendations are greater than five decades old and require reexamination. This concern is amplified by the growing economic and environmental risks confronting farmers and crop advisors in the absence of contemporary calibration data.

Recent reach in the North Central region has indicated a need to revise state-specific guidelines. In Iowa, Mallarino (2023) has continuously updated the critical soil-test concentrations and fertilizer recommendations for P and K in Iowa. These updates are justified by substantial improvements in laboratory quality, the observed variability in yield response magnitudes, and an increased recognition of the inherent uncertainty in soil-test results. In Wisconsin, Jones et al. (2022) reported updated critical soil-test concentrations for P and K in corn and soybean, along with newly developed interpretations for extraction methods other than the Bray-1 test, which had not previously been available for these crops. Kaiser et al. (2023) also updated P and K fertilizer recommendations for Minnesota's major regional crops, employing Bray-1 and Olsen soil-test methods for P and ammonium acetate for K determination.

Therefore, the objectives of this study are to: (1) develop Illinois soil-test interpretations for P and K in soybean and corn using routine soil-test P and K methods to support the forthcoming revision of the Illinois Agronomy Handbook; (2) generate calibrated P and K fertilizer rate recommendations that integrate the 4R nutrient stewardship principles and key system practices ; and (3) establish preliminary criteria for assessing farm-specific economic and agronomic risks using ROI-based metrics.

MATERIALS AND METHODS

Site Descriptions and Management

Field experiments were conducted at sixteen locations in Illinois and two locations in southern Wisconsin across multiple years from 2022 to 2025. Multiple experimental sites were established at separate trials at each location, resulting in 110 site-years of P trials and 80 site-years of K trials (254 and 341 site x year x soil-test level combinations, respectively). Trials encompassed sixteen soil series with textures ranging from silt loam and silty clay loam to loamy fine sand, with all series included representing major soils in Illinois cropland. Soil organic matter ranged from 1.8 to 5%, and soil pH varied from acidic to slightly alkaline based on samples collected from the 6-inch depth. All trials followed a randomized complete block design with either (i) a full factorial arrangement of phosphorus (0 to 150 lb P_2O_5 ac^{-1}) and potassium (0 to 180 lb K_20 ac^{-1}) fertilizer rates or (ii) included all P and K rates independently, replicated four times. Phosphorus was applied in the fall after soil samples were collected as triple super phosphate (0-46-0) at all P rates and as ammonium polyphosphate (10-34-0) at rates of 25 and 50 lb P_2O_5 ac^{-1} in the spring at planting. Potassium was applied at potassium chloride (0-0-60) in the fall. All site-years were managed at corn-soybean rotations with each crop grown every year at most sites. All but 4 sites per year were managed with conventional tillage and the remainder were no-till.

Soil samples were collected in the fall and spring (6-inch depth) and analyzed for P using the Bray-1 (BP), Mehlich-3-colorimetric (M3P-COL), and Mehlich-3-ICP (M3P-ICP) methods. Soil samples were analyzed for K using the Mehlich-3 (M3K) and Ammonium Acetate extractions (AAK). Soil pH (1:1 ratio of soil or deionized water), Sikora buffer pH, and soil organic matter (loss on ignition) were also analyzed on most soil samples. All analysis methods followed the procedures suggested by the NCERA-13 north-central region soil testing committee (Frank et al., 1998) Laboratory analysis was conducted at the University of Wisconsin-Madison Soil and Forage Analysis Laboratory and select sampled analyzed at Radicle Lab® (Radicle Agronomics-Precision Planting, AGCO Corp.), using Microflow technology, which provides chemical soil-test data through a slurry method.

Statistics and Data Analysis

Differences among treatments corresponding to the different P_2O_5 and K_2O application rates were evaluated using analysis of variance (ANOVA) at a significance level of $p \leq 0.01$, and mean separation was performed using Fisher's Least Significant Difference (LSD) test. Relative grain yield (RY) was calculated for each trial by expressing the mean yield of the unfertilized treatment (averaged across replications) as a percentage of the mean yield of the treatments that produced the statistically maximum yield. This approach to determining relative yield is referred to as the "StatMAX" method (Pearce et al., 2022).

Regression analyses were conducted to compare the amounts of P and K extracted by each soil test across all trials. Relationships between relative yield response and soil-test values for each method were evaluated using the subset of response trials. For each P and K extraction method, relationships between relative yield and soil-test concentration were examined, and ranges of critical concentrations were identified by fitting segmented polynomial models, including linear-plateau (LP), quadratic-plateau (QP), and rise-to-maximum (EXP) models based on the 95–99% RY criteria. The use of multiple models to determine a range of critical soil-test concentrations is a widely documented approach in nutrient response research (Mallarino, 2003;Clover & Mallarino, 2013). All three models were statistically significant for all soil-test methods ($P \leq 0.001$). All statistical analyses, response-curve fitting, and critical concentration determinations were performed in RStudio version 2025.05.1 (Posit Software, PBC).

RESULTS AND DISCUSSION

Soil-test P&K method comparison

Correlations between soil test P and K analyzed are presented in Figure 1. Soil-test P values measured by BP, M3P-COL, and M3P-ICP ranged from 3 to 69, 3 to 54, and 13 to 127 ppm P, respectively. The strongest relationship was observed between the BP and M3P-COL tests ($R^2 = 0.99$), with a near 1:1 ratio (slope = 0.93). This result is consistent with previous evaluations of soil P tests (Mallarino & Jones, 2018; Jones et al., 2022) and supports the use of the same soil-test interpretations for BP and M3P-COL in several north-central states. In contrast, the M3P-ICP test showed weaker relationships with both BP and M3P-COL ($R^2 = 0.60$). Previous research in Wisconsin has shown varying relationships between colorimetric and ICP determined STP for fine and coarse textured soils (Jones et al., 2022). Similarly, correlations between soil K tests showed that STK values measured by M3K and AAK ranged from 51 to 343 and from 48 to 315 ppm K, respectively. The M3K and AAK tests exhibited a strong relationship ($R^2 = 0.96$), also characterized by a near 1:1 ratio (slope = 0.97), comparable to the relationship observed between the BP and M3P-COL phosphorus tests. This relationship is consistent with other North Central states using a single interpretation guideline for both AAK and M3K extracted STK values (Mallarino et al., 2023).

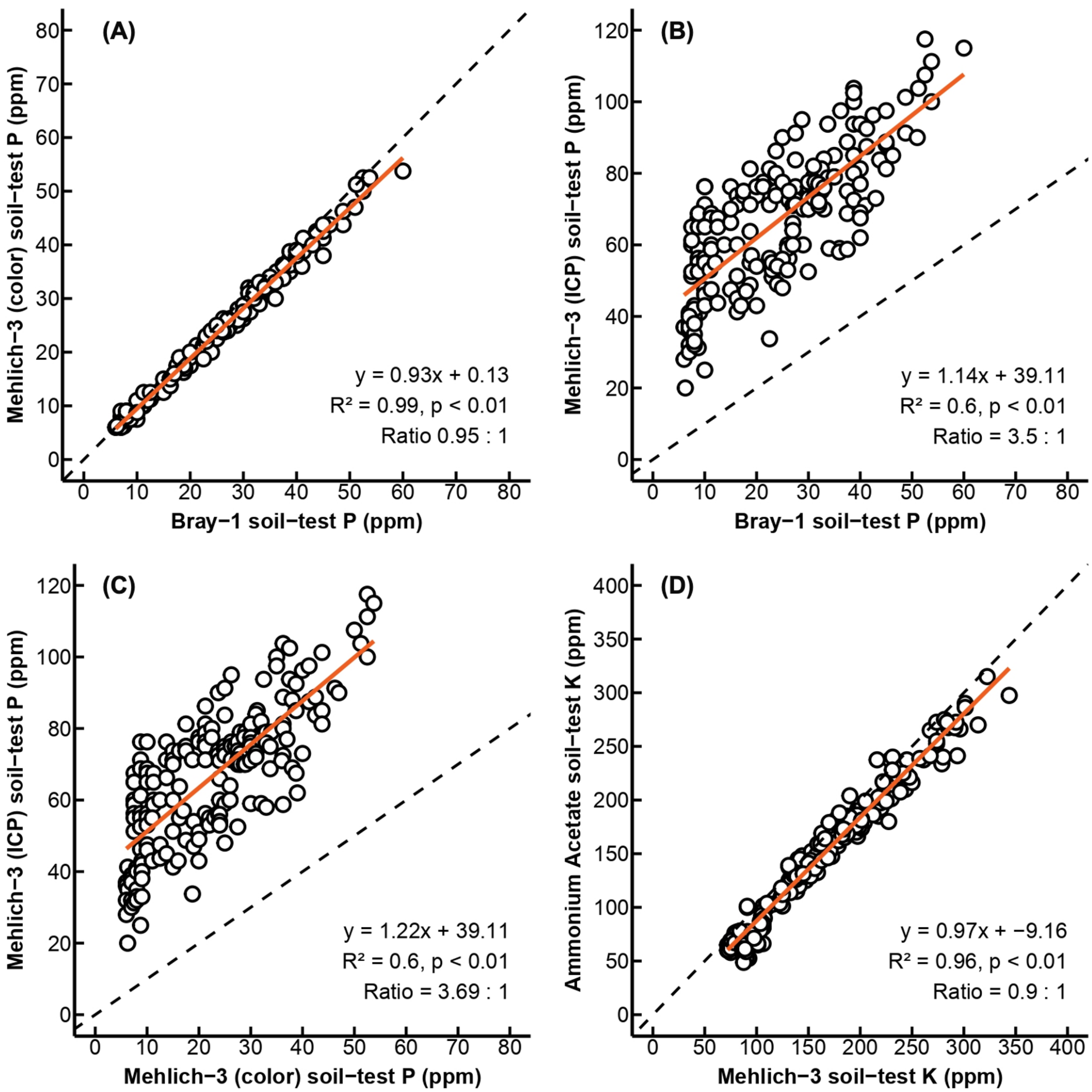

Figure 1. Correlations between the amounts of soil P (A; B; C) and K (D) extracted by the BP, M3P-COL, M3P-ICP, AAK, and M3K methods.

Another comparison among soil-test methods involved evaluating the seasonal variation of soil-test P and K values for the M3P-COL and M3K methods (Figure 2). Results showed similar patterns for both nutrients, with soil-test P and K values being higher in the spring sampling than in the fall. These findings are consistent with previous research (Breker, 2017; Murrell et al., 2021), which has documented seasonal variability in nutrient extraction associated with nutrient losses from crop residues and the influence of rainfall (Rosolem & Steiner, 2017). This pattern further reinforces the importance of standardized sampling and soil-test calibration research procedures to minimize variability when determining appropriate P and K fertilization rates.

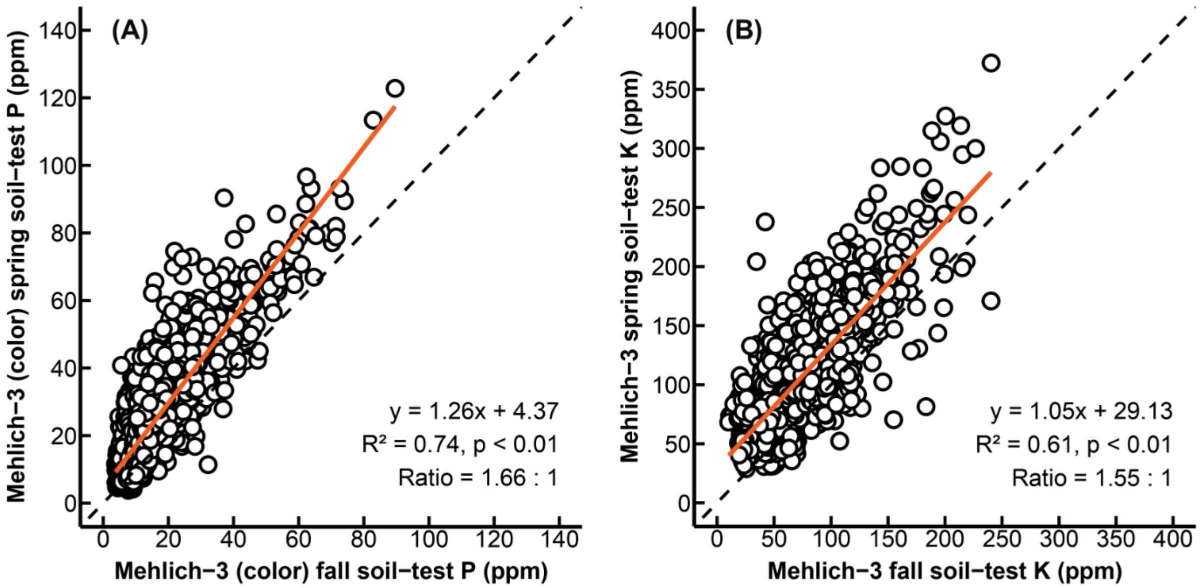

Figure 2. Correlations between the amounts of soil P (A) and K (B) extracted by the M3P-COL and M3K methods during fall and spring samplings at same field trials.

Correlation and identification of critical soil test ranges

Only field correlation of the M3P-COL and M3K tests from fall-collected samples are shared in this paper. Correlation and calibration of all aforementioned tests is being completed, however, insufficient site-years of analysis are completed to date. Figure 3 shows relationships between corn and soybean relative grain yield response to P and soil-test P measured using the M3P-COL method. Relative yield increased (e.g., the response to fertilization decreased) as soil-test P increased, although the goodness of fit varied among specific models and soil-test procedures. The M3P-COL test indicated critical concentration ranges of 10–16 ppm P, which are lower, but similar, than the P critical concentrations reported in other Midwestern states (Jones et al., 2022; Mallarino, 2023). Although the values observed in this study are broadly consistent with previous reports, continued refinement of these critical concentrations will require additional multi-site and multi-year data that reflect current high-yielding cropping systems. It is important to note that model fitting is only one of multiple criteria for critical concentration selection, and additional evaluations of probabilities of fertilizer response, and economic break-even analysis should also be considered.

Figure 4 shows the relationship between relative yield for corn and soybean and soil-test K measured using the M3K method. The critical concentration (CC) range estimated for the M3K test was 109–183 ppm K (Figure 5). In this case, the CC values were higher or similar than those reported in other Midwestern studies (Barbagelata & Mallarino, 2013;

Jones et al., 2022). Our preliminary results vary slightly from current Illinois guidelines developed by Dr. Roger Bray (Bray, 1945).

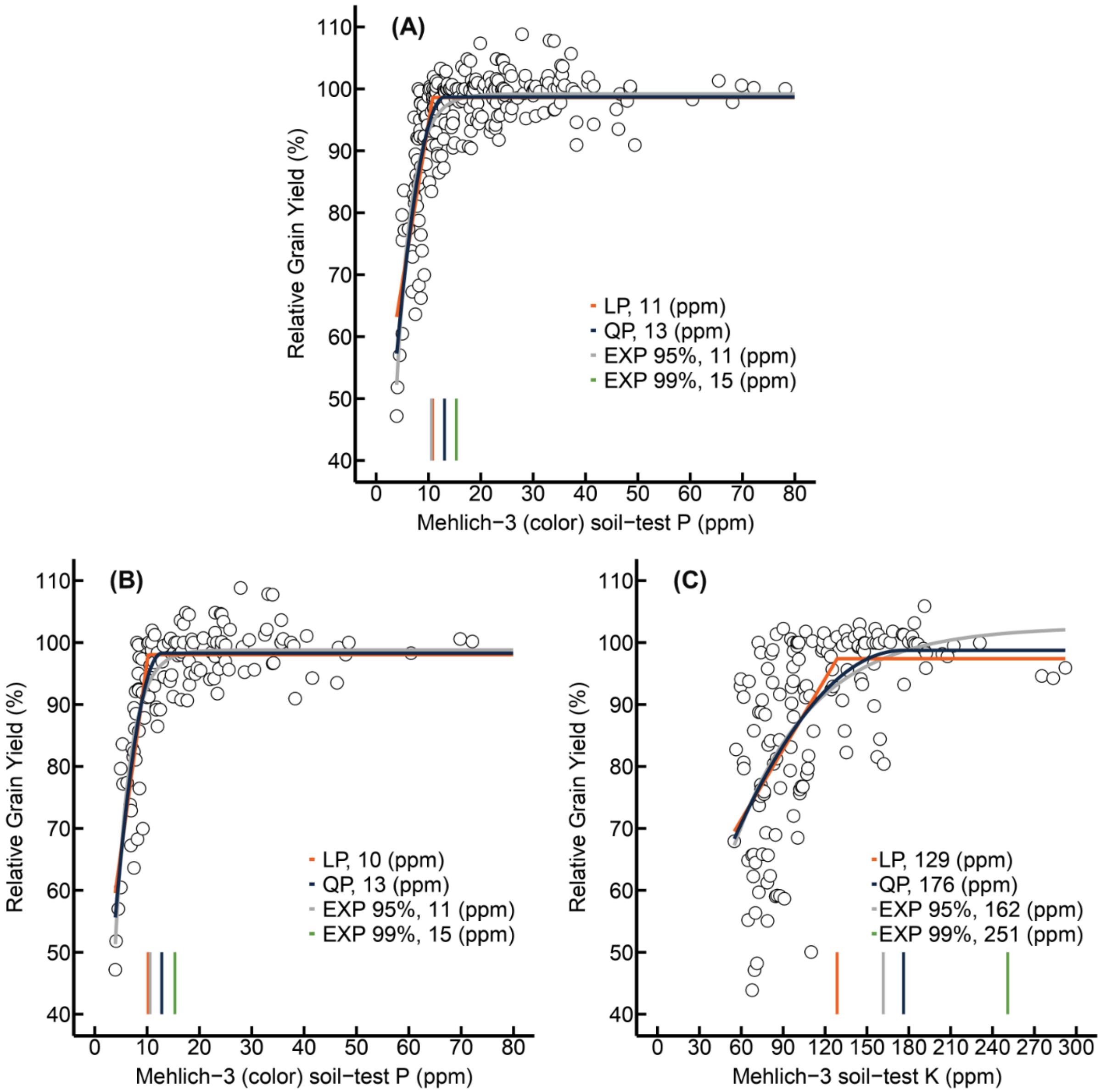

Figure 3. Relationship across all trials and years between corn and soybean (A), only corn (B) and only soybean (C) yield response to P and soil-test M3P-COL (ppm). LP, linear-plateau; QP, quadratic-plateau; EXP, exponential rise-to-maximum model at 95-99 relative grain yield (%). All models significant at $p \leq 0.01$.

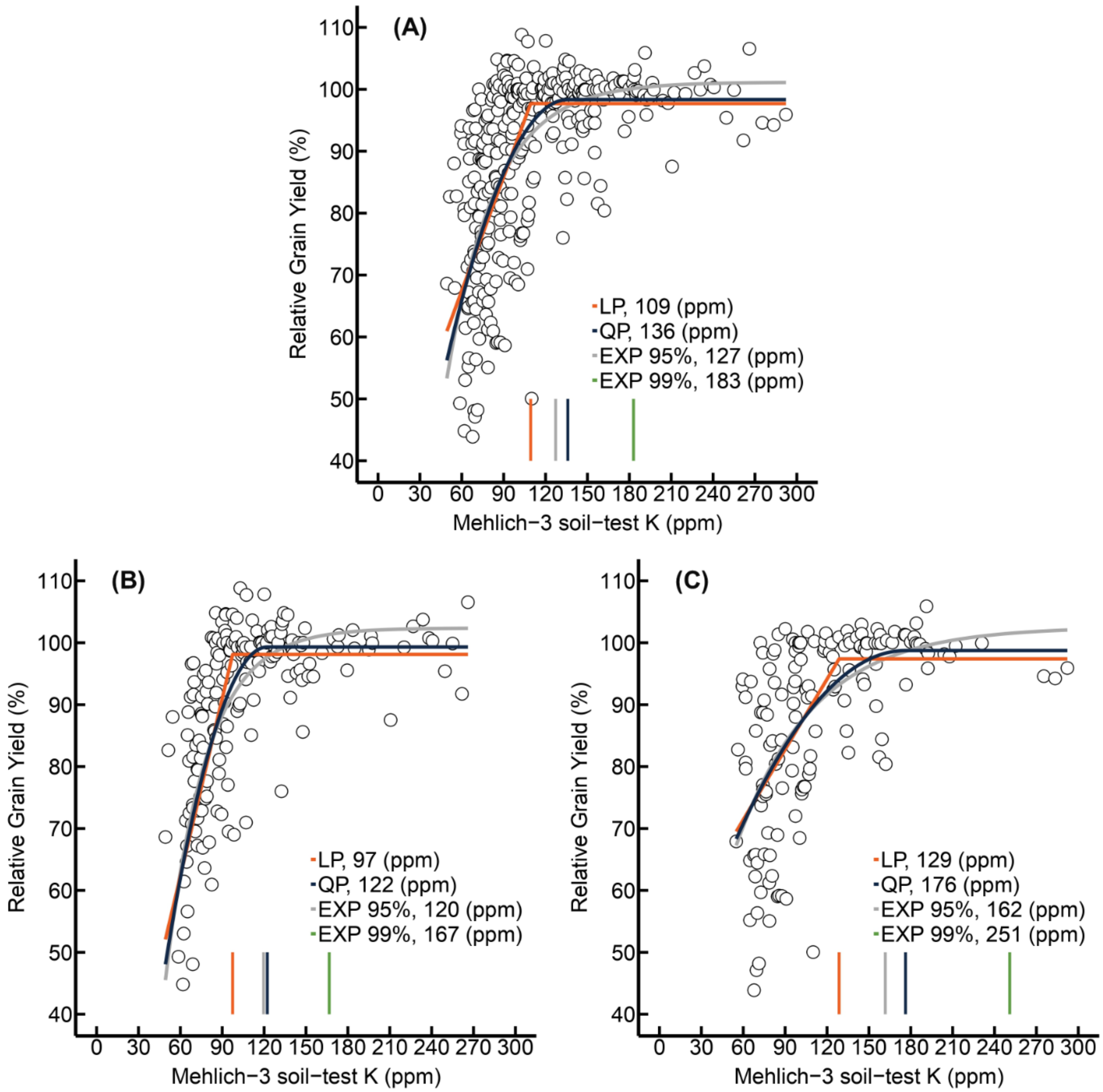

Figure 4. Relationship across all trials and years between corn and soybean (A), only corn (B) and only soybean (C) yield response to K and soil-test M3K (ppm). LP, linear-plateau; QP, quadratic-plateau; EXP, exponential rise-to-maximum model at 95-99 relative grain yield (%). All models significant at $p \leq 0.01$.

Rate response and calibration for optimum P&K rates

The phosphorus rate–response results are presented in Figure 5. For each rate–response trial, an ANOVA was conducted to classify sites as responsive or non-responsive to P fertilization. In responsive sites, the control plots averaged 9 ppm and 8 ppm of P (M3P-COL) for corn and soybean, respectively. Regression models indicated maximum yield response in corn at P application rates between 33 and 44 lb P_2O_5 ac^{-1}, whereas soybeans showed maximum response at rates between 65 and 107 lb P_2O_5 ac^{-1}. These results are consistent with those reported in other Midwestern states (Slaton, 2011; Mallarino, 2023) indicating a high probability of crop response to P fertilization in fields where soil-test P values fall below the critical concentration. The large differences between corn and soybean optimum rates may be biased to the larger corn dataset, however, clear soybean P response indicates the importance of considering soybean P demand, regardless of when P fertilization takes place in the rotation.

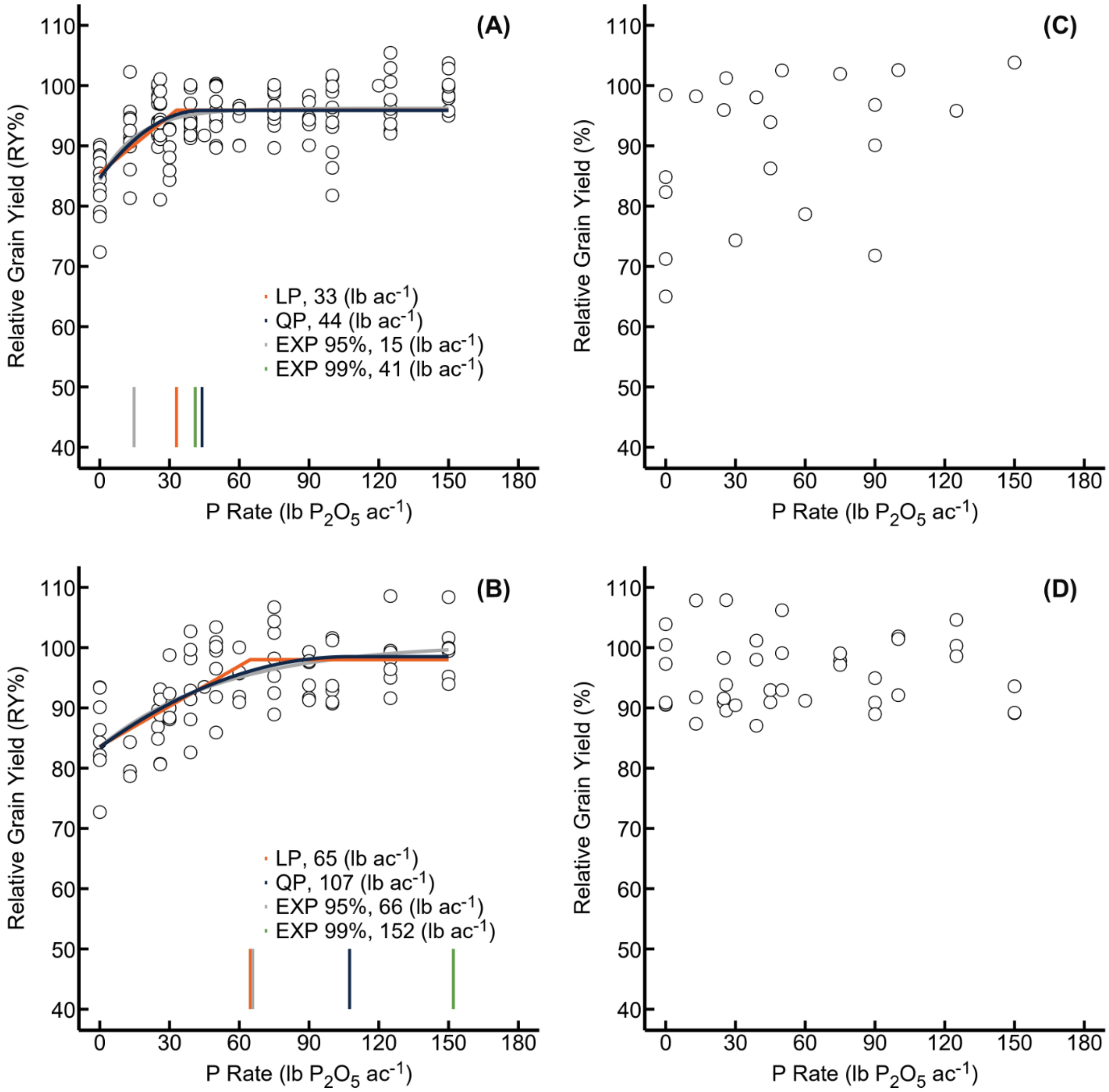

Figure 5. Relationship across all trials and years between corn (A) and soybean (B) yield response to P fertilizer and their non-responsive sites (C; D). LP, linear-plateau; QP, quadratic-plateau EXP, exponential rise-to-maximum model at 95-99 relative grain yield (%).

The same methodology was applied to the potassium rate–response results presented in Figure 6. In responsive sites, the control plots averaged 55 ppm and 47 ppm K (M3K) for corn and soybean, respectively. Regression models indicated maximum yield response in corn at application rates between 70 and 78 lb K_2O ac^{-1}, whereas soybean showed maximum response at rates between 45 and 89 lb K_2O ac^{-1}. Although a clear yield response to K fertilization was detected, the mean values of maximum response for both crops were lower than those reported in the literature for similar high-productivity field conditions. It is important to note that these optimum rates are singularly focused on yield response, and do not include a "build" component, as many state guidelines, including Illinois, do.

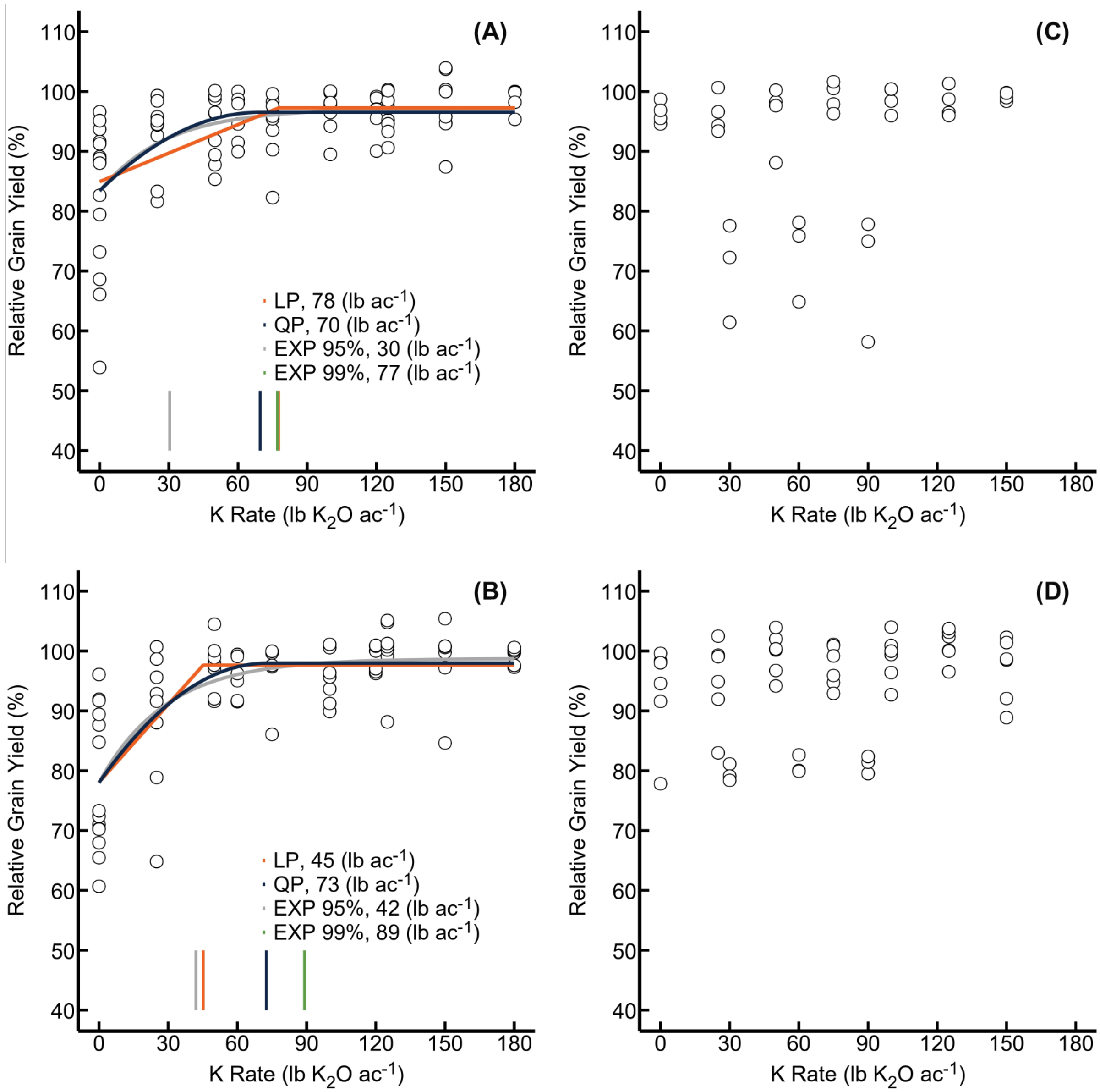

Figure 6. Relationship across all trials and years between corn (A) and soybean (B) yield response to K fertilizer and their non-responsive sites (C; D). LP, linear-plateau; QP, quadratic-plateau; EXP, rise-to-maximum model at 95-99 relative grain yield (%).

Comparison of broadcast TSP and banded APP 10-34-0

An additional analysis performed in this study evaluated the effects of fertilizer application timing, placement, and P source. Figure 7 illustrates the comparison between broadcast-applied TSP and banded ammonium polyphosphate (APP). For each treatment, an analysis of variance (ANOVA) was conducted using a significance threshold of $p < 0.01$. Although these results are preliminary, they provide evidence that may contribute to improved understanding of fertilizer management practices interaction with initial soil-test value and warrant further investigation.

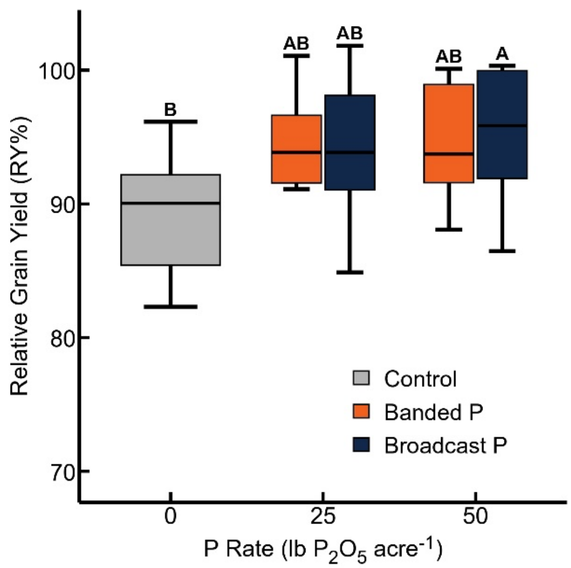

Figure 7. Comparison of broadcast and banded P applications on relative grain yield. Different letters denote significant treatment differences according to ANOVA ($p \leq 0.01$).

First, only responsive sites were included in the analysis. Across these sites, the mean STP concentration was 9 ppm (M3P-COL), indicating a very low initial soil fertility status. This condition aligns with the findings of Bordoli & Mallarino (1998) and Kaiser et al. (2025), who reported that yield responses to P fertilization, including those associated with different placement strategies and fertilizer sources, occur predominantly under very low or low STP conditions. While the cost of different phosphorus sources varies, additional research is needed to characterize the yield response across a broader range of STP levels and to better quantify the role of these fertilizer sources in both maintenance and build-up (STP construction) management strategies.

Second, starter fertilizer affected relative grain yield only when broadcast P was not applied. The greatest increase was observed at the lowest broadcast rate (25 lb P_2O_5 ac^{-1}); however, yield at this rate did not differ statistically from the other broadcast or band-applied fertilizer rates, despite a visually apparent curvilinear trend across the fertilizer gradient. Although further research across additional sites and years is needed, the results presented here indicate that under conditions of low STP and compared to small broadcast phosphorus application rates, starter fertilization could partially offset limited soil P availability.

CONCLUSIONS

This study demonstrated strong agreement among commonly used P and K soil-test extractants and identified critical concentration ranges of 10–16 ppm for M3P-COL and 109–183 ppm for M3K. These findings suggest that P thresholds are generally consistent with regional benchmarks, whereas K thresholds may exceed current Illinois guidelines and merit further validation. Yield responses to fertilization were observed primarily under low soil-test conditions, underscoring the importance of soil-test–based, site-specific decision making. Under depressed commodity price conditions, strategies that emphasize maintaining soil-test levels near the lower end of the critical ranges and prioritizing fertilization in confirmed responsive fields could be explored as potentially cost-efficient options, subject to further economic analysis. Continued multi-site, multi-year research will be necessary to refine and validate these recommendations for modern Illinois production systems.

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U.S. MIDWEST DAIRY MANURE NUTRIENT OBSERVATIONS 2012-2022

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ABSTRACT

Dairy manure is a source of organic nutrients with variable manure characteristics. This analysis drew 2012-2022 data from ManureDB, the manure and organic amendment database developed by the University of Minnesota. Thousands of solid dairy and liquid dairy manure samples across 2012-2022 were evaluated for book value comparisons, temporal trends, and regional differences for total N, NH_4-N, P_2O_5, and K_2O analytes. The only significant trend detected in the Midwest (MW) region was a decreasing trend of P_2O_5 in solid dairy manure across 2012-2022. The analyte medians for the animal manure categories were compared to the MWPS (MidWest Plan Service) and ASABE (American Society of Agricultural and Biological Engineers) analyte book values when available. Data from ManureDB suggested that total N, P_2O_5, and K_2O was lower for solid dairy manures than ASABE summaries. When comparing the region, analyte, and year combinations, we found that the MW-NE regions exhibited a significant difference of 73% for solid dairy manure and 64% for liquid dairy manure, and the MW-SE region comparison demonstrated a significant difference of 84% for solid dairy and 100% for liquid dairy manure. Regional differences appeared to influence manure nutrient composition; however, the lack of consistent labeling regarding manure storages, bedding type and inclusion, and treatments complicated the ability to draw conclusions on these regional differences. ManureDB's growing database allows for improved snapshots of U.S. dairy manure, manure nutrient benchmarking, and an updated data source for agricultural and environmental modeling.

INTRODUCTION

The University of Minnesota created a manure and organic amendment nutrient database called ManureDB to aggregate manure nutrient characteristics. By 2025, ManureDB had over 550,000 samples across 1998-2025 (Bohl Bormann et al., 2025a). The database aggregates agricultural laboratory data across the U.S. and was first released to the public in 2023 with data attributed to specific regions across the US and spanning back to 1998. With many dairies located in the MW, dairy manure is a crop nutrient source utilized on nearby fields. These manure nutrients can vary greatly depending on animal housing, water utilization, animal type and genetics, climate, and manure treatment and storage. The goal of this study was to examine if concentrations of manure total nitrogen (N), phosphorus (P_2O_5), potassium (K_2O), and total N component, ammonium-N (NH_4-N) had significant trends, regional differences, and book value differences over the years 2012-2022 for MW liquid and solid dairy manure. This updated survey of manure characteristics can assist with farmer benchmarking, agricultural and environmental modelling, and manure management planning.

MATERIALS AND METHODS

The manure nutrient data for this analysis was pulled from ManureDB in February 2024 (Bohl Bormann et al., 2025a). Specific details on the ManureDB's design, data input and cleaning, and features can be found in Bohl Bormann et al. (2025b). The dairy manure samples were divided into liquid with <10% total solids and solid with >10% total solids categories. We focused on samples from the MW, which included IA, IL, IN, MI, MN, MO, OH, and WI for this study. For the 2012-2022 period there were >16,000 solid and >43,000 liquid MW dairy samples.

Because the data is not normally distributed medians, median absolute deviations (MAD), and relative median deviations (RMD) were calculated instead of means, standard deviations, and coefficient of variations. The MAD was calculated by finding the median of a data set, subtracting the median from each value in the dataset, and then finding the median from those calculations. The RMD was calculated by dividing MAD by median and multiplying by 100. The non-parametric Mann-Kendall trend test was used using the 'MannKendall' function in R (McLeod, 2022; R Core Team, 2023) to calculate test statistics and 2-sided p-values, identifying increasing, decreasing, or no significant trends. The non-parametric Mann-Whitney U test was selected to compare regions in the same year, for those regions with at least 500 samples within the 2012-2022 timeframe (MW, Northeast (NE), and Southeast (SE)) for four analytes (total N, NH_4-N, P_2O_5, and K_2O) using the wilcox_test and P.adjust functions from the R package 'coin' ((Hothorn et al., 2023; R Core Team, 2023).

For comparison to the previously published book values, we compared ManureDB analyte medians to the similar species manure type for the ASABE (ASABE, 2005) and MWPS (Lorimor et al., 2004) nutrient mean book values. Sometimes MWPS and ASABE had several values for a species to account for different life stages or manure storages. In those cases, the range of the highest and lowest analyte values for a species was compared to the ManureDB median and a percent difference was calculated by subtracting the ManureDB median from the closest book value number divided by the closest book value number, then multiplied by 100. The data file, R code, and output are found in Bohl Bormann et al., 2024a.

RESULTS AND DISCUSSION

ManureDB and Book Value Comparisons

We found differences between ManureDB and book values, although it is difficult to discern if these are due to changes in manure concentrations or greater quantities and locations now included. (Table 1 and Figure 3). The MW liquid dairy manure medians were less than MWPS means for total N, P_2O_5, and K_2O and greater for NH_4-N. The MW solid dairy manure medians were less than MWPS means for total N and NH_4-N and less than ASABE means for total N, P_2O_5, and K_2O.

Table 1. Descriptive statistics of as-received Midwest dairy manure sample characteristics in ManureDB, for 2012 to 2022.

Liquid dairy manure (<10% total solids)							**Solid dairy manure (>10% total solids)**						
Source/ Analyte	Median	MAD[b]	RMD[c]	25%[d]	75%[e]	Count	**Source/ Analytes**	Median	MAD[b]	RMD[c]	25%[d]	75%[e]	Count
	lbs/1000 gal		**%**	lbs/1000 gal				lbs/ton		**%**	lbs/ton		
ManureDB Midwest Region[a]							**ManureDB Midwest Region[a]**						
Total N	18.2	6.6	36%	13.3	22.5	43,346	**Total N**	8.2	4.2	51	6	12.2	16,338
NH_4-N	8.3	5.0	59%	4.8	11.7	21,318	**NH_4-N**	1.6	2.1	130	0.08	3	7,500
P_2O_5	7.4	3.7	50%	4.8	9.8	43,278	**P_2O_5**	3.5	2.1	59	2.4	5.9	16,332
K_2O	17.8	5.8	33%	14.0	21.7	43,365	**K_2O**	6.7	3.8	57	4.8	11.2	16,331
MWPS[f]							**MWPS[f]**						
Total N	27-31						**Total N**	9-10					
NH_4-N	5-6						**NH_4-N**	2					
P_2O_5	14-15						**P_2O_5**	3-4					
K_2O	19-28						**K_2O**	5-7					
ASABE[g]							**ASABE[h]**						
Total N	5.8, 25					2,707	**Total N**	10.6-14					666
NH_4-N	6.7, 11.7					2,707	**NH_4-N**						
P_2O_5	3.3, 25					2,707	**P_2O_5**	6-11.4					666
K_2O	10.8, 40					2,707	**K_2O**	9.6-16					666

[a]ManureDB (Bohl Bormann et al. 2025a); [b]median absolute deviation; [c]relative median deviation; [d]25th percentile; [e]75th percentile; [f]Dairy cow, heifer, calf, and herd range of means (Lorimor et al., 2004); [g]Dairy lagoon effluent, slurry means (ASABE, 2005), [h]Dairy scraped concrete, earthen lots means (ASABE, 2005).

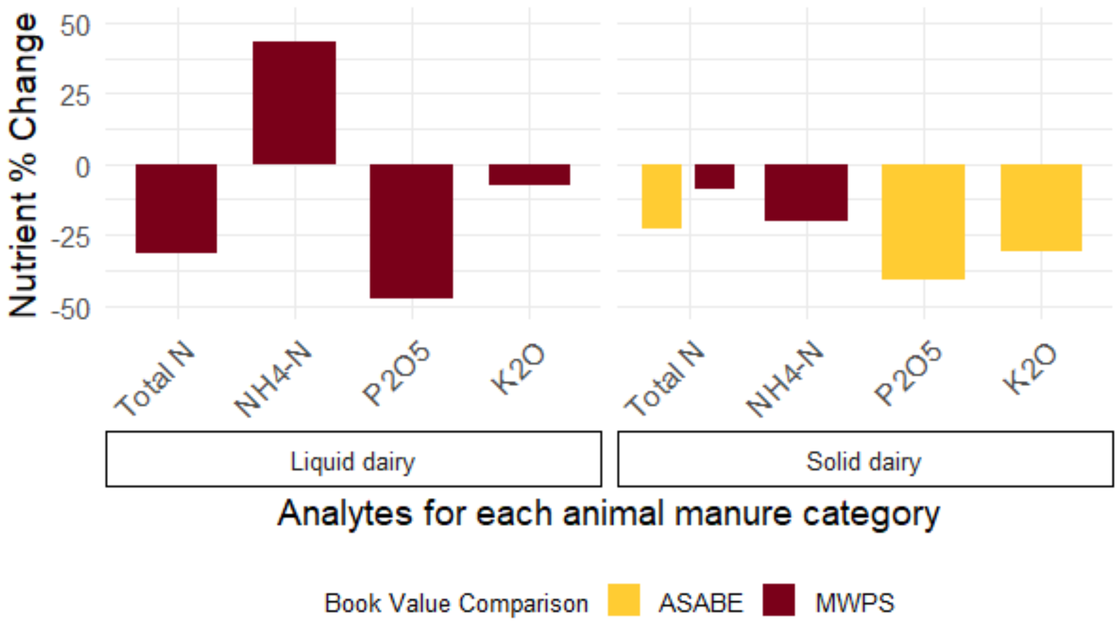

Figure 3. Percent change of manure characteristics (total N, NH_4-N, P_2O_5, and K_2O) from book values (ASABE and MWPS) for Midwest region liquid and solid dairy manure categories from 2012-2022.

Regional Nutrient Comparisons

Regional differences were noticeable in both liquid and solid dairy manure nutrient concentrations (Table 2, Figures 4 and 5) with regions significantly different for more than half of the years for all the analytes. The MW-SE comparison had more years significantly different than the MW-NE comparison for both liquid and solid dairy manure.

Table 2. The percentage of years between 2012-2022 with significant differences between regions for N, NH_4-N, P_2O_5, and K_2O comparisons. Liquid (<10% total solids) and solid (>10% total solids) dairy manures were reported separately.

	Liquid dairy manure		Solid dairy manure	
Analyte	MW-NE	MW-SE	MW-NE	MW-SE
	% of years significantly different			
Total N	64	100	64	91
NH_4-N	73	100	82	100
P_2O_5	55	100	73	100
K_2O	64	100	73	45

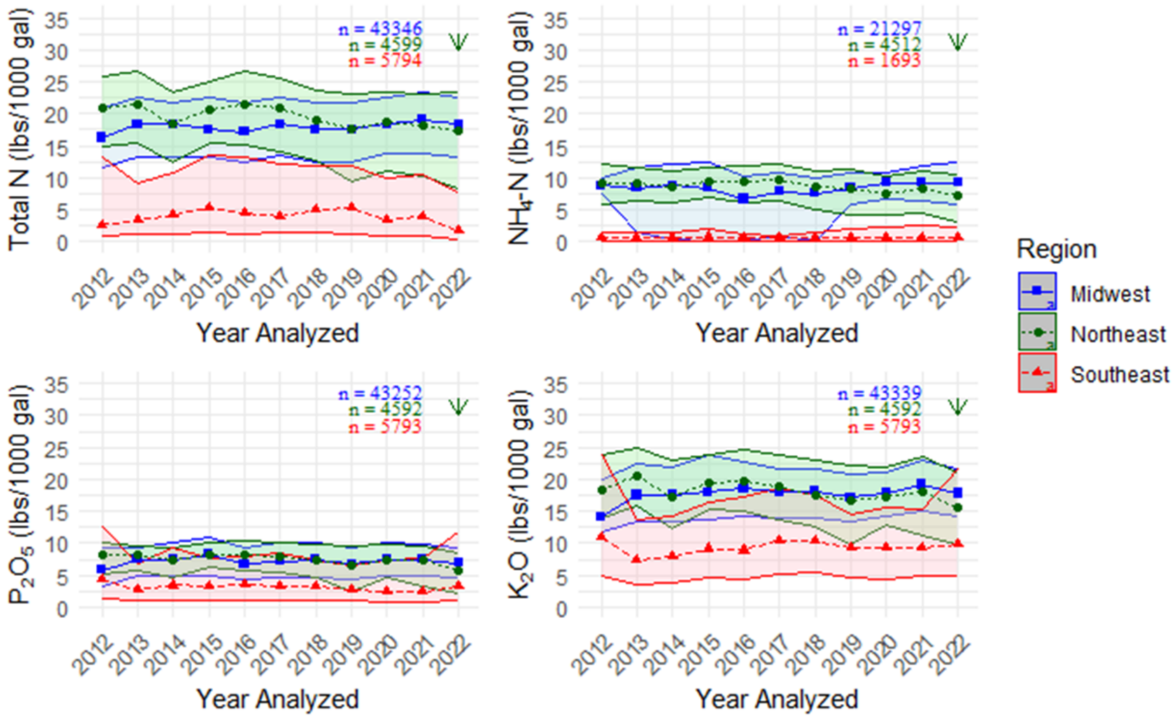

Figure 4. Liquid dairy manure total N, NH_4-N, P_2O_5, and K_2O medians from 2012-2022 for the Midwest, Northeast, and Southeast regions. Only regions with at least 500 samples and samples for each year were included in this analysis. ↓Indicates a significant decreasing trend, which was only found for the northeast region.

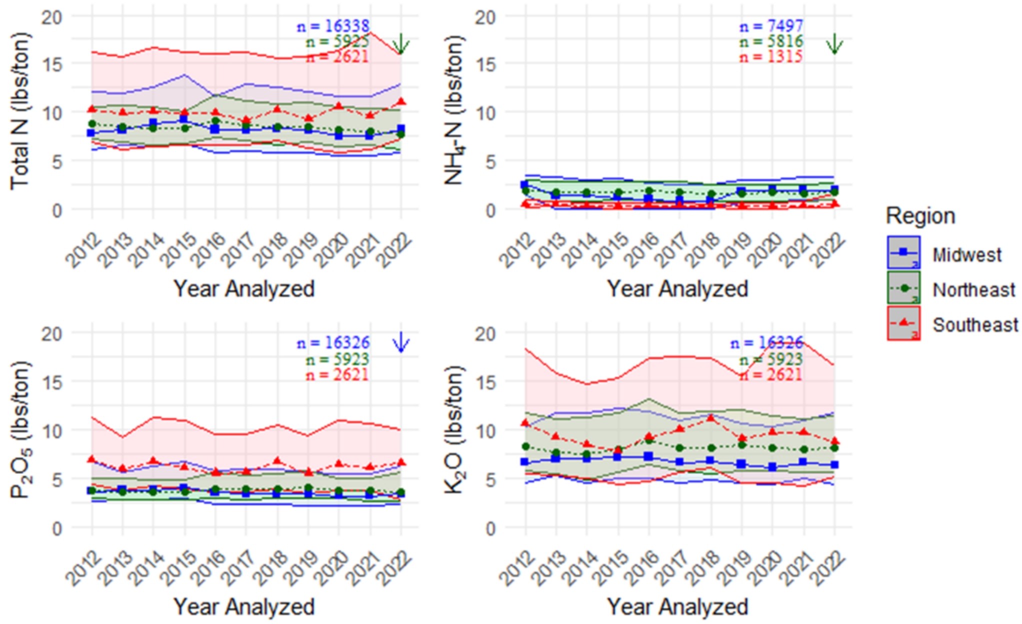

Figure 5. Solid dairy manure total N, NH4-N, P2O5, and K2O medians from 2012-2022 for the Midwest, Northeast, and Southeast regions. Only regions with at least 500 samples and samples for each year were included in this analysis. ↓Indicates a significant decreasing trend and the color of the arrow matches the color of the region.

Midwest Dairy Nutrient Trends

Solid dairy manure had the only significant MW nutrient trend with a decreasing P_2O_5 trend (Figure 5). While this trend was likely too small to impact agronomic nutrient management planning, it will be helpful to monitor as the database continues to add data annually. The MW liquid dairy manure did not have any significant trends over this period.

Future Plans

Work is underway to evaluate other manure sample metadata in addition to region such as total solids, storage type, animal type, manure type, and bedding type for updating the ASABE Manure Production and Characteristics standard ASAE D384.2. The ManureDB team will continue to incorporate new data from past and new collaborators into ManureDB, improve the website and its features, and archive data annually in the USDA National Agricultural Library's Ag Data Commons (Bohl Bormann et al. 2024b). On farm manure sampling is still strongly encouraged as manure nutrient concentrations vary greatly.

ACKNOWLEDGEMENTS

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IMPACT OF AMMONIA REDUCTION MANAGEMENT PRACTICES IN LAND APPLIED MANURE ON NITROGEN LOSSES and NITROGEN USE EFFICIENCY

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ABSTRACT

Dairy manure is a valuable nitrogen (N) source in crop production, but N losses through volatilization and leaching diminish its nutrient value and pose environmental risks. Proper manure management practices can enhance nitrogen use efficiency (NUE) and mitigate these environmental concerns. This ongoing two-year field study evaluates different manure application methods and assesses their tradeoffs regarding N leaching and NUE. The study involves six experimental treatments, each applying 94 m^3 ha^{-1} of liquid dairy manure through different methods: injection, incorporation, surface broadcast, and two treatments with urease inhibitor-one injected and one surface broadcast. Additionally, there are control plots with no manure application. Ammonia emissions are measured through a closed stainless chamber using FTIR technology and daily fluxes are calculated while cumulative N leached during the growing season is determined using resin cartridges. Preliminary results suggests that ammonia emissions tend to be lower with manure injection especially when the manure is treated with urease inhibitor compared to when manure is surface applied. In contrast, the results show that manure injection and incorporation resulted in the greatest significant NO_3^--N leaching with averages of 104 kg ha^{-1} and 108 kg ha^{-1} respectively, in comparison to surface manure application (79 kg ha^{-1}). These findings highlight how the implementation of manure application strategies to mitigate NH_3 emissions influences other N transformations, dynamics and loss pathways which is critical towards making informed agronomic decisions that optimize crop productivity while ensuring environmental conservation

INTRODUCTION

Dairy manure is a major plant nutrient source, especially nitrogen (N) in crop production, most notably in the agricultural regions of the Midwest US. Dairy cows can excrete between 50-130 kg of N annually through manure and urine (Powell et al., 2011; Nennich et al. 2006). The excreted N contains different proportions of both the organic and inorganic N fractions. Inorganic N is readily available for plant and microbial absorption and contains larger amounts of ammonium (NH_4^+-N) and ammonia (NH_3) (Aguirre-Villegas et al 2017). The organic N fraction undergoes microbial mineralization under conducive environmental conditions converting it into inorganic forms that can readily be utilized by plants (Cusick et al., 2006). Urinary N is primarily present as urea and can rapidly hydrolyze in the presence and activity of urease enzyme produced by microbes often present in the manure or even in the soil (Ketterings et al., 2005; Wyer et al., 2022; Cordero et al., 2019). This degradation process results in production of NH_3 and carbon dioxide (CO_2) emissions. The NH_3 in aqueous solution is present as both volatile NH_3 and nonvolatile NH_4^+-N (Moraes et al., 2017).

Over the past few decades, there has been a discernible rise in atmospheric NH_3 concentrations. In the United States, between 2008 to 2018, atmospheric NH_3 concentrations have increased by more than 40% and this has been attributed to both natural and anthropogenic sources such as agricultural production (Toro et al., 2024). With increasing demand for animal products, livestock production is seen as a primary driver of the rising NH_3 emissions. It accounts for approximately 60% of the national emissions while the usage of synthetic fertilizers contributes an additional 20% (Schultz et al., 2019). NH_3 and nitrous oxide (N_2O) are the major gaseous N losses from manure that are of key concern (Rotz 2004; Aguirre-Villegas et al., 2017). The loss of N from manure not only diminishes its fertilizer value affecting crop yields, but also poses a potential threat across various ecosystems in the environment.

Research indicates that N losses as emissions are typically higher during land manure applications, often falling between 30% to 53% (Aguirre-Villegas et al., 2017; Powell et al., 2011). Different manure management practices may minimize NH_3 losses to the atmosphere but may increase the risk of nitrate leaching that still poses a risk of environmental degradation. It becomes crucial to conduct research that fully addresses these tradeoffs to optimize manure nutrients to enhance nitrogen use efficiency and promote crop productivity while balancing environmental impacts.

MATERIALS AND METHODS

Experimental Design

Two years field experiments were conducted at the University of Wisconsin-Madison, Arlington Agricultural Research Station located in Columbia County, Wisconsin from 2024 and 2025. The predominant soil classification at the station is a Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls). The experiemental set-up was a randomized complete block design comprising of six treatments and four replications; manure injection at 15 cm depth (INJ), manure incorporation in less than 1-hour of application (INC), manure with urease inhibitor and then injected at 15 cm (IHB_inj), manure with urease inhibitor and then surface applied (IHB_s), manure surface broadcast (SURF), and plots with no manure application as the control (NoM). Each experiemental plot measured 9 m wide by 76 m long.

Manure was sourced from the University of Wisconsin-Madison Emmons Blaine Dairy Cattle farm located at the Research Station. Manure was uniformly applied across the plots at a target rate of 94 m^3/ha. Surface manure was applied using a splash plate on a raised Jamesway coulter injector. For incorporation, manure was surface-applied and immediately mixed to 15 cm with a chisel plow. Injection treatments used a Jamesway coulter injector with five units mounted on a toolbar, placing manure at 15 cm depth. Following manure application, corn silage was planted.

Measurement of Nitrogen Leaching and Ammonia Volatilization

Nitrogen leaching was determined cumulatively at a depth of 90 cm using ion exchange resin cartridges also referred to as Self -Integrating Accumulators (SIA) developed by the German company TerrAquat (Bischoff, 2007). Three resin catridges were buried in the soil in each experimental plot prior to manure application and these were retrieved after 6-months. The resin catridges were divided intro three layers from the top *i.e* upper layer (5 cm), mid layer (1 cm), and lower layer (4 cm). The lowest layer will be discarded as it acts as a buffer for any upward solute movement due to diffusion and capillary rise (Bischoff et al., 2007). The first layer was used to determine the accumulated N leaching flux while the second layer was utilized as an internal blank whose results were subtracted from the first layer (Bischoff et al, 2007).

The 6-month inorganic N cumulative leaching flux will be calculated as kg of N per hectare using the equation as shown below (Wey et al, 2021).

$$\text{Nitrogen flux } (kg\ N\ ha^{-1}) = \frac{C\ x\ V\ x\ M_{layer}}{M_{subsample} * A}\ x\ 10^{-2}$$

C: measured N concentration (mg N L^{-1})

V: volume of the extracting solution (0.04 L)

M_{layer}: weight of the resin-sand mixture layer (g)

$M_{subsample}$: weight of resin-sand mixture extracted (10 g)

A: area of the resin cartridge (0.0079 m^2)

Ammonia emissions were measured using an FTIR follwoung a chamber based methodology outlined in the USDA-ARS GRACEnet protocol (Parkin and Venterea, 2010). Measurements were taken immediately after manure application and in the subsequent hours; 0, 3, 24, 28, 48, 52 and 96 hours after manure application.

Soil Sampling and analysis

Soil samples were collected at depths of 0-15, 15-30, and 30-60 cm using a 2-cm soil probe from each experimental plot prior to the start of the experiment and monthly following the application of dairy manure and planting of corn silage. These soil samples were extracted using 2M KCl and were analyzed for inorganic N concentration.

PRELIMINARY RESULTS AND DISCUSSION

Cumulative ammonia emissions

Ammonia volatilization was greatest in the surface manure application reaching a cumulative average of 8.5 kg of ammonia within the 96 hours of manure application compairing all experimental treatments (Figure 1). The addition of urease inhibitor during manure surface application led to almost a 50% decrease in the ammnonia volatilization compared to surface application without urease ihnihibitor. In general, manure injection led to the lowest ammonia emissions in comparisons with all the treatments that received manure although there was no significant differences of adding urease inhibitor during manure injection.

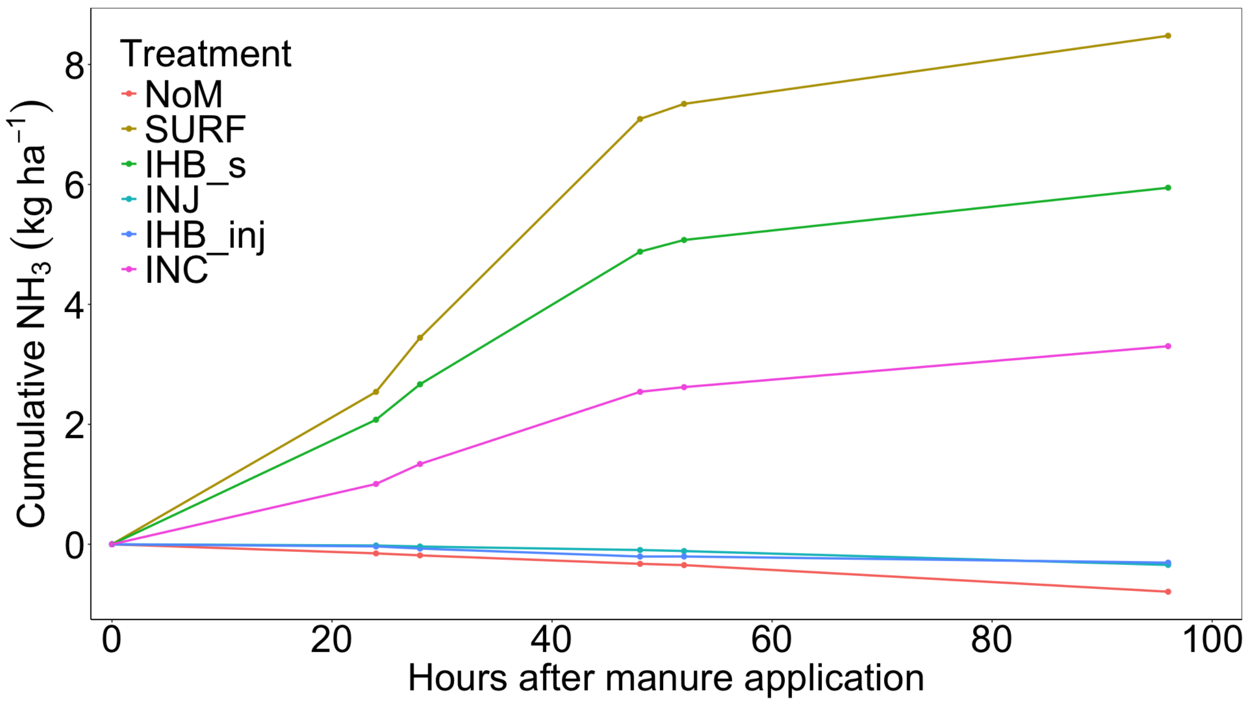

Figure 1: Mean cumulative ammonia volatilization with 96 hours of manure application

Potential Nitrogen Leached

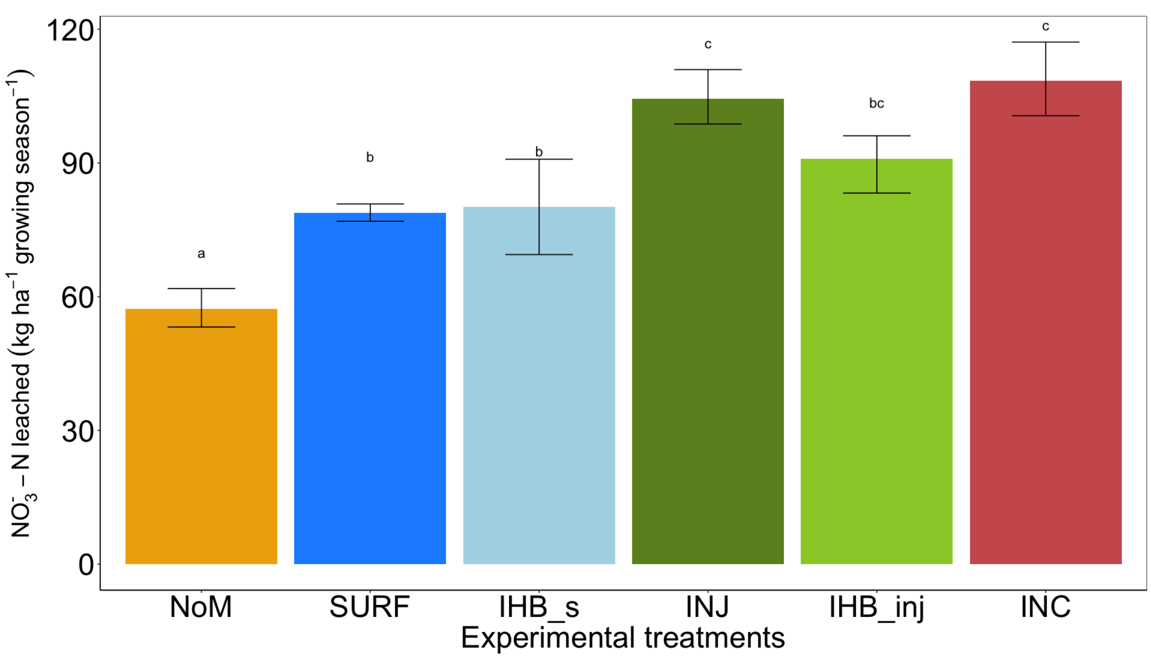

Figure 2: Cumulative N leached during 6-months following manure application

Surface manure applications with or without urease inhbitor resulted into significant decrease in nitrate leaching compared to manure incorporation and injection with or without the urease inhibitor (Figure 2). On average manure incorporation led to the greatest nitrate leaching of 108.4 kg ha^{-1} although this was not statistically different from manure injection with or without urease inhibitor. These findings suggest that treatments with greater ammonia volatilization may result in lower nitrate leaching possibly because of a reduced soil N pool, whereas those that minimize ammonia losses may be associated with greater N leaching.

Corn silage yield

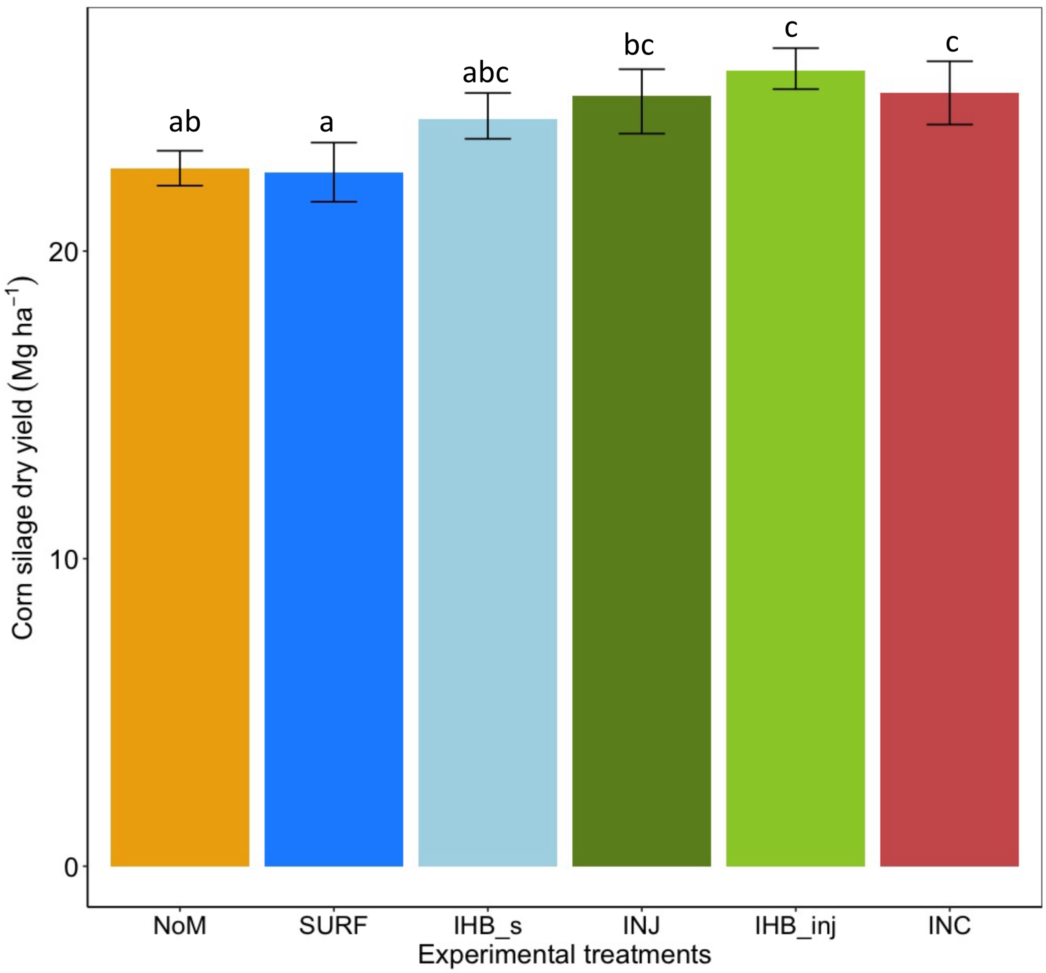

Figure 3: Average corn silage dry yield across the experiemental plots

The greatest corn silage yield (25.9 Mg Ha^{-1}) was obtained under the manure inejction with urease inhibitor although this was not statistically different from manure injection without inhibitor and manure incopration (Figure 3). Although both the manure injection and inhibitor had resulted into the greatest nitrate leaching, they still maintained a higher yield compared to the manure surface application treatment.

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EVALUATING NITROGEN AND SULFUR FERTILIZATION ON SOYBEAN YIELD FOLLOWING CEREAL RYE

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ABSTRACT

Cover crops such as cereal rye (Secale cereale L.) are widely promoted for their environmental benefits, including nutrient sequestration, reduced nitrate leaching, and soil conservation. However, their influence on subsequent soybean (Glycine max L.) yield and nutrient dynamics remains inconsistent, especially under varying nitrogen (N) and sulfur (S) fertilization regimes. Field trials were conducted during 2024 and 2025 across three sites in Central Illinois—Monmouth, Perry, and Urbana—to evaluate the effect of cereal rye and fertilization on soybean growth, tissue nutrient concentration, and yield. Treatments were arranged in a randomized complete block design with a factorial combination of two cover crop treatments: no cover (NC) and cereal rye (CR), and four fertilizer treatments: untreated control (UTC), N, S, and N+S. Cereal rye biomass and nutrient content varied across locations and years. Soybean biomass was lower following cereal rye at all three locations. Fertilization treatments containing N increased early- and mid-season N tissue concentrations, and those with S increased early- and mid-season S tissue concentrations. Reduced soybean yield following cereal rye was observed only at Urbana. Soybean yield responses to fertilizers alone depended on the location. Monmouth showed higher yields with N+S, Perry had higher yields with UTC, and Urbana showed no significant effect. Soybean yield responded positively to CR-N+S, reaching the highest levels, while in Perry and Urbana, the interaction effect was not significant. Overall, the effects of cereal rye and different fertilizer regimes on soybean yield varied across locations; however, soybean yield following CR combined with N+S was consistently similar or higher than that of NC-UTC, suggesting that using CR as a cover crop can enhance soybean production sustainability.

INTRODUCTION

The United States ranks as the second-largest soybean (Glycine max L.) producer in the world, with 113 metric tons, representing 29% of the total global production (USDA-FAS, 2024)The Midwest produces more than 80% of the soybeans in the United States, with Illinois as the leading producer with 16% of the total USA production(USDA-NASS, 2024). Illinois's predominant cropping system is a biennial corn [Zea mays (L.) Merr.] and soybean rotation. This system demands high fertilizer inputs, primarily nitrogen, which during fallow winter and spring months leads to significant N03-N leaching (Owens et al., 1995; Ruffo et al., 2004).

Among the environmental benefits of cover crops, especially cereal rye (Secale cereale L.), are nitrogen sequestration, reduction in N03 leaching, improved soil nutrient cycling, enhanced water infiltration, and soil erosion control, all of which support long-term agricultural sustainability (Ruffo et al., 2004; Wagena & Easton, 2018). Although these environmental benefits are well documented, the agronomic benefits for soybean production remain debated. Multiple studies across the Midwest region of the US have shown that cereal rye can increase (Moore et al., 2014), decrease (Eckert, 1998), or have no effect on soybean yield (De Bruin et al., 2005). These mixed results have created uncertainty among farmers and have limited the adoption of this cover crop. Furthermore, they highlight the need for more detailed research to better understand the system and develop adaptive management strategies to achieve more consistent soybean yield optimization.

Soybean yield reductions following cereal rye termination have been attributed to planter interference and incomplete termination, which can lead to stand reductions(Schipanski et al., 2014). However, the possibility that cereal rye's nutrient uptake may result in lower nitrogen (N) and sulfur (S) levels, both critical for soybean development and nodulation, has been overlooked. Many studies have investigated the impact of nitrogen fertilization at different stages of soybean growth, generally finding little to no yield increase, with results heavily influenced by environmental factors such as weather and soil types (Mourtzinis et al., 2018; Vonk et al., 2024) Similarly, research on sulfur has shown that increasing S fertilization does not consistently boost soybean yield (Fleuridor et al., 2023; Letham et al., 2021).

The limited existing literature indicates that the effects of nitrogen or sulfur on soybean yield are inconclusive and highly location-dependent. Moreover, these studies often did not consider cereal rye as a cover crop, focusing instead on the effects of either nitrogen or sulfur alone. Therefore, this research aims to: 1) evaluate the impact of cereal rye on soybean yield in Central Illinois, and 2) examine how nitrogen, sulfur, and their combination influence soybean yield following cereal rye cover crop.

MATERIALS AND METHODS

Experimental Design, Cereal Rye Cover Crop and Soybean Management.

The experiment was conducted in 2024 and 2025 across 3 site-years in Central Illinois. Field trials were established in small plots at Northwestern Illinois Agricultural Research and Demonstration Center near to Monmouth, Warren Co., in JWCC Agricultural Education Center near to Perry, Pike Co., and UIUC Crop Science & Education Center near to Urbana, Champaign Co., Predominant soils in Monmouth, Perry and Urbana were muscatune silt loam, Bluford silt loam and Flanagan silt loam, respectively, classified as moderate to poorly drained.

The experiment was arranged using randomized complete block design with 4 replications per site. Each replication had eight treatments in a 2-way factorial combination, where cover crop factor had two levels: cereal rye [CR] and no cereal rye (NC), and the fertilizer factor with four levels: unfertilized check [UTC], Nitrogen [N] (40 lbs. N ac^{-1} as Urea), Sulfur [S] (20 lbs. S ac^{-1} as pelletized Gypsum), and the combination of N and S in their respective rates [N+S]. Fertilizers were broadcasted at planting. The cereal rye cover crop was no-till drilled after corn harvest during mid to late October, with a target seeding rate of 50 lbs. ac^{-1} on 7.5-inch rows. The cereal rye termination was targeted at 12-16 inches tall or two weeks before soybean planting by spraying glyphosate (N-phosphonomethyl glycine) at 1 qt ac^{-1} rate. Soybean was no-till planted with 30-inch row spacing at 150.000 seeds ac^{-1}. For both growing seasons, Monmouth was planted in mid-May, Perry in late April, and Urbana in late May. Two rows per plot were harvested using an experimental combine. All yields were adjusted to 13% moisture.

In Season Sampling

Before termination, cereal rye aboveground biomass was sampled from a 5.4 ft^2 quadrats at four random locations in each plot. Samples were oven-dried at 140ºF , ground to pass a 1-mm screen using a Wiley mill and analyzed for nutrient concentrations by a commercial laboratory (A&L Great Lakes, Fort Wayne, Indiana). At the same moment, composite soil samples (between 8 and 12 cores at two depth) were collected from each block for the cereal rye and no cereal rye plots. For soybean, at V4 growth stage aboveground biomass was collected

During soybean growing season, Whole-plant biomass samples were collected at V4 growth stage from two 1-meter subsamples to make a composite sample per plot. Stand counts were taken at the same moment by counting 4 linear meters per plot. A composite sample of 30 most recently mature trifoliate leaves were taken at R2 growth stage. Samples were processed and analyzed for nutrient concentrations following the same procedures as cereal rye biomass.

Statistical Analysis

Data was analyzed using R software version 4.5.1. A linear mixed effects model was performed to analyze the response variables across years. Cover crop and fertilizer treatment was set as fixed effects, and year and block was included as random effects. Mean differences were calculated using Tukey's HDS test at a significant level of alpha 0.10.

RESULTS AND DISCUSSION

Cover Crop growth, N and S analysis, and baseline soil testing.

Cereal rye spring biomass and nutrient concentrations varied considerably across locations and years (Table 1). These differences across locations can be explained by the varying termination timings, with Monmouth being terminated in late April, Perry in mid-April, and Urbana in early May, in both years. The C:N ratio ranged from 14 to 30 across sites and years, with lower values in 2025 at Monmouth due to higher N concentrations, indicating potentially faster residue mineralization. In contrast, the higher ratio at Urbana in 2025 suggests early-season N immobilization and slower decomposition potential.

Table 1. Average cereal rye aboveground biomass, nitrogen (N) and sulfur (S) concentration, total N and S content, and C:N ratios for 2024 and 2025 growing seasons.

Year	Biomass	N conc	S conc.	N cont.	S cont.	C:N
	lb ac^{-1}	----------%------------		---------- lb ac^{-1}-----		ratio
			Monmouth			
2024	489	1.93	0.15	9	0.75	22
2025	827	3.14	0.23	26	1.93	14
			Perry			
2024	1158	1.64	0.14	19	1.66	26
2025	1429	1.71	0.15	25	2.10	25
			Urbana			
2024	2127	1.65	0.13	35	2.75	26
2025	1351	1.44	0.14	20	1.87	30

Table 2. Spring soil test levels at 0-6 inches depth sampling in each site. (NC = no cover; CR = cereal rye).

Year	Treatment	Depth	OM	pH	Bray-1 P	S	K
		(in)	%		lb ac^{-1}	lb ac^{-1}	lb ac^{-1}
			Monmouth				
2024	CR	6	4.22	7.2	54.5	33.6	294.5
	NC	6	4.08	7.1	50.5	41.4	300.5
2025	CR	6	3.72	6.9	53	44.8	210
	NC	6	3.8	7	58	44.8	238
			Perry				
2024	CR	6	2.2	5.6	25	34.7	209.5
	NC	6	2.22	5.3	26	41.4	223
2025	CR	6	2.6	6	20	34.7	233.5
	NC	6	2.45	6	23.5	29.1	232
			Urbana				
2024	CR	6	3.4	6.8	59	45.9	235
	NC	6	3.33	6.7	59.5	45.9	249
2025	CR	6	4.22	6.6	52.5	48.2	306
	NC	6	4.08	6.4	36	50.4	289.5

Soybean Growing Season Response to CC and Fertilizers Treatments.

Monmouth

Soybean aboveground biomass measured at the V4 growth stage showed a significant effect for the main factors, cover crop and fertilizer, but not for their interaction. Averaging across years, soybean biomass was significantly lower in plots following cereal rye (NC = 442 vs CR = 405 lb ac^{-1}, Table 3). The application of N and N+S resulted in significantly higher biomass compared to the untreated control. N concentration at early-season did not differ between treatments, nor the interaction. In contrast, sulfur fertilization was reflected in S tissue concentration early in the season, showing a significant interaction. Treatments that included sulfur in both NC (0.29%) and CR (0.31%) showed the highest S concentration compared to UTC (0.24%) and N alone (NC = 0.23%, CR = 0.20%). The N:S ratio was significant for the interaction; treatments under CC and NC with N fertilization had the highest N:S ratio due to lower sulfur concentrations.

Mid-season N concentrations showed significant differences for the main effects and their interaction. CR without fertilizer treatment had the lowest N concentration (5.42 %) compared to other treatment interactions, which ranged from 5.69% to 5.57 %. Additionally, S concentration and N:S ratio were significantly affected by the fertilizer's main effect. The S concentration in S (0.34%) and N+S (0.35%) treatments was significantly higher compared to N (0.32%) alone or UTC (0.32%), resulting in a higher N:S ratio in treatments with low S levels such as N (17.2) and UTC (16.9). This indicates that early-season trends continued through mid-season.

After two growing seasons, soybean yield was significantly affected by fertilizer and its interaction with the cover crop (Table 6). The application of N+S (73.8 bu ac-1) and N (71.8 bu ac-1) resulted in significantly higher yields compared to the UTC (67 bu ac-1). S application (70.7 bu ac-1) was not statistically different from any other treatment. Regarding the interaction, soybean yield ranged from 75 to 70.6 bu ac-1, with CR-N+S showing the highest yield response and NC-N the lowest; however, they were not statistically different, except for CR-UTC, which yielded 62.7 bu ac-1.

Table 3. Effects of cover crop, fertilizer, and their interactions on soybean nutrient concentrations, aboveground biomass, and plant population at early (V4 growth stage) and mid-season (R2) at Monmouth.

	V4 Growth Stage					R2 Growth Stage		
	N conc.	S conc.	N:S	DM Biomass	Plant Population	N conc.	S conc.	N:S
	%			lb ac^{-1}	pl ac^{-1}	%		
Cover Crop								
NC	4.10	0.26	16.0	442 a†	133393	5.68 a	0.34 a	16.6
CR	4.08	0.26	16.1	405 b	132272	5.57 b	0.33 b	16.7
Fertilizer								
N+S	4.16	0.27 b	18.4 a	446 a	128455	4.96 a	0.35 a	16.1 c
N	4.04	0.22 d	16.8 b	467 a	133600	4.75 ab	0.32 b	17.2 a
S	4.08	0.30 a	15.2 c	408 ab	133517	4.82 a	0.34 a	16.4 bc
UTC	4.08	0.24 c	13.6 d	374 b	135758	4.50 b	0.32 b	16.9 ab
CC:Fertilizer								
NC-N+S	4.17	0.26 b	15.3 cd	451	127957 a	5.69 a	0.35	16.2
NC-N	4.06	0.23 c	17.4 b	480	130446 a	5.69 a	0.34	16.9
NC-S	4.08	0.29 ab	14.2 de	448	137417 a	5.67 a	0.35	16.5
NC-UTC	4.11	0.24 c	16.9 b	391	133268 a	5.67 a	0.33	17.0
CR-N+S	4.15	0.27 b	15.1 d	441	128953 a	5.66 a	0.35	16.2
CR-N	4.03	0.20 d	19.4 a	455	136753 a	5.57 ab	0.32	17.5
CR-S	4.08	0.31 a	13.1 e	368	129616 a	5.64 a	0.35	16.4
CR-UTC	4.04	0.24 c	16.7 bc	357	138247 a	5.42 b	0.32	16.9
p-values								
CC	0.432	1.000	0.633	0.077	0.604	0.003	0.050	0.615

Fertilizer	0.138	<0.001	<0.001	0.012	0.114	0.045	< 0.001	< 0.001
CC:Fertilizer	0.889	0.002	0.002	0.657	0.100	0.090	0.300	0.536

†Treatments means within a column followed by different letters are significantly different at p < 0.1 by the Tukey's HSD test.

Perry

Soybean aboveground biomass measured at the V4 growth stage showed a significant effect only for the main factor, cover crop. Averaged across years, soybean biomass was significantly lower in plots following cereal rye (NC = 362 vs CR = 290 lb ac-1, Table 4). Additionally, plant population was significantly reduced in plots with cereal rye.

N concentration early in the season showed significant effects from cover crop and fertilizer main effects, but not from their interaction. Cereal rye reduced N concentration to 3.43% compared to plots under NC (3.55%). The application of fertilizer containing N significantly increases N tissue concentration (N+S = 3.52%, and N = 3.72%). Similarly, fertilizers containing S (S = 0.28% and N+S = 0.26%) showed higher S tissue concentrations. Likewise, the N:S ratio varies significantly among fertilizer treatments, ranging from 17.3 (N) to 11.9 (S). N application resulted in a higher N:S ratio due to the reduction in S concentration.

Mid-season N concentrations varied significantly among the main effects. Plots with cereal rye had a lower value (4.65%) compared to NC (4.90%). For the fertilizer main effect, S fertilizer resulted in a lower N tissue concentration (4.66%). Regarding S tissue concentration, plots without fertilization had the lowest concentration (0.28%).

After two growing seasons, soybean yield ranged from 71 to 62 bu ac-1 and was significantly affected by the main effect of fertilizer (Table 6). UTC showed the highest yield; however, it was not statistically different from the N+S and N fertilizer treatments, except for sulfur.

Table 4. Effects of cover crop, fertilizer and their interactions on soybean nutrient concentrations, aboveground biomass and plant population at early (V4 growth stage) and mid-season (R2) at Perry.

	V4 Growth Stage					R2 Growth Stage		
	N conc.	S conc.	N:S	DM biomass	Plant Population	N conc.	S conc.	N:S
	%			lb ac-1	pl ac-1	%		
Cover Crop								
NC	3.55 a†	0.25	14.5	362 a	128871 a	4.90 a	0.31	16.0 a
CR	3.43 b	0.25	14.0	290 b	114556 b	4.65 b	0.30	15.5 b
Fertilizer								
N+S	3.52 ab	0.27 a	13.1 bc	359	123891	4.91 a	0.32 a	15.1 b
N	3.72 a	0.21b	17.3 a	336	121734	4.82 ab	0.29 bc	16.5 a
S	3.35 b	0.28 a	11.9 c	310	120738	4.66 b	0.30 ab	15.0 b
UTC	3.38 b	0.23 b	14.6 b	300	120489	4.73 ab	0.28 c	16.4 a
Interaction								
NC-N+S	3.62	0.26	13.9	394	131940	5.02	0.32	15.5
NC-N	3.84	0.22	17.7	388	129451	4.94	0.29	17.0
NC-S	3.33	0.29	11.9	332	126630	4.78	0.31	15.3
NC-UTC	3.43	0.24	14.5	336	127459	4.89	0.30	16.6
CR-N+S	3.42	0.27	12.5	324	115842	4.81	0.32	14.9
CR-N	3.60	0.21	17.0	284	114016	4.70	0.29	16.2
CR-S	3.37	0.29	12.0	268	114846	4.54	0.31	14.9

CR-UTC	3.34	0.23	14.7	284	113518	4.58	0.28	16.4
p-values								
CC	0.042	0.958	0.340	0.001	< 0.001	< 0.001	0.251	0.060
Fertilizer	< 0.001	< 0.001	< 0.001	0.206	0.934	0.069	< 0.001	< 0.001
CC:Fertilizer	0.364	0.735	0.599	0.842	0.983	0.973	0.735	0.866

†Treatments means within a column followed by different letters are significantly different at p < 0.1 by the Tukey's HSD test.

Urbana

As with other locations, soybean aboveground biomass was significantly lower in plots following cereal rye (113 lb ac-1) than in the no cover crop (171 lb ac-1, Table 5). Additionally, this site showed a significant interaction, where NC+S (425 lb ac-1) had the highest biomass compared to CR+S (253 lb ac-1). Mid-season, the sulfur concentration and N:S responses persisted throughout the season with the same significant levels observed at V4. After two growing seasons, soybean yield was only significantly affected by the cover crop, with cereal rye producing 61.4 bu ac-1 compared to NC with 63.9 bu ac-1 (Table 6).

Table 5. Effects of cover crop, fertilizer and their interactions on soybean nutrient concentrations, aboveground biomass in early (V4 growth stage) and mid-season (R2) at Urbana.

	V4 Growth Stage				R2 Growth Stage		
	N conc.	S conc.	N:S	DM biomass	N conc.	S conc.	N:S
	%			lb/ac	%		
Cover Crop							
NC	4.09	0.29 b†	13.7 a	171 a	4.94	0.32	15.6
CR	4.02	0.30 a	13.1 b	133 b	4.87	0.32	15.4
Fertilizer							
N+S	4.09	0.3143 a	13.0 b	366 a	4.89	0.32 ab	15.2 b
N	4.05	0.2846 b	14.2 a	339 ab	4.99	0.30 b	16.4 a
S	4.01	0.3246 a	12.4 b	329 ab	4.83	0.32 a	14.8 b
UTC	4.05	0.2912 b	14.0 a	312 b	4.89	0.31 ab	15.4 b
Interaction							
NC-N+S	4.07	0.31	13.3	397 ab	4.87	0.32	15.1
NC-N	4.09	0.28	14.4	343 abc	5.07	0.31	16.6
NC-S	4.08	0.31	13.0	425 a	4.83	0.32	15.0
NC-UTC	4.11	0.29	14.4	350 abc	4.98	0.32	15.6
CR-N+S	4.10	0.32	12.9	335 bc	4.91	0.32	15.3
CR-N	4.01	0.28	14.1	315 cd	4.91	0.30	16.3
CR-S	3.95	0.33	12.0	253 d	4.84	0.33	14.7
CR-UTC	4.00	0.29	13.6	274 cd	4.80	0.32	15.4
p-values							
CC	0.108	0.098	0.012	< 0.001	0.237	0.920	0.562
Fertilizer	0.723	< 0.001	< 0.001	0.067	0.291	0.065	< 0.001
CC:Fertilizer	0.645	0.610	0.738	0.006	0.404	0.874	0.927

†Treatments means within a column followed by different letters are significantly different at p < 0.1 by the Tukey's HSD test.

Table 6. Effect of cover crop and fertilizer treatment and their interaction on soybean yield across year by location in central Illinois.

	Soybean Yield (bu ac^{-1})		
	Monmouth	Perry	Urbana
Cover Crop			
NC	71.8	68.4	63.9 a†
CR	69.8	67.3	61.4 b
Fertilizer			
N+S	73.8 a	68.8 ab	62.1
N	71.8 a	67.6 ab	63.3
S	70.7 ab	64.5 b	61.2
UTC	67.0 b	70.6 a	64.0
CC:Fertilizer			
NC-N+S	72.5 a	69.8	61.6
NC-N	70.6 a	71.0	62.7
NC-S	72.8 a	62.0	60.0
NC-UTC	71.3 a	70.9	61.4
CR-N+S	75.0 a	67.8	62.5
CR-N	70.9 a	64.1	63.9
CR-S	70.7 a	66.9	62.4
CR-UTC	62.7 b	70.4	66.6
p-values			
CC	0.132	0.500	0.085
Fertilizer	0.005	0.073	0.492
CC:Fertilizer	0.025	0.103	0.687

†Treatments means within a column followed by different letters are significantly different at $p < 0.1$ by the Tukey's HSD test.

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EVALUATING NEAR-INFRARED SPECTROSCOPY FOR PREDICTING SOIL CHEMICAL PROPERTIES IN KANSAS

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ABSTRACT

Soil testing is fundamental for accurate fertilizer recommendations and effective nutrient management. However, traditional wet chemistry methods are time-consuming, labor-intensive, and costly. Near-infrared spectroscopy (NIRS) offers a faster and more sustainable alternative by estimating soil chemical properties from light absorption and reflection between 350 and 2500 nm. This study aimed to develop Kansas-specific NIR calibration models to evaluate the applicability of this technique for predicting key soil properties, including soil pH, cation exchange capacity (CEC), soil organic carbon (SOC), nitrate (NO_3), phosphorus (P), and potassium (K). A total of 950 soil samples were analyzed at the Kansas State Soil Testing Laboratory using standard wet chemistry methods and scanned with a FOSS DS3 spectrometer. Laboratory analyses served as reference values, and spectral data were used as predictors in the calibration models. Spectra were preprocessed to reduce noise and scattering effects. Seventy percent (70%) of samples were used for calibration and thirty percent (30%) for validation. Calibration models were developed using multivariate techniques, primarily partial least squares regression (PLSR). Results showed strong predictive performance for pH (R^2 = 0.88; RMSEP = 0.32) and SOC (R^2 = 0.88; RMSEP = 0.59), but weak prediction for CEC, P, K, and NO_3^-. Out-of-sample evaluation with 115 independent Kansas soils confirmed consistent performance for pH, moderate transferability for SOC, and poor prediction for P. Overall, results indicate that while NIRS effectively captures organic and water-related signals, it fails to reliably predict inorganic nutrients. Despite its appeal as a rapid and chemical-free method, NIRS currently lacks the reliability required to replace conventional soil testing for routine fertilizer recommendation.

INTRODUCTION

Near-infrared spectroscopy (NIRS) has emerged as a potential alternative to conventional wet-chemistry analysis for several soil chemical properties (Li et al., 2025). Its main advantages include rapid analysis, low operational cost, and the ability to measure samples without chemical reagents. However, accurate prediction requires well-developed calibration models (Gozukara et al., 2025).

Modern applications such as precision agriculture and soil carbon monitoring rely on large numbers of soil analyses. For example, grid-based soil sampling is used to generate high-resolution soil fertility maps, and repeated sampling is required to detect changes in soil organic carbon stocks for carbon crediting programs (Hutengs et al., 2019). These applications demand analytical methods that are fast, cost-effective, and scalable, making NIRS an attractive option.

The objective of this study was to develop Kansas-specific NIR calibration models for predicting soil chemical properties using a FOSS DS3 spectrometer and to evaluate their potential for operational soil testing.

MATERIALS AND METHODS

A total of 950 soil samples were obtained from the Kansas State Soil Testing Laboratory, representing a wide range of soil types and chemical characteristics. Samples were air-dried at 35 to 40 °C, ground, and passed through a 2-mm sieve. Standard laboratory analyses were conducted for pH (1:1 soil–water), cation exchange capacity (CEC, summation method), soil organic carbon (SOC, loss on ignition), nitrate (NO_3^-, KCl extraction), phosphorus (P, Mehlich-3 extraction), and potassium (K, ammonium acetate extraction).

All samples were scanned using a FOSS DS3 NIR spectrometer to obtain raw spectra. Spectral preprocessing was applied to reduce noise, correct light-scattering effects, and improve signal quality. Standard normal variate (SNV) was used because it normalizes each spectrum by its mean and standard deviation, thereby minimizing multiplicative scattering effects.

Calibrations were developed using partial least squares regression (PLSR). PLSR projects the spectral matrix into a set of latent variables that are uncorrelated and capture most of the variance in the original spectra. This approach effectively addresses multicollinearity and is widely used for NIRS applications.

Samples were divided into training and testing sets using the Venetian blinds procedure. In this method, samples are indexed in block and each block is iteratively used as a validation segment while the remaining blocks form the training set. Final model evaluation used approximately 70 percent of samples for calibration and 30 percent for internal testing.

Model performance was assessed by comparing predicted and measured values in the testing set. Evaluation metrics included the coefficient of determination (R^2), root mean square error of prediction (RMSEP), slope, and bias. An additional out-of-sample evaluation was conducted using 115 independent soil samples with reference values available for pH, SOC, and P.

RESULTS AND DISCUSSION

Cross-validation showed that only soil pH and SOC were predicted with acceptable accuracy. Soil pH achieved an R^2 of 0.88 with an RMSE of 0.32 pH units, and SOC reached an R^2 of 0.88 with an RMSE of 0.59 percent. Other soil properties showed much lower predictive value despite some appearing to have moderate correlations. CEC had an R^2 of 0.58 (RMSE 3.21 cmolc kg^{-1}), NO_3^- had an R^2 of 0.27 (RMSE 16.37 ppm), and Mehlich-3 P had an R^2 of 0.62 but a large RMSE of 53 ppm. Potassium (K) showed a high R^2 of 0.86; however, the large RMSE of 99 ppm indicates that the model lacked useful precision for practical interpretation.

Out-of-sample evaluation using 115 independent soil samples confirmed these trends. Soil pH maintained similar accuracy (R^2 0.82; RMSE 0.32), whereas SOC showed reduced performance (R^2 0.58; RMSE 0.59). Mehlich-3 P remained non-predictive in the external dataset. The low bias observed for SOC suggests that including a wider range of SOC values in the external set may further improve transferability.

Overall, these results indicate that reliable predictions were obtained only for soil pH and partially for SOC. The mineral components measured through wet chemistry cannot be effectively replaced by NIRS because the spectral range used does not interact with the chemical bonds characteristic of inorganic ions, which limits predictive capacity. Although NIRS is rapid and cost-efficient, its applicability for soil testing remains restricted to a small subset of soil properties.

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FIGURES

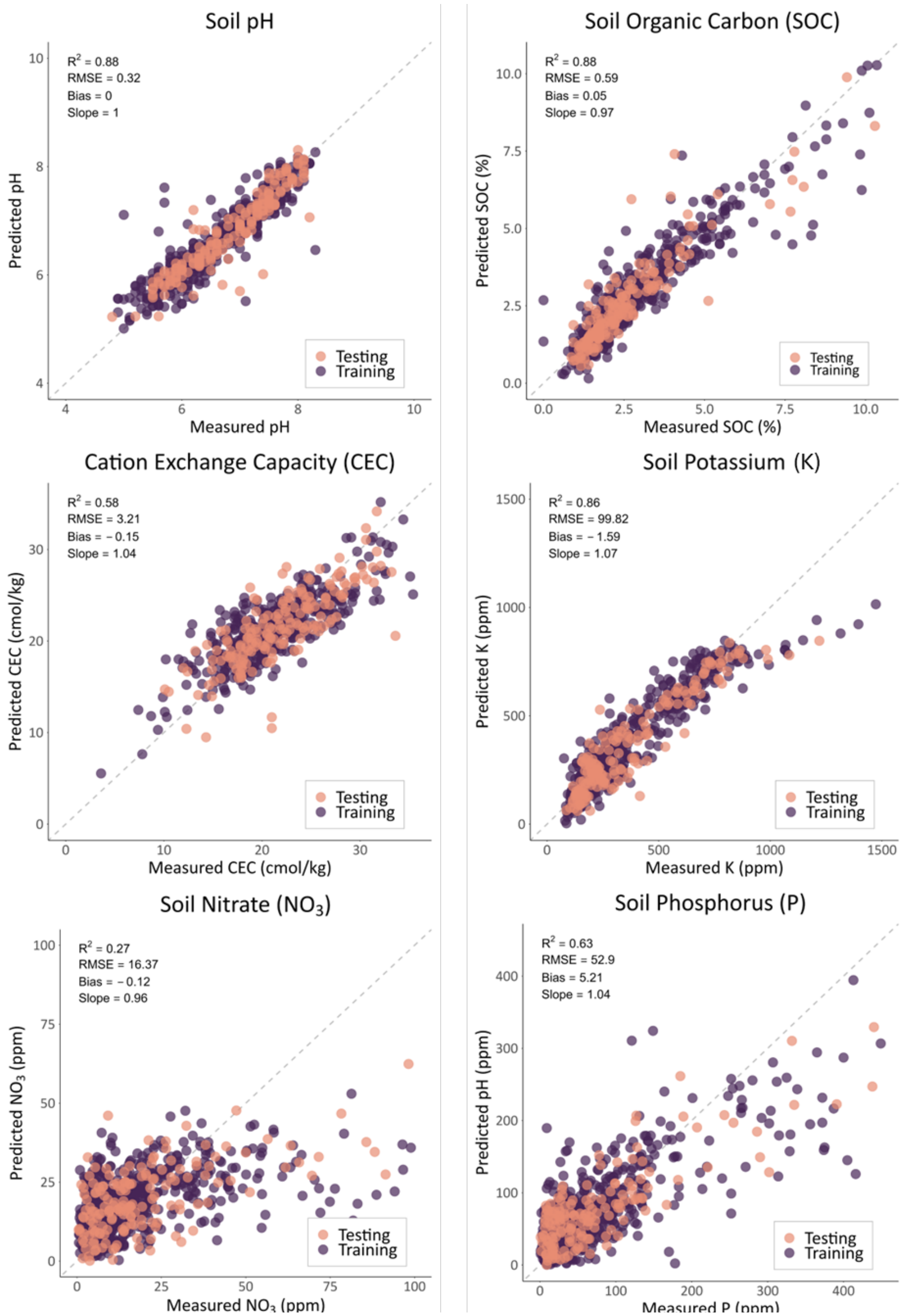

Figure 1. Cross-validation results for PLSR models predicting soil pH, SOC, CEC, K, NO_3^-, and P using NIR spectra. Points represent measured versus predicted values for training and testing subsets, with corresponding R^2, RMSE, bias, and slope statistics.

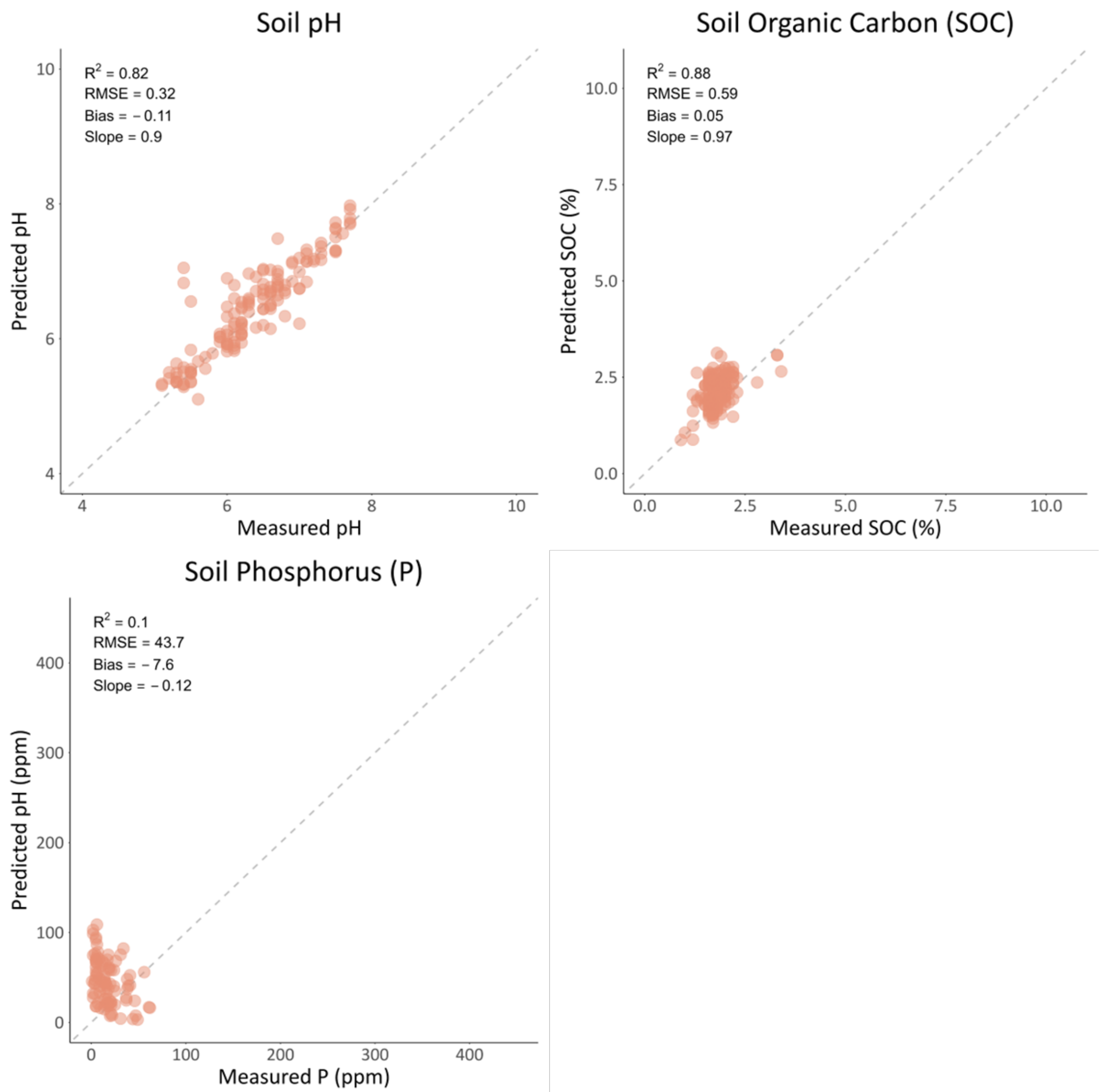

Figure 2. Measured versus predicted values for soil pH, SOC, and Mehlich-3 P in the out-of-sample evaluation using 115 independent soil samples. Accuracy metrics (R^2, RMSE, bias, slope) indicate consistent model performance for pH, reduced accuracy for SOC, and very limited predictive ability for P.

EFFICIENT NITROGEN STRATEGIES FOR HYBRID WINTER RYE

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ABSTRACT

Efficient nitrogen (N) management is essential to maximize hybrid winter rye (*Secale cereale*) yield. Given limited information on how N rates, application timing, and fertilizer sources affect production in the U.S. Midwest, yield responses were evaluated under various N management strategies. This experiment included a pre-plant application of 30 lb N ac^{-1} in the fall, followed by spring applications to evaluate eight N rates (0–210 lb N ac^{-1}) and investigate the effects of two N sources (urea and SuperU®) and two split application schedules. The split applications consisted of an initial 30 lb N ac^{-1} in March, followed by second applications of 30 or 60 lb N ac^{-1} in April or May, resulting in total N rates of 60 or 90 lb N ac^{-1}. In the first year, yield response to N rates followed a quadratic plateau, with an optimum N rate of 18 lb N ac^{-1} and maximum yield of 62 bu ac^{-1}. At 60 lb N ac^{-1}, urea and SuperU® applied in March produced similar yields (62–65 bu ac^{-1}), whereas split applications reduced yield by 5–8 bu ac^{-1}. At 90 lb N ac^{-1}, a split of 30 lb N ac^{-1} in March and 60 lb N ac^{-1} in April resulted in the highest yield (71 bu ac^{-1}), while other split timings reduced yield (59–61 bu ac^{-1}). Overall, modest spring N applications (approximately 20 lb N ac^{-1}), following an initial pre-plant fall application, were sufficient to achieve near-maximum yield, with minimal differences observed between the use of urea or SuperU®.

INTRODUCTION

Nitrogen (N) is the primary yield-limiting nutrient in cereal production, and improving N management remains essential for balancing agronomic productivity with environmental stewardship. Low recovery of applied N caused by volatilization, leaching, and denitrification continues to challenge both economic efficiency and water quality goals in the U.S. Midwest (Cassman et al., 2002; Snyder et al., 2009). As a result, strategies that increase nitrogen use efficiency (NUE) by better synchronizing N availability with crop demand have become a priority in modern cereal systems.

Conservation-based practices such as no-till and diversified crop rotations are increasingly adopted in the northern Great Plains because they enhance soil organic matter, biological activity, and N mineralization, which may reduce reliance on fertilizer inputs (Blanco-Canqui and Lal, 2008; St. Luce et al., 2017). Winter cereals may particularly benefit from these systems because their early spring growth allows them to capture mineralized N that might otherwise be lost (Campbell et al., 2011).

Despite progress in wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.), limited information exists regarding N management for hybrid winter rye (*Secale cereale*) under North American conditions. Recent advances in hybrid breeding have increased yield potential and nutrient uptake capacity, yet regional N recommendations for rye are still largely extrapolated from other small grains and may not reflect its distinct root architecture, canopy development, and seasonal N dynamics (Lollato et al., 2019). In addition, few studies have evaluated how fertilizer source and spring application timing affect hybrid rye performance within conservation systems, even as producers seek more precise N strategies to improve profitability and reduce environmental risk.

Therefore, the objectives of this study were to quantify the grain yield response of hybrid winter rye to increasing N rates and to identify the agronomic and economic optimum N rate (EONR) under southeastern South Dakota conditions. A secondary objective was to evaluate how fertilizer source and spring application timing influence yield within a no-till production system.

MATERIALS AND METHODS

Experimental Design

This study was conducted at the Southeast Research Farm (SERF) in Beresford, SD (43.0° N, 96.8° W) from October 2024 to August 2025. The soil is classified as an Egan silty clay loam, and the previous crop was soybean. Hybrid winter rye cv. 'Receptor' was planted using a no-till drill at 800,000 seeds ac^{-1}, 1 in depth, and 7.5 in row spacing. The experimental design was a randomized complete block design with four replications. Each plot measured 15 ft × 50 ft (0.009 ac), totaling approximately 0.96 ac for the trial area.

Fourteen N treatments were established to generate two complementary datasets: (i) N-rate response and (ii) timing and source effects. The rate study included eight total N rates (0, 30, 60, 90, 120, 150, 180, and 210 lb N ac^{-1}) following a uniform pre-plant application of 30 lb N ac^{-1} in the fall. The source trial evaluated two N sources: urea (46% N) and a stabilized urea containing 0.85% dicyandiamide (DCD) and 0.06% N-(n-butyl) thiophosphoric triamide (NBPT) (SuperU®, Koch Agronomic Services, Wichita, KS). The timing portion evaluated two split spring applications consisting of 30 lb N ac^{-1} in March plus an additional 30 or 60 lb N ac^{-1} in April or May for total N rates of 60 and 90 lb N ac^{-1}.

Daily precipitation and temperature data (March–July 2025) were obtained from the NOAA National Centers for Environmental Information (NCEI, 2025). Data were accessed through the Climate Data Online portal (https://www.ncdc.noaa.gov/cdo-web/), representing the post-dormancy and peak water-demand phases critical for rye yield formation.

Soil Sampling and Analysis

Before spring N applications, 20 soil cores per replication were collected in a zigzag pattern at 0–6 in and 6–24 in depths. Samples were stored in coolers, transported to South Dakota State University (Brookings, SD), refrigerated until processing, air-dried, ground, and sieved (2 mm). Chemical analyses were performed by Ward Laboratories Inc. (Kearney, NE), a certified commercial laboratory using standard soil fertility procedures.

Crop Management and Harvest

Weed control was achieved with bromoxynil (Buctril®, 2,6-dibromo-4-cyanophenyl octanoate; Bayer CropScience, Research Triangle Park, NC) applied on May 23, 2025, at 2 pt ac^{-1}. Plots were harvested on August 13, 2025, using a Wintersteiger Quantum Pro combine harvester (WINTERSTEIGER AG, Ried im Innkreis, Austria). Grain weight was recorded and adjusted to 14% moisture for yield determination.

Statistical Analysis

Data were analyzed using a randomized complete block design with four replications. Residual plots indicated no violations of normality or homogeneity of variance assumptions. Treatment means for the timing and source experiment were compared by ANOVA followed by Tukey's HSD test at $P \leq 0.05$. Outliers identified through diagnostic plots were removed prior to analysis to ensure model accuracy and homogeneity of residuals.

The economic optimum nitrogen rate (EONR) was determined using a quadratic-plateau regression model (Cerrato and Blackmer, 1990; Scharf et al., 2005) fitted to grain yield data from the N-rate trial. A nitrogen price of US$ 0.65 lb^{-1} N and a rye grain price of US$ 5.80 bu^{-1} were used to calculate the economic optimum, reflecting current national market values (USDA-ERS, 2025; USDA-NASS, 2025). The resulting price ratio (N price:grain price) was 0.11. Modeling was conducted using JMP® Student Edition (Version 18.2.2; SAS Institute Inc., Cary, NC) with nonlinear least-squares procedures to estimate EONR and the corresponding yield values.

RESULTS AND DISCUSSION

Grain Yield Response to N Rate

Grain yield of hybrid winter rye responded to N rate following a quadratic-plateau relationship (Fig. 1). Yield increased with N additions up to an agronomic optimum of 18 lb N ac^{-1}, achieving a maximum yield of 62 bu ac^{-1}. Beyond this rate, yield plateaued, indicating no additional response to further N inputs. Yields were lower than expected likely due to early season drought conditions. The economic optimum N rate (EONR) was 10 lb N ac^{-1}, resulting in a yield of 61 bu ac^{-1}. The relatively low N requirement suggests that residual soil N and mineralization from the previous soybean (*Glycine max* [L.] Merr.) crop were sufficient to support early growth under no-till management.

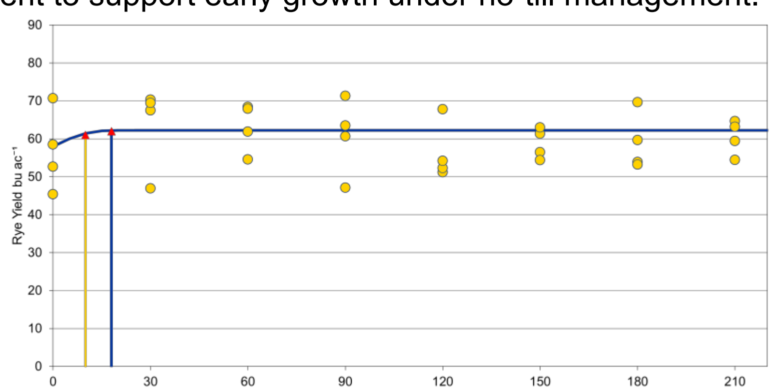

Fig. 1. Relationship between hybrid winter rye grain yield and applied N rate modeled with a quadratic-plateau function. The agronomic optimum N rate (AONR) was 18 lb N ac^{-1} (62 bu ac^{-1}), while the economic optimum N rate (EONR) was 10 lb N ac^{-1} (61 bu ac^{-1}).

Similar quadratic-plateau responses to N rate have been reported for winter wheat and barley in the northern Great Plains, with optimum N rates commonly ranging between 60 and 100 lb N ac^{-1} (Halvorson et al., 2002; Campbell et al., 2011). The much lower optimal N rate observed here may reflect a combination of high residual mineral N after soybean, the enhanced N retention typically associated with conservation systems, and reduced yield due to early season drought conditions (Blanco-Canqui and Lal, 2008). Such results align with previous observations that diversified rotations and minimal tillage improve synchronization between soil N supply and plant uptake, thereby lowering fertilizer demand without compromising yield potential (Varvel, 2000; St. Luce et al., 2017).

N Source and Timing Effects

At the 60 lb N ac^{-1} rate, rye yield averaged 65 bu ac^{-1} for SuperU® and 62 bu ac^{-1} for urea when applied in March, with no statistical difference (P > 0.05) between sources. Compared to single applications, split applications of SuperU® (March + April or March + May) produced lower yields (59 and 55 bu ac^{-1}, respectively), representing a 5–10 bu ac^{-1} reduction. At the 90 lb N ac^{-1} rate, the timing of N application had a greater influence. The March + April SuperU® split produced the highest yield (71 bu ac^{-1}, group A), while March single applications of either source yielded moderately (68 and 59 bu ac^{-1} for SuperU® and urea, respectively). However, delaying the second split to May reduced yield to 62 bu ac^{-1}. These results indicate that early-season N availability is critical for maximizing rye yield and that splitting up the N application did not improve yield substantially (Fig. 2).

Comparable findings have been reported in winter wheat and barley systems, where early N application enhances tiller survival and head density, leading to greater yield stability (Grant and Flaten, 2019; Lollato et al., 2019). Conversely, delayed topdressing beyond the stem-elongation phase has been shown to limit N uptake and reduce kernel set under dry spring conditions (St. Luce et al., 2017). The superior performance of the March + April split at 90 lb N ac^{-1} in this study supports the concept that maintaining available N through early reproductive growth stages enhances grain formation, while later splits (March + May) provide minimal physiological benefit.

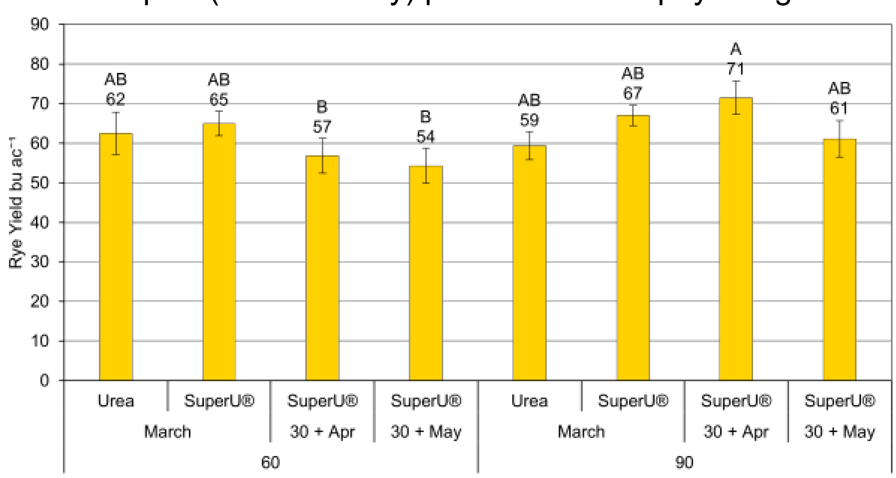

Fig. 2. Mean grain yield of hybrid winter rye as affected by N source (urea, SuperU®) and spring application timing (single and split). Bars represent treatment means ± standard error. Different letters indicate significant differences at $P \leq 0.05$ (Tukey's HSD).

Economic Interpretation

Economic analysis showed diminishing returns to N inputs beyond the agronomic optimum. The calculated price ratio of 0.11 (US$ 0.65 lb^{-1} N: US$ 5.80 bu^{-1} grain) identified an EONR of 10 lb N ac^{-1}, corresponding to near-maximum yield (98% of yield at the agronomic optimal N rate). The net return to N decreased beyond this rate, emphasizing the limited economic benefit of excessive fertilization under moderate N requirements.

The nitrogen price of US$ 0.65 lb^{-1} N reflects current national fertilizer costs (USDA-ERS, 2025), while the rye grain price of US$ 5.80 bu^{-1} represents the 2024 U.S. marketing-year average reported by USDA-NASS (2025). While hybrid cultivars were used in this study, national market data do not differentiate prices between hybrid and open-pollinated rye.

Similar economic relationships between N investment and yield gain have been observed for cereal systems across the U.S. Midwest, where EONR values generally occur at 90–95% of the agronomic optimum N rate (Scharf et al., 2005; Kitchen et al., 2017). These findings highlight the importance of balancing input costs with marginal yield response, particularly when price ratios are below 0.15. Under such conditions, conservative N rates applied early in the season provide optimal profitability while minimizing risk of N loss and environmental impact (Raun and Johnson, 1999).

Climatic Context and Implications

During the 2025 growing season (March–July), mean monthly air temperature ranged from 41 °F in March to 75 °F in July, averaging slightly above the 30-year mean (Fig. 3). Precipitation was below average in April (1.7 in) and May (2.0 in), indicating mild early-season water stress during tillering and stem elongation. In contrast, July precipitation (8.0 in) exceeded the long-term mean (2.7 in) and likely favored grain filling.

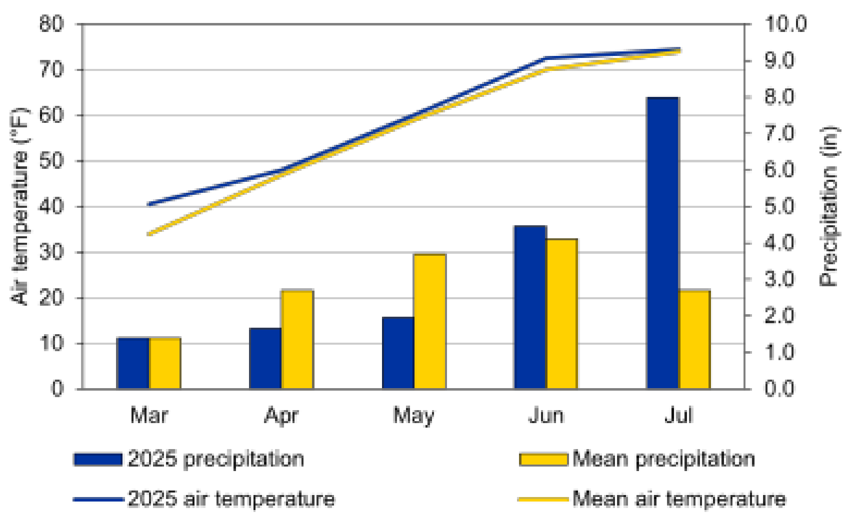

Fig. 3. Monthly air temperature and precipitation during the 2025 growing season compared with the 30-year mean (1994–2024) at Beresford, SD.

Weather variability is a known driver of N response in northern small-grain systems (Campbell et al., 2011). The pattern observed here, a dry spring followed by wetter mid-summer, may have temporarily limited early N uptake but later supported strong grain filling. At the state level, South Dakota rye yield in 2025 (55 bu ac^{-1}) was comparable to 2024 (56 bu ac^{-1}) (USDA-NASS, 2025), suggesting that while local weather likely influenced physiological development at this site, it did not represent a statewide yield penalty. Overall, the conditions provided a realistic framework to evaluate N management strategies for hybrid rye under variable spring moisture typical of the region.

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FATE OF ^{15}N-LABELED UREA APPLIED IN-SEASON FOR CORN IN EASTERN NORTH DAKOTA

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ABSTRACT

Nitrogen (N) fertilizers represent a major investment for North Dakota cropping systems as evidenced by the 890,000 tons of N used by producers in 2024 alone. If these inputs are to be beneficial to the producer and not harmful to the environment, they must be managed efficiently. To evaluate the efficacy of split-N applications, ^{15}N-labeled fertilizer was applied to three different soil types in eastern North Dakota, including an irrigated sand, a smectite-rich clay, and clay loam developed on glacial till above a marine bedrock unit of shale. Treatments included a single application of 140 lbs ac^{-1} broadcasted at planting and two treatments with 30% applied at planting and 70% applied in-season as a surface dribble, where the entirety of one treatment (Split-^{15}N) is ^{15}N-labeled and only the first application of another treatment is ^{15}N-labeled (Split-1st^{15}N). With 2025 being the first year of the study, only yield data is reported here and averaged 200 bu ac^{-1} for Oakes, 181 bu ac^{-1} for Gardner, and 192 bu ac^{-1} for Langdon. All three of these sites were responsive to the addition of N, though there were no significant differences in yield between fertilized treatments. The complete dataset will include total-N and -^{15}N uptake in both grain and stover so that fertilizer ^{15}N uptake efficiency and percent of N derived from fertilizer and soil can be calculated.

INTRODUCTION

Nitrogen (N) is an essential plant nutrient and especially important for corn (*Zea mays L.*) production where growers often supplement crop needs with synthetic N fertilizers that contribute to input costs. Nitrogen must be managed efficiently for maximum return on investment, but predicting N availability for cropping systems can be complicated due to the inherent dynamics of the N cycle. Though Nitrogen uptake efficiency (NUE) is an important tool to evaluate N management, fertilizer N uptake efficiency (FNUE) focuses on the fertilizer addition alone and allows producers to make informed decisions about inputs (Hauck et al., 1994). The project detailed here was conducted on three sites in North Dakota and involved production systems located in Cavalier, Cass, and Dickey counties, where fertilizer N usage in 2024 was 45,400 tons, 41,800 tons, and 8,500 tons, respectively (Novak, 2025). Considering this, an increase in FNUE would result in substantial savings for producers in years of high input cost and low commodity price, in addition to reducing environmental pollution.

Split-applying N can increase FNUE and reduce N loss by supplying the input during periods of peak uptake (Bender, 2013), but is not a common practice in North Dakota. Several studies throughout the U.S. using FNUE by the difference method ($FNUE_{diff}$) have evaluated fertilizer timing and concluded that there can be a positive (e.g., Eckert, 1990; Fernandez, 2016), negative (Jokela & Randall, 1989; Clark, 2020) or negligible (e.g., Davies et al., 2020; Preza-Fontes, 2021) impact of in-season N applications. These findings are also consistent where the isotopic method has been used (Spackman, 2024; Wang et al., 2016), though numerous studies have found that the efficacy of split applications is often dependent on site-specific factors such as soil texture and precipitation. Trials evaluating in-season application conducted in wet years often report an increase in efficiency or yield (Davies et al., 2020), whereas dry years do not (Rutan & Steinke, 2018), likely due to the exacerbating impact of added rainfall on N loss. Regardless of precipitation, N loss occurs in all soil textures with denitrification being more common for finer textured soils (Aulakh et al., 1991) and leaching for coarse textured soils (Korsaeth et al., 2001).

This research will provide locally relevant data on corn uptake of fertilizer ^{15}N for key areas and soil types in eastern North Dakota. Field studies in locations with vastly different soil types, including an irrigated sandy loam, a dryland expanding clay, and a clay loam developed on shale with potential to fix NH_4^+, were established utilizing ^{15}N-labeled urea to determine FNUE. The data reported herein are preliminary and future work is detailed below.

MATERIALS AND METHODS

Three field trials were established on crop production fields in Gardner, Oakes, and Langdon, ND having been under row crop production for 50+ years. All three sites can be categorized as conventional-till systems receiving spring cultivation with either a field cultivator (Gardner and Langdon) or a disk (Oakes), while only the Gardner site received vertical tillage in the fall. Based on initial fertility measurements, each site received 50 lbs of phosphorus pentoxide (P_2O_5) ac^{-1} as monoammonium phosphate (MAP) and only Oakes received 80 lbs of potassium chloride (KCl) ac^{-1} to ensure P and K were not limiting. At each site before any fertilizer was applied, a composite of nine soil cores were taken from the 0-6, 6-12, 12-24, 24-36 in depths, dried, ground, and analyzed for soil parameters reported in Table 1.

Table 2: Characterization of study sites

Location & Soil Series[1]	Sampling Depth	Textural Class[2]	CEC	pH	Total N	Potentially Mineralizable N
	in		meq/100g		g kg^{-1}	mg/kg^{-1}
Oakes, ND	0-6	sl	12.89	7.62	1.239	163.77
Embden	6-12	sl	11.31	7.50	0.817	122.34
(C-S)	12-24	ls	7.56	7.93	0.375	59.00
	24-36	ls	6.12	8.22	0.195	30.37
Gardner, ND	0-6	c	41.25	7.72	2.336	245.00
Fargo	6-12	c	38.35	7.79	1.451	158.56
(C-S)	12-24	c	38.18	8.04	0.889	91.32
	24-36	c	34.56	8.41	0.706	68.98
Langdon, ND	0-6	cl	31.52	7.46	2.573	314.52
Vang	6-12	cl	24.76	7.31	2.232	334.48
(C-S-B)	12-24	cl	28.09	7.82	0.902	135.79
	24-36	cl	21.74	8.39	0.444	60.74

[1]Crop rotation indicated in parentheses: C, corn (*Zea mays* L.); S, soybean (*Glycine max* L. Merr.); B, barley (*Hordeum vulgare* L.).
[2] As determined by the hydrometer method: sl, sandy loam; ls, loamy sand; c, clay; cl, clay loam.

At each site, 75 ft^2 plots were arranged in a randomized complete block design with four treatments and four replications including ample border to prevent cross contamination of ^{15}N. The N rate used was determined with the North Dakota N Rate Calculator, developed by NDSU Extension (Franzen, 2022), which is based on maximum economic yield (Goettl, 2024). Rate windows generated for each site included a rate of 140 lbs N ac^{-1}, and was thus used as the total rate for all locations.

The four treatments are detailed in Table 2, and include a zero-N check (UTC), a 100% rate of ^{15}N-labelled urea broadcasted at planting (Single-^{15}N), and two treatments with 30% applied at planting and 70% applied in-season as a surface dribble, where the entirety of the Split-^{15}N treatment is ^{15}N-labeled and only the first application of the Split-1st^{15}N treatment is ^{15}N-labeled. For broadcast applications made at planting, liquid urea was applied with Excellis Maxx at a rate of 25 oz. liquid ton^{-1}, which includes the nitrification inhibitor *dicyadiamide* (DCD) and the urease inhibitor *N-(n-butyl) thiophosphoric triamide* (NBPT). To ensure consistent and accurate application, a calibrated boom back-pressured with CO_2 was used for the initial additions at Gardner and Oakes on May 14th and 18th, respectively. Applications were accomplished prior to a rain event the following day, except at Langdon, where incorporation was provided via chisel plow to planting on May 27th.

Table 2. Treatment summary

Treatment	1st application[1]	2nd application[2]
UTC	None	None
Single-^{15}N	140 lbs ^{15}N ac^{-1}	None
Split-^{15}N	42 lbs ^{15}N ac^{-1}	98 lbs ^{15}N ac^{-1}
Split-1st^{15}N	42 lbs ^{15}N ac^{-1}	98 lbs ^{na}N ac^{-1}

[1]applied as surface broadcast
[2]applied as surface dribble

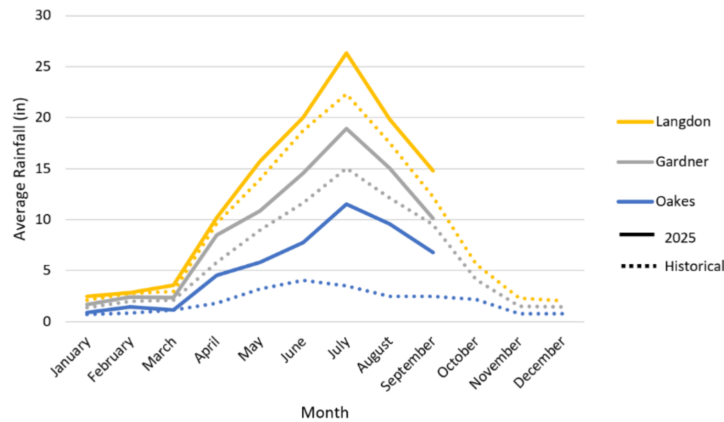
The in-season applications of fertilizer took place on July 2nd, July 2nd, and July 7th, for Oakes, Gardner, and Langdon, respectively, when the crop reached the V6 growth stage. At all sites, the remaining 98 lbs N ac^{-1} for Split-^{15}N and Split-1st^{15}N was applied with the same CO_2 back pressure system modified to accommodate a surface-band application. Similar to the first application, sites were fertilized just before a rain event to aid in incorporation.

Post R6, all ears in the center two rows were harvested by hand, shelled, and thoroughly mixed before taking a subsample, which was tested for moisture content using a commercial moisture tester. Preliminary data was analyzed using a linear mixed model with site and treatment as fixed effects and replication as a random effect. Mean separations were performed using Tukey's HSD and residuals were inspected using Shapiro-Wilks's test.

PRELIMINARY RESULTS AND DISCUSSION

While temperatures in the growing season of 2025 were consistent with historical norms at each site, precipitation was above average for all three sites, even without inclusion of irrigation that was carried out in Oakes (Fig. 1). For both historical and 2025 precipitation, the quantity received was highest for Langdon, then Gardner, then Oakes. As depicted in Table 3, there were significant yield differences between the Oakes and

Figure 1. Rainfall during the study period, as reported by the North Dakota Agricultural Network (NDAWN) alongside historical norms. Oakes, ND 2025 totals include irrigation. Gardner historical norms are reported from Galesburg, ND (16 km NW of Gardner).



Gardner sites, but not the Langdon site. All three sites were responsive to the 140 lbs N ac^{-1}, regardless of application timing. There were no significant differences in yield between the single and split applications, which is unsurprising considering the numerous other studies finding yield to be unaffected by timing (Davies et al., 2020; Preza-Fontes, 2021). Similarly, there was no significant difference between Split-^{15}N and Split-1st^{15}N treatments, validating the assumption that ^{15}N content did not impact yield.

Table 3. 2025 Yield

Site	Treatment	Yield[1] (bu a^{-1})
Oakes	Single-^{15}N	222 (70)
	Spilt-^{15}N	224 (72)
	Split-1st^{15}N	225 (72)
	UTC	131
Gardner	Single-^{15}N	190 (51)
	Spilt-^{15}N	196 (56)
	Split-1st^{15}N	212 (69)
	UTC	125
Langdon	Single-^{15}N	205 (33)
	Spilt-^{15}N	201 (30)
	Split-1st^{15}N	209 (35)
	UTC	154
Statistics		
Treatment	< 0.0001	
Site	0.006	
Treatment x Site	NS	
Treatment effect		
	Single-^{15}N	206a
	Spilt-^{15}N	207a
	Split-1st^{15}N	215a
	UTC	137b
Site effect		
	Oakes	200a
	Gardner	181b
	Langdon	192ab

[1]Percent fertilizer N response indicated in parentheses, calculated as 100 x (fertilized yield – unfertilized yield) / unfertilized yield.

FUTURE WORK

The strength of the project detailed comes from the ^{15}N component that will allow for the distinction between soil- and plant-N. Isotopic analyses are currently underway for the first growing season and will be carried out for all grain and biomass samples to determine total N and fertilizer ^{15}N uptake. These data will be used to calculate FNUE by both the difference and isotopic method, as well as the percent of N derived from the fertilizer (NDFF) and soil (NDFS). This project will be replicated during the 2026 growing season to include six site-years in eastern North Dakota. To understand the impact of soil properties on single- versus split-N applications, additional characterization measurements will be made and include organic carbon (C), bioavailable P and K, smectite:illite ratio, as well as inorganic N (NO_3^-, exchangeable NH_4^+, and fixed NH_4^+).

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DETERMINING THE ECONOMIC OPTIMUM NITROGEN RATE FOR DIFFERENT COVER CROP SYSTEMS USING ON-FARM PRECISION EXPERIMENTATION

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ABSTRACT

Successful integration of cover crops into corn-soybean production systems requires adjusting interconnected management factors. Nitrogen (N) is a critical input in corn production, and because cover crops influence nitrogen dynamics, it is essential to evaluate both as an integrated system. To address this, field trials in two locations near Moultrie County, Illinois, were established in the fall of 2023 and 2024 as part of a four-year (2024–2027) project aimed at improving understanding of nitrogen and cover crop interactions in corn-soybean rotations. Corn and soybean are grown each year. For corn sites, cover crops were planted after soybean harvest using an air drill with dual bins to variable rate seed and chemically terminated two weeks before planting corn. Strip-till with a shank (6-in depth) was used in the fall and a strip freshener in spring prior to corn and soybean planting. Four cover crop systems were used prior to corn: no cover crop, 50 lb austrian pea ac^{-1}, 40 lb winter barley ac^{-1}, 25 lb pea ac^{-1} + 20 lb barley ac^{-1}; with five nitrogen rates applied to each (56, 108, 158, 210 and 266 lb N ac^{-1}). Prior to soybean, cover crops were planted using only two systems: no cover crop or 40 lb barley ac^{-1}. Soil samples for corn were collected at the V6 growth stage from two depths (0-12 and 12-24 inches), and plant tissue samples were taken at both V6 and R6 (grain and stover) to determine total nutrient uptake. Corn and soybean yield data were post-processed in QGIS. As-applied N data were also evaluated, and plots that did not achieve the target nitrogen rate were eliminated. Quadratic, linear-plateau, and quadratic-plateau models were used to evaluate the relationship between N rate and corn yield using the *nlraa* package in R. Best fit models were selected based on AIC and R^2. Soybean yield did not differ significantly ($p \leq 0.1$) between the no cover crop and barley treatment (88.8 and 89.0 bu ac^{-1}, respectively), indicating that barley cover cropping did not affect soybean yield in 2025. Effects of N rate and cover crop on corn yield varied by year. In 2024, barley and pea+barley treatments consistently reduced yields across all N rates compared to no cover crop. In contrast, corn yield in 2025 only differed between the no cover crop and barley at the lowest N rate. The EONR for corn varied by site-year and cover crop treatment, ranging from 108 to 179 lb N ac^{-1} in 2024 and from 144 to 177 lb N ac^{-1} in 2025, with overall higher EONR values observed in 2025 compared to 2024. In 2024, barley increased EONR relative to all other treatments, indicating greater N fertilizer demand. In 2025, barley continued to increase EONR among the cover crop treatments, whereas the no cover crop treatment required the highest N rate. These contrasting responses highlight site-year dependence, which the full-scale project will address through multi-environment evaluations of integrated nitrogen and cover crop management across Illinois.

INTRODUCTION

Corn grown in the highly productive U.S. North Central region relies on commensurate nitrogen (N) supplied by fertilizer and soil organic N mineralization. As mineralized organic N is inherent, though at varying amounts, profitable fertilizer N management entails supplying what the corn crop and soil system requires to supplement already available soil N. A portion of the N fertilizer input is recovered by plants in the year of application and remaining N can be stored in soil organic matter or lost (Canisares et al., 2021; Sebilo et al., 2013). Therefore, farmers wanting to change cropping system components that affect soil N supply or fertilizer N recoverability may shift potential corn yield and N loss outcomes. For example, interest or incentivization in cover crops and reduced tillage continues to grow for Illinois farmers.

Cover crops are primarily adopted with goals to reduce soil erosion and N loss by nitrate (NO_3-N) leaching. In aligning function with reliability, cereal rye (*Secale cereale* L.) is the most common cover crop used in corn-soybean rotations in the North Central region. Leguminous cover crops can fix atmospheric N into plant-available forms, and after termination, a portion of this N ideally becomes available to subsequent cash crops. For instance, winter annual legumes grown before corn have been shown to replace approximately 60 lb N ac^{-1} (Perrone et al., 2020). Despite various proposed and documented benefits, cover crops represent an additional component within the cropping system and therefore influence soil-to-plant water and nutrient relationships. Integrating cover crops may require adjustments to crop and fertilizer management and timing, which can increase input requirements, management complexity, and, ultimately, production costs.

To effectively quantify the influence of cover crops on N dynamics within soybean-corn systems, a comprehensive and systematic evaluation framework is required. Quantifying crop response to N begins with the implementation of N rate experiments, in which multiple fertilizer levels are applied to characterize yield responses to N. On-farm precision experimentation (OFPE) provides a framework for conducting these trials at high spatial resolution, enabling the assessment of N responses across production fields while accounting for spatial variability. Complementary measurements of soil and plant N help to understand pathways of N cycling within the system, including fertilizer recovery, soil N contributions, and potential N losses.

Evidence from an Eastern Nebraska multi-year trial showed no consistent change in corn yield and N demand after cereal rye, hairy vetch, a rye vetch mix, or no cover crop across three seasons (de Almeida et al., 2025). In the Upper US Midwest region, corn inter-seeded red clover was shown not to provide a significant N fertilizer equivalence, despite improved corn yields in one of four site years (Francis et al., 2025). In Indiana, corn yield responses to N applications were found to vary with rye cover crop, with late-vegetative N applications decreasing yield in all site-years following rye cover crop, while early N applications were optimal (Seavers & Quinn, 2025). Another study with rye in Kentucky showed that lower N requirements are needed when application is split and corn is followed by the cover crop (Quinn et al., 2023). In South Dakota, another study that examined the impact of different cover crop compositions on corn N requirements and yield found that while cover crops can reduce the economic optimum N rate (EONR), their effect on yield varies, particularly influenced by precipitation levels (Bielenberg et al., 2023).

Although cover crops are widely tested as an influence on N supply, retention, and environmental losses in corn systems, there is a lack of on-farm and data-intensive analysis that quantifies how different cover crop species modify corn N requirements, particularly regarding the EONR, as well as on N management recommendations, which are shown to be variable and weather dependent.

Given these considerations, we want to understand what the effects of the cover crop management strategies on soil and plant N status, optimum N fertilizer rate, and economic return to N under different cover crop strategies are. To address this, we the following general and specific objectives: i) to evaluate the effects of cover crop species on soybean and corn yield using OFPE; ii) Quantify how different cover crop systems influence corn EONR; iii) Assess the economic performance of cover crop systems compared to no cover crop; iv) Investigate soil N availability and plant N uptake across cover crop treatments.

MATERIALS AND METHODS

On-farm soybean and corn experiments

Two on-farm experiments were conducted in Central Illinois, where soybean and corn are grown each year. Field 1 was corn in 2024 and soybean in 2025, while field 2 was corn in 2025. For corn sites, cover crops were planted after soybean harvest using an air drill with dual bins to variable rate seed; and chemically terminated two weeks before planting corn. Strip-tillage with a shank set to a 6-in depth was used in the fall and a strip freshener in spring prior to corn and soybean planting. Prior to soybean, cover crops were planted using two systems: no cover crop or 40 lb barley ac^{-1}. Prior to corn, four cover crop systems were used: no cover crop, 50 lb austrian pea (*Pisum sativum*) ac^{-1}, 40 lb winter barley (*Hordeum vulgare* L.) ac^{-1}, 25 lb pea ac^{-1} + 20 lb barley ac^{-1}; with five total N rates applied to each: 56, 108, 158, 210 and 266 lb N ac^{-1}. Nitrogen fertilizer was applied at a base rate of 56 lb N ac^{-1} injected at planting as liquid urea ammonium nitrate (32-0-0, UAN); and UAN injected between the rows at corn growth stage V6 (sidedress) at rates of 0, 52, 102, 154, and 210 lb N ac^{-1}. Phosphorus and potassium were applied based on soil-test results and were managed to be nonlimiting.

Soil and plant analysis

Composite soil samples for corn were collected at growth stage V6 prior to sidedress N application at 0-12 and 12-24-in depths. and analyzed for nitrate and ammonium (Bundy and Meisinger, 1994). Whole corn plants were collected at V6 and analyzed for total mineral nutrients (Zarcinas et al., 1987) and total aboveground corn biomass (stover and grain separated) were collected at R6 and analyzed for total mineral nutrients to calculate nutrient uptake.

Yield data processing and statistical analysis

Yield monitor data for soybean and corn were acquired at the end of the season and post-processed in QGIS to remove errors. As-applied N data were also evaluated, and plots that did not achieve the target N rate were eliminated from the analysis. The experimental layout was a Latin square design (Bullock et al. 2019). For each site-year, the relationship between N rate and corn yield was evaluated using quadratic, linear-plateau, and quadratic-plateau models with the *nlraa* (Miguez, 2023) package in RStudio (R Core Team, 2024). Best fit models were selected based on the Akaike Information Criterion (AIC) and R^2. The EONR was calculated as the N rate that maximized economic return to N (RTN), with RTN defined as (corn yield × corn price) − (N rate × fertilizer price). The maximum return to N (MRTN) was calculated using [(YEONR – Y0N) × corn price] – (EONR × fertilizer price), where YOENR is the yield at EONR and Y0N is the *a* coefficient derived from the models. Profitable ranges were calculated to bracket the N rate that maximized return to N, where return to N is \$1 ac^{-1} less than the MRTN. Economic calculations used a 10:1 corn price to N fertilizer price ratio (\$5 bu^{-1} and \$0.50 lb N^{-1}).

Analysis of Variance (ANOVA) was conducted to evaluate the effect of soil N availability on cover crop systems, the corn biomass difference among cover crop systems, as well as the V6 and total uptake difference among cover crop systems. Treatment effects were considered significant at $p \leq 0.1$, and the Fisher's Least Significant Difference (LSD) was used to assess the difference between the means of the treatments.

RESULTS AND DISCUSSION

Grain yield and Economic Optimum N Rate for corn

Soybean yield did not differ significantly ($p \leq 0.1$) between the no cover crop and barley treatment (88.8 and 89.0 bu ac^{-1}, respectively). In corn, the effects of N rate and cover crop on yield varied by year. In 2024, barley and pea+barley cover crop systems consistently reduced yields across all N rates compared to no cover crop (Fig. 1). In contrast, corn yield in 2025 only differed between the no cover crop and barley at the lowest N rate. Site- and year-dependent yield response to N rate and cover crop systems has been well-documented in previous other North Central region research. In 2024, growing season precipitation was 41 in. with notably wet April (8.2 in.) and July (7.1 in.), while temperature abnormalities were few. In contrast, the 2025 growing season was considerably drier (24 in.), particularly in June (2 in.) and August (0.6 in.), with frequent temperature abnormalities higher than usual. Warmer and drier conditions observed in 2025 reflected the limited corn yield potential and restricted cover crop biomass development relative to the cooler, wetter 2024 growing season

Following the trend, EONR varied by year and cover crop treatment, ranging from 108 to 179 lb N ac^{-1} in 2024 with corresponding YEONR ranging from 250 bu ac^{-1} to 259 bu ac^{-1}. In 2025 EONR values ranged from 144 to 177 lb N ac^{-1} with YEONR between 229 and 233 bu ac^{-1}. Overall, higher EONR values were observed in 2025 compared to 2024 (Fig. 1). When compared to the regional benchmark EONR of 187 lb N ac^{-1} derived from the Corn Nitrogen Rate Calculator (based on a corn price of \$5 bu^{-1} and N fertilizer price of \$0.50 lb N^{-1}), both years exhibited lower N requirements than the regional N rate guidelines for central Illinois. In 2024, barley increased EONR relative to all other treatments, indicating greater N fertilizer demand. In 2025, barley continued to increase EONR among the cover crop treatments, whereas the no cover crop treatment required the highest N rate. Although the no cover crop accumulated more biomass at V6 than the cover crop treatments, this early advantage turned into higher N requirements and greater yield penalties relative to the cover crop treatments as dry conditions emerged during the growing season. The pea treatment continued to demand less N compared to barley in 2025, with the mix showing the lowest N demand in this year.

Overall, partial profits were greater for the no cover crop system in both years (Table 1). In 2024, partial profit differences between the pea and no cover crop treatments were \$60 ac^{-1} in 2024 and \$49 ac^{-1} in 2025, values comparable to typical conservation program payments that aim to offset cover crop adoption costs. It should be noted that the cover crop seed cost was held constant across 2024 and 2025 and was \$58 ac^{-1} for the pea system. Despite requiring less fertilizer N, the pea treatment resulted in the lowest profit in 2025 due to its higher seed cost. When considering the return to N, calculated as MRTN, values in this study ranged from \$64 to \$837 ac^{-1}, compared to the regional benchmark of \$473 ac^{-1} for Central Illinois (based on a corn price of \$5 bu^{-1} and fertilizer price of \$0.50 lb N^{-1}). In 2024, overall MRTN values were lower (\$64 to \$543 ac^{-1}), particularly under the no cover crop and pea systems (null MRTN and \$64 ac^{-1}), which exhibited weaker N responses. In 2025, MRTN values were higher (\$482 to \$837 ac^{-1}) with the barley and mix systems showing stronger economic responses to N (\$837 ac^{-1} and \$803 ac^{-1}, respectively.

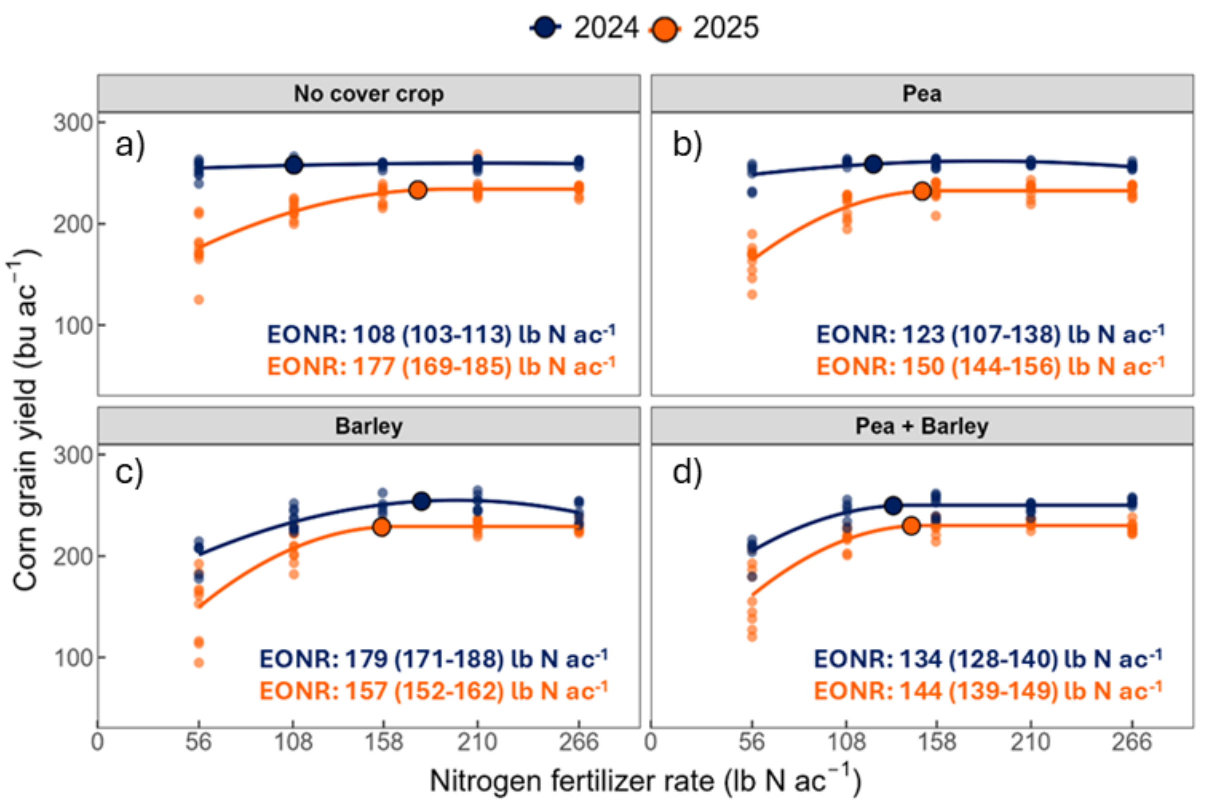

Figure 1. Relationship between N fertilizer rate and corn grain yield from four cover crop systems: a) No cover crop; b) Austrian pea 50 lb ac^{-1}; c) Winter barley 40 lb ac^{-1}, and d) Austrian pea 25 lb ac^{-1} + winter barley 20 lb ac^{-1} in 2024 and 2025. Orange and

blue big dots represent the EONR calculated using a 10:1 corn price to nitrogen fertilizer price ratio (\$5 bu^{-1} and \$0.50 lb N^{-1}) and respective profitable N rate range at \$1 ac^{-1} below and above the MRTN. Continuous orange and blue lines are the models fitted.

Table 1. Optimum nitrogen rate, yield, return to N, and partial profit, for each cover crop system in 2024 and 2025.

	Cover crop rate					Cost[4]				
Year	Barley	Pea	Optimum N rate[1]	Prof. N range[2]	Yield[3]	Barley	Pea	Yield return	MRTN[5]	Partial profit[6]
	---------- lb a^{-1} ----------				bu a^{-1}	---------- \$ ac^{-1} ----------				
24	0	0	108	103 - 113	258	0	0	1290	-	1236
24	0	50	123	107 - 138	259	0	58	1295	64	1176
24	40	0	179	171 - 188	254	15	0	1270	431	1165
24	20	25	134	128 - 140	250	8	29	1250	543	1146
25	0	0	177	169 - 185	233	0	0	1165	482	1077
25	0	50	150	144 - 156	232	0	58	1160	750	1028
25	40	0	157	152 - 162	229	15	0	1145	837	1051
25	20	25	144	139 - 149	230	8	29	1150	803	1041

[1] Optimum N using a 10:1 corn to N fertilizer price ratio (\$5 bu^{-1} and \$0.50 lb N^{-1})

[2] Profitable N rate range, which is \$1 ac^{-1} below and above the MRTN

[3] Yield at the optimum N rate

[4] Prices paid for cover crop seed: \$0.38 lb^{-1} winter barley and \$1.15 lb^{-1} austrian pea

[5] Maximum Return to Nitrogen, no calculations performed when EONR was the same as other N rates

[6] Partial profit = (corn yield x \$5) - [(N rate x \$0.50) + (cover crop seed cost)]

Soil nitrogen availability and plant nitrogen uptake for corn in 2025

Pre-sidedress soil inorganic N values indicated differences among cover crop systems (Fig. 2). The no cover crop treatment had the greatest soil N content, followed by pea, whereas the barley and pea+barley systems showed significantly lower values compared to the no cover crop treatment ($p \leq 0.1$). These results show that grass cover crop-based systems reduced potentially available soil N early in the season relative to no cover crop. Soil inorganic N at V6 was significantly higher for no cover and pea treatment, however pea treatment did not differ from barley and the mix. These patterns were carried through to early-season corn growth. Corn biomass at V6 for the no cover crop treatment had the greatest biomass accumulation, followed by pea, while barley and the mix produced the lowest biomass. Similarly to what happened to pre-sidedress soil inorganic N, the grass cover crop-based systems limited vegetative growth relative to the no cover crop and the pea treatments. The corn N uptake at V6 reinforced this trend. Corn in the no cover crop treatment uptake the most N early in the season, indicating both higher soil N availability and greater biomass accumulation. The pea treatment exhibited moderate N uptake, reflecting intermediate soil N conditions. Both barley and the mix resulted in the lowest V6 N uptake, somewhat mirroring the reduced early-season N supply and lower biomass.

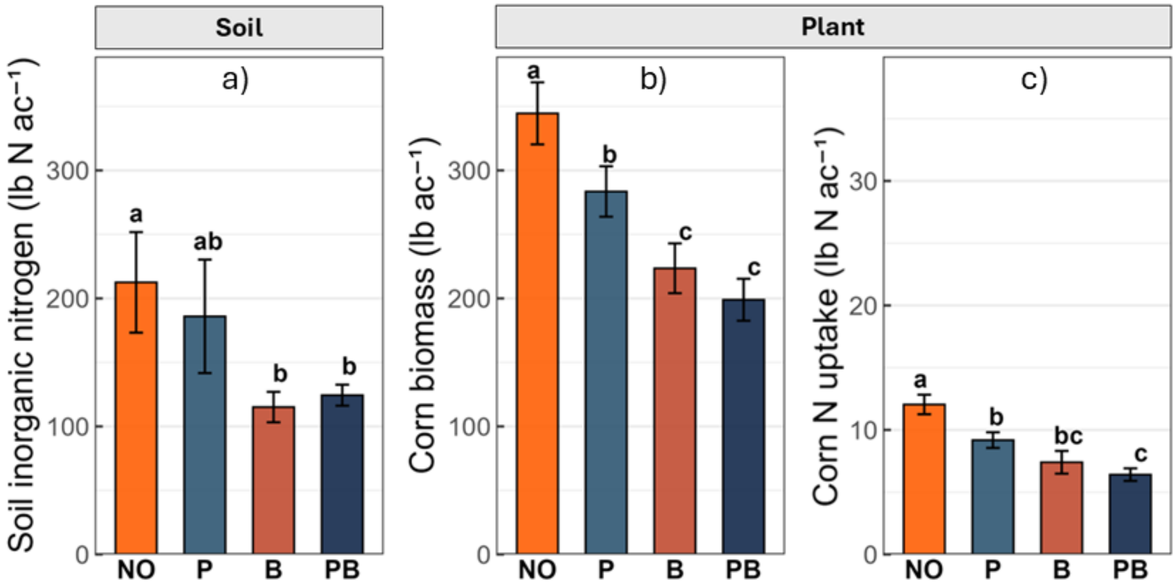

Figure 2. a) Pre-sidedress soil inorganic N (NO_3-N + NH_4-N) for corn at 24-inch depth; b) corn biomass and c) corn N uptake for the cover crop systems NO) No cover crop; P) Austrian pea 50 lb ac^{-1}; B) Winter barley 40 lb ac^{-1} and PB) Austrian pea 25 lb ac^{-1} + winter barley 20 lb ac^{-1} at V6 stage in 2025. Different small letters mean significant statistical differences at $p \leq 0.1$. Error bars represent the standard error of the mean.

Soil NO_3-N measured at 12-in depth in 2025 also help to illustrate early-season N dynamics among cover crop systems. The highest NO_3-N levels occurred in the no cover crop system (19 ppm), followed closely by the pea treatment (17 ppm). Barley and the mix had substantially lower concentrations, around 10 and 11 ppm, respectively. When interpreting12-in depth NO_3-N concentrations in terms of the Illinois Pre Sidedress Nitrate Test (PSNT) guidelines, none of the treatments exceeded the >25 ppm threshold where no sidedress N would be recommended. All treatments fell within the intermediate 10–25 ppm decision range, where recommended sidedress N is calculated as the difference from 25 ppm multiplied by 12 lb N per ppm. Under this framework, the no cover crop and pea systems (17–19 ppm) would require around 72 and 96 lb N ac^{-1}, whereas the barley and mix systems (testing 10 and 11 ppm) would indicate a substantially larger sidedress requirement (around 167 and 170 lb N ac^{-1}). These 12-in NO_3-N patterns are consistent with the total soil inorganic N trends observed at V6, where barley systems exhibited the strongest early-season N limitation, and no-cover and pea maintained comparatively greater N availability.

The patterns in soil N supply at V6 were also reflected in plant uptake patterns across N fertilizer rates (Fig. 3).

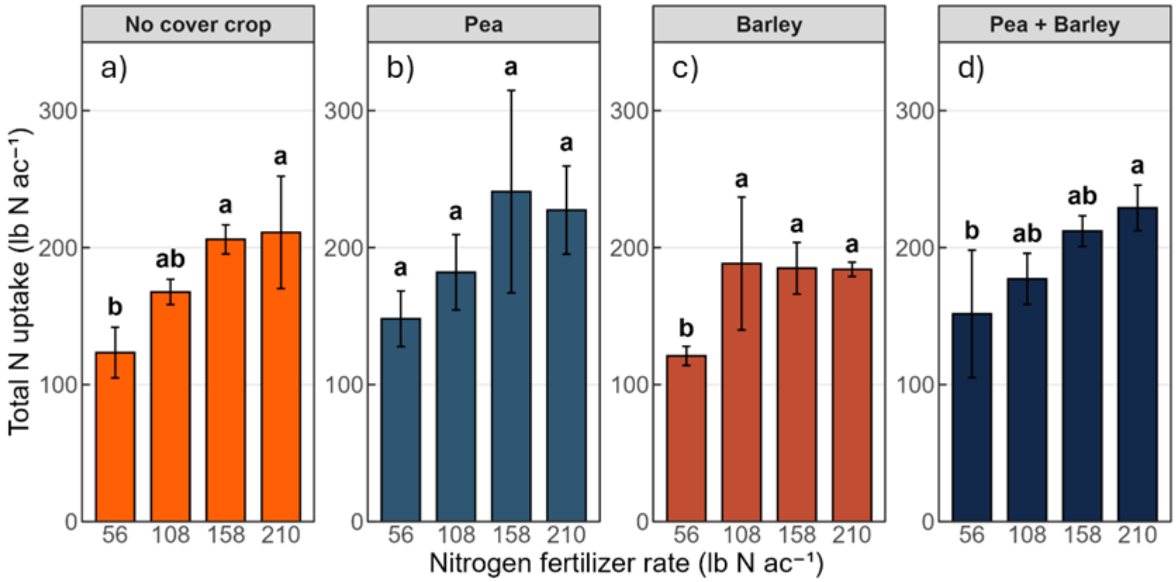

Figure 3. Total nitrogen uptake at N fertilizer rates of 56, 108, 158, and 210 lb N ac^{-1} across cover crop systems: a) No cover crop; b) Austrian pea 50 lb ac^{-1}; c) Winter barley 40 lb ac^{-1}, and d) Austrian pea 25 lb ac^{-1} + winter barley 20 lb ac^{-1} in 2025. Error bars represent the standard error of the mean.

Across all cover crop systems, total plant N uptake increased with N fertilizer rate, reaching its maximum between 108 and 210 lb N ac^{-1}. In contrast, N uptake at the V6 stage remained low across treatments but was relatively greater for the no cover crop and pea systems, which also exhibited the highest soil inorganic N concentrations. The limited N uptake before V6 suggests that most N accumulation occurred later in the season, which is well-documented, and after V6 in response to fertilizer additions. The no cover crop treatment showed a sharp increase from 123 to 206 lb N ac^{-1}, with a plateau around 210 lb N ac^{-1}. Pea exhibited the highest total N uptake overall, reaching 241 lb N ac^{-1} at 158 lb N ac^{-1} and slightly declining thereafter, suggesting a potential additive contribution from both fertilizer N and biologically fixed N. In contrast, barley peaked earlier (188 lb N ac^{-1} at 108 lb N ac^{-1}) and then plateaued, implying that a portion of available N was utilized elsewhere. The mixed system showed a steady increase in total N uptake with rate (152 to 229 lb N ac^{-1}), indicating a balance in N dynamics between barley and pea. None of the cover crop treatments differed in total N uptake for 158 and 210 lb N ac^{-1} rates. These results are also found in previous studies showing that high-biomass, high C:N cereal residues (barley) can temporarily immobilize inorganic N during early corn growth, while low C:N legume residues (pea) release N more synchronously with crop demand (Andrade et al., 2023; Tadiello et al., 2022). Mixtures can moderate extremes; site and timing control net mineralization versus immobilization (Camarotto et al., 2018; Carciochi et al., 2021). Together, soil N availability and uptake patterns demonstrate how cover crops influence early-season N dynamics, with the main N demand occurring after the V6 stage when applied sidedress N effects take precedence over the early influence of the cover crop system.

CONCLUSION

Cover crop system affected optimum N rates (EONR) and economic return to N (MRTN), though effects varied considerably by year. For all cover crop systems, yield at the EONR differed from no cover crop 1 to 8 bu ac^{-1} in 2024 and 1 to 3 bu ac^{-1} in 2025, suggesting cover crop seed cost and increases in fertilizer N demand affect profitability greater than yield losses. Yield losses with cover crops were greatest at the lowest N rates, which, although below most farmer-applied N rates, do affect the yield response function and determination of the MRTN and EONR. Yield, soil N availability and plant uptake did not differ between no cover crops and winter peas. The pea treatment increased N demand compared to no cover crop in one year and decreased in the other, while always demanding less N than barley. Barley also increased N demand compared to no cover crop in one year and decreased in the other, but always demanded more N than pea and the mix. The mix showed mixed responses for N demand, and despite reduced yield in 2024 across N rates, it did not reduce yields in 2025, except at the lowest rate. The mix showed low and similar to barley early-season soil N availability; however, it showed increased total N uptake across the N rates. It is also important to note that the fall and spring strip tillage and early cover crop termination in our study suggest that an approach useful to lessen the yield reductions of cover crops at the optimum N rate.

The results demonstrate that cover crops did not affect soybean yield in the short term. In corn, however, cover crop integration altered N fertilizer demand but not always in ways that reduced fertilizer requirements or improved short-term profitability. Although cover crops provide well-recognized soil and environmental benefits, the highest economic returns in this study were observed under no cover systems. For the legume cover crop, much of the economic difference was attributed to the cost of cover crop seed rather than differences in yield or N response. For instance, pea produced yields comparable to the no cover system, with similar early-season soil N availability and slightly greater total N uptake; however, its higher seed cost limited partial profit. Additional data across multiple seasons is needed to determine whether the N cycling benefits of legumes, such as pea, can offset their establishment costs over time. Furthermore, the effectiveness of pea cover crops in reducing soil erosion or nutrient losses remains uncertain. Continued long-term monitoring will be essential to capture the cumulative impacts of cover crops on yield stability, N fertilizer demand, and nutrient cycling over time.

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LINKING SOIL PROPERTIES AND WEATHER VARIABILITY TO NITROGEN FERTILIZER NEEDS

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ABSTRACT

Soil Nitrogen (N) availability is known to be affected by weather and soil characteristics. Current fertilizer recommendations are generally based on yield goals, soil type, and past productivity; however, these methods frequently fail to account for the constantly changing interactions between soil chemical, biological, physical, and weather variables that influence N availability. This limitation increases uncertainty in estimating the economic optimum nitrogen rate (EONR), potentially reducing both profitability and environmental sustainability. Studies were conducted from 2021 to 2024 at 44 sites in central and eastern South Dakota to assess the utility of soil health indicators in improving N fertilizer recommendations. Soil samples (0-6inches, 6-24inches) were collected prior to planting and fertilization. Soil health tests were performed on the 0-6 inches depth samples and the soil nitrate N test for both depths. Nitrogen was applied at rates ranging from 0 to 240lbs/ac, and the EONR was calculated for each site. In this paper, we will discuss the correlation among soil biological, chemical, and physical tests along with weather variables. Furthermore, we will explore the relationships between EONR and individual soil tests and weather data and identify the combination of soil tests for the predictability of EONR. The goal of this study is to improve nitrogen fertilizer recommendations by determining the extent to which soil health indicators and weather variables impact EONR.

INTRODUCTION

Nitrogen (N) is a crucial nutrient that often limits crop productivity in corn (*Zea mays L.*). Current fertilizer recommendations are generally based on yield goals, soil type, and past productivity; however, these methods frequently fail to account for the constantly changing interactions between soil chemical, biological, physical, and weather variables that influence N availability. In addition to causing agricultural production inefficiencies, inaccurate N rate decisions can also harm the environment and reduce farmer profits. (Struffert et al., 2016). As a result, growers and researchers are increasingly seeking tools that can capture the dynamic behavior of soil nitrogen and improve the precision of N recommendations.

Soil health testing has emerged as a potential solution for improving N management by providing information on nutrient cycling mechanisms related to N rate response (Norris et al., 2020). Although soil health testing alone may not consistently forecast the best N rates, it has the potential to complement existing yield-based and soil testing approaches. When integrated, these assessments have the potential to improve the accuracy of N fertilizer recommendations and reduce uncertainty in decision-making.

Incorporating weather variability alongside soil health and soil properties further strengthens this approach, given the major role of temperature and precipitation in shaping soil N availability and crop uptake (Tremblay et al., 2012). Temperature controls microbial mineralization, nitrification, and denitrification, whereas rainfall distribution affects nitrogen leaching and volatilization losses. Years with early-season drought may inhibit mineralization, resulting in less N being available, whereas overly wet springs might increase nitrate loss from the soil profile. As a result, nitrogen requirements might vary significantly from year to year, even within the same area. Incorporating weather data, such as growing degree days, cumulative precipitation, and rainfall variability, into soil measurements creates a more comprehensive framework for predicting N requirements and economic returns. (Wang et al., 2020). Emerging research suggests that integrating soil health and weather variables could improve the prediction of the economic optimum nitrogen rate (EONR) by capturing both soil N supply potential and conditions that influence N transformations and crop uptake. The objective of this study was to examine the relationships between EONR and soil biological, chemical, and physical indicators, and weather variability to determine if soil health metrics and weather could be used to improve N fertilizer recommendations.

MATERIALS AND METHODS

The study was conducted in 44 sites across central and eastern South Dakota from 2021–2024. Each treatment was replicated four times in a randomized complete block design (RCBD). Sites represented diverse soil types and management histories. Nitrogen treatments ranged from 0 to 240 lbs/ac in increments of 40 lbs/ac. The N fertilizer source was urea (46-0-0) as SuperU (Koch Fertilizer LLC) broadcast on the soil surface. Soil samples were collected from 0–6 and 6–24 inches prior to planting and fertilization. Soil samples were sent to Ward Laboratories (Kearney, NE) for soil analysis. Soil health indicators, including soil nitrogen, enzymes, soil carbon, and soil texture, were analyzed, which are included in Table 1. These tests were performed on 0-6 inches, while the Soil nitrate (NO_3^--N) concentrations test was performed on both (0-6 and 6-24 inches) depths. Weather variables (total precipitation, average temperature, and growing degree days) were evaluated for each site using local weather station data, which are included in Table 2. Weather data were aggregated for the early season, late season, and full season. Pearson correlations were calculated among soil health indicators, weather variables, and EONR. Random forest modeling was used for ranking the importance of variables that most influenced EONR. Analyses were conducted using R 4.5.1.

RESULTS AND DISCUSSION

Soil nitrogen was consistently one of the most important variables likely because soil N directly drives crop growth and fertilizer needs. Soil nitrates were a key driver of N fertilizer requirements, suggesting that sites with higher initial N availability or more active microbial populations may require higher N applications to reach EONR.

Water-extractable total N (H2OTotalN) was the strongest predictor (importance = 14.66), indicating that plant-available water-extractable N in the surface soil is the primary driver of the N fertilizer requirement. This aligns with Hu et al. (2024) who found that synchronizing early-season N availability (nitrate and ammonium) under straw-return systems significantly improved yields. Nitrate in topsoil increased EONR, reflecting available N for uptake. Accumulated nitrate N in the 0–24 in. layer also had a strong effect on EONR, confirming that deeper N availability is important. Sand content increased EONR slightly. Organic matter in the topsoil reduced EONR slightly (possibly due to higher inherent fertility). Deeper organic matter increased predicted N need; it reflects mid-layer fertility contribution. Cation exchange capacity deeper in the profile contributed moderately to EONR predictability. Further, the strong influence of nitrate N in the surface and 0–24 cm layers reinforces that measurable available N pools (e.g., NO_3-N) are key to accurately estimating N fertilizer needs.

Early-season minimum temperature increased EONR, while late-season cold stress reduced EONR. Early-season heat reduced predicted EONR while late-season warmth increased N requirement. Higher early-season rainfall diversity likely improves soil N cycling, N mineralization, and N use efficiency; reduces fertilizer requirement variability, while maximum precipitation during the full season can either increase or decrease EONR depending on timing. So, early-season heavy rainfall can flush applied N, requiring higher EONR. The well-distributed early rainfall reducing EONR, heavy early rainfall increasing it (likely due to leaching), align with the interactive findings of Donovan et al. (2025), who found that water and N interactions strongly influence net N mineralization and enzyme activity. Thus, accounting for weather allows for a more dynamic N recommendation model rather than a static rate.

POXC, ACE protein, soil respiration, and total C had a low-moderate influence on EONR, likely linked to N cycling but indirect. Organic matter & active C pools support microbial N supply, but they are indirect predictors compared to chemical N measurements. Soil C, not a primary predictor, but it helped in understanding soil fertility dynamics. Enzymes such as N-acetylglucosaminidase (NAG) and β-glucosidase (BG) showed moderate contribution. Enzymatic activity reflects soil microbial function and nutrient cycling efficiency. While not as influential as direct N measures, enzymes helped explain variability in N availability under different soil conditions.

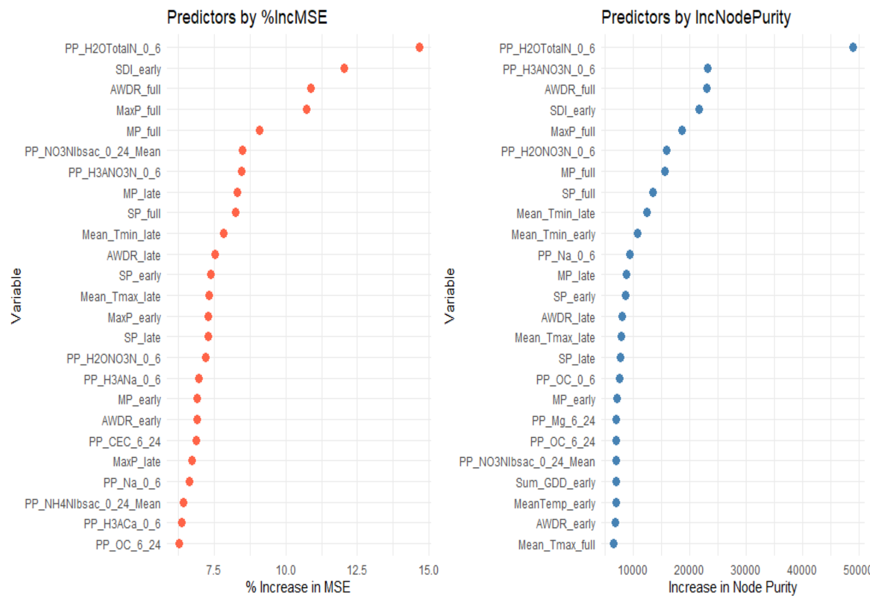

Figure 1: Random Forest variable importance plots ranking measured soil and weather variable on their influence of economic optimum nitrogen rate (EONR).

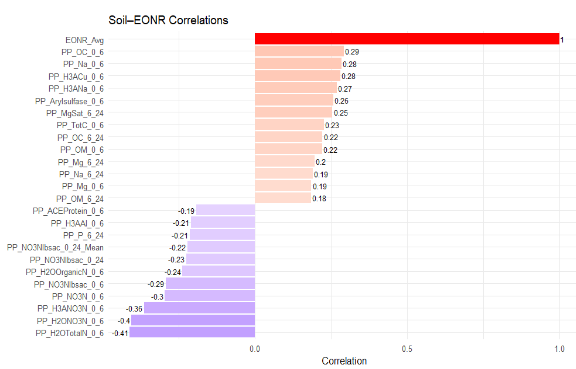

Figure 2: Pearson correlation matrix showing relationships among soil variables and EONR.

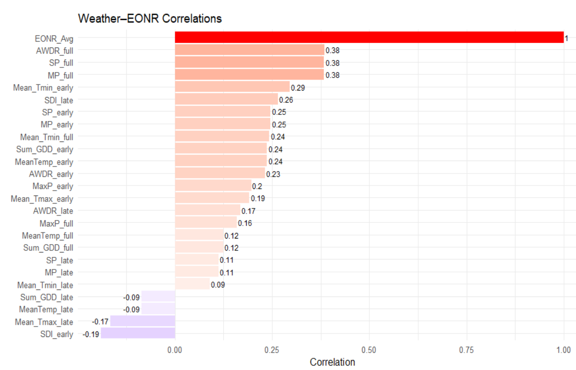

Figure 3: Pearson Correlation Matrix showing relationships among weather variables and EONR.

Table 1: Soil Test Measurements with descriptions and acronyms.

Preplant Soil Measurement	Description
Soil Nitrogen	
H2O Total N	Water-extractable Total N
NO3-N	KCl extraction of NO3-N

H3ANO3-N	Haney H3A extraction of NO3-N
H2ONO3-N	Haney H2O extraction of NO3-N
NH4N	KCl extraction of NH4-N
Soil Health Test	
Arylsulfatase	
β-Glucosidase	
N-Acetyl-β-Glucosaminidase	
ACE Protein	
Soil Respiration	
Soil Carbon and Other Tests	
OC	Organic Carbon
OM	Organic Matter
CEC	Cation Exchange Capacity
Soil Texture	Sand, Silt, and Clay

Table 2: Weather Variables evaluated

Weather Parameter and Acronyms	
Tmin	Minimum Temperature
Tmax	Maximum Temperature
GDD	Growing Degree Days
MP	Mean Precipitation
MaxP	Maximum Precipitation
SDI	Shannon Diversity Index
AWDR	Abundant and well-distributed rainfall
Early season	March 1-June 30
Late season	July 1-September 30
Full season	March 1- September 30

CONCLUSIONS

EONR is influenced by both soil health indicators and weather variability. Nitrate N distribution in both 0–6 and 6-24 inches layers was highly related to N fertilizer needs, emphasizing the importance of monitoring both shallow and deep N availability. Precipitation timing and intensity strongly influenced N uptake, while early- and late-season temperatures altered N fertilizer requirements. Well-distributed rainfall reduced EONR, whereas early-season heavy rainfall increased it likely by applied N being leached. Integrating soil N variables (especially water extractable N) and weather data can likely improve estimates of EONR.

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EFFECTS OF NITROGEN AND IRRIGATION MANAGEMENT ON SUGAR BEET YIELD, SUGAR CONCENTRATION, AND NITROUS OXIDE EMISSIONS

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ABSTRACT

Sugar beet (*Beta vulgaris* L.) is an important sugar-producing crop, accounting for about 55% of total sugar production in the United States. Optimizing nitrogen (N) and irrigation management is essential for achieving profitable and sustainable beet production. Excessive N application can lower sugar quality and increase nitrous oxide (N_2O) emissions, a potent greenhouse gas and ozone-depleting compound. This study evaluated the effects of irrigation and N fertilizer (urea) rates on sugar beet yield, sugar concentration, and N_2O emissions in Western Nebraska. The field experiment was conducted at the University of Nebraska Panhandle Research and Extension Center, Scottsbluff, NE, using a split-plot randomized complete block design with four replications. The main plot factor was irrigation level, full irrigation (100% of crop water requirement) and deficit irrigation (75%) and the split-plot factor was N rate (0, 50, 80, 100, 125, and 150% of the current university recommended rate). Nitrogen application significantly increased beet yield and N_2O emissions, whereas irrigation level had no significant effect on yield, sugar concentration, or cumulative N_2O emissions. Beet yield increased linearly with N rate, with 50% of the recommended N rate sufficient to achieve maximum yield under both irrigation regimes. Sugar concentration remained stable, showing a slight decrease as N rate increased. Although not statistically significant, full irrigation tended to produce higher yields and lower N_2O emissions compared to deficit irrigation. Overall, applying 50% of the recommended N rate under full irrigation can improve yield while minimizing N_2O emissions, providing a sustainable management strategy for sugar beet production in Western Nebraska.

INTRODUCTION

Sugar beet (Beta vulgaris L.) is an important sugar-producing crop, accounting for about 55% of total sugar production in the United States (USDA-ERS, 2023). Nebraska ranks sixth in U.S. sugar beet production, contributing significantly to the nation's sugar supply. Optimizing fertilizer nitrogen (N) and irrigation management is crucial for sustainable sugar beet production in the Nebraska Panhandle, where semi-arid conditions require substantial irrigation inputs.

Nitrogen is an essential nutrient for sugar beet growth and directly influences both root yield and sugar concentration. Adequate N promotes vegetative growth and yield, while excess N can reduce sugar concentration and increase impurities, leading to lower sugar recovery and reduced economic returns (Draycott, 2008). Overapplication of N also contributes to environmental issues, including increased emissions of nitrous oxide (N_2O), a potent greenhouse gas with a global warming potential nearly 300 times greater than carbon dioxide (Perera & Maharjan, 2021). N_2O emissions from sugar beet systems are largely driven by fertilizer N rates and soil moisture conditions (Maharjan et al., 2014).

Irrigation plays a vital role in achieving optimal beet yield and sugar concentration by maintaining favorable soil moisture for nutrient uptake and root development. However, irrigation management also influences N_2O emissions through its control over soil aeration and denitrification processes. Excessive irrigation can enhance N losses via leaching and gaseous emissions, whereas deficit irrigation may limit crop growth and sugar accumulation. Therefore, understanding the combined effects of fertilizer N and irrigation levels on beet performance and N_2O emissions is critical for improving productivity, quality, and environmental sustainability.

Previous studies have shown that sugar beet yield and sugar recovery are highly responsive to N management and environmental conditions, with optimum N rates varying across regions and seasons (Tarkalson et al., 2012; Maharjan & Hergert, 2019). However, limited information is available on how irrigation levels interact with N rates to affect beet yield, sugar concentration, and N_2O emissions in Western Nebraska.
The objective of this experiment was to assess the effects of urea-N rates and irrigation levels (full and deficit) on beet yield, sugar concentration, and N_2O emissions in the Nebraska Panhandle.

MATERIALS AND METHODS

This experiment was conducted in 2025 at the University of Nebraska–Lincoln (UNL) Panhandle Research, Extension, and Education Center (PREEC) in Scottsbluff, NE (41°03′39″ N, 103°40′54″ W; elevation 1198 m) to evaluate the effects of nitrogen (N) and irrigation management on sugar beet yield, sugar concentration, and N_2O emissions. The experiment followed a split-plot design with four replications. The main-plot factor was irrigation (Full and Deficit), and the split-plot factor was urea-N rates (0, 50, 80, 100, 125, and 150% of the recommended N rate based on the current UNL algorithm). The UNL algorithm accounted for the yield goal, pre-plant soil test N, and soil organic matter mineralization. The yield goal was 78.45 Mg ha-1 and pre plant soil test N indicated 66 kg N ha^{-1}. The corresponding N application rates were 0, 97, 155, 194, 243, and 291 kg N ha^{-1}. Urea was surface broadcast uniformly in all fertilized plots at crop emergence and incorporated into the soil with irrigation. Irrigation was supplied through a sprinkler system twice weekly. The full (100%) irrigation treatment received 18.98 inches of water, and the deficit (75%) treatment received 14.78 inches at the end of the season. The full (100%) irrigation level was determined based on weekly crop water-use data for sugar beet.

Soil N_2O fluxes were measured using a LI-7820 N_2O/H_2O trace gas analyzer equipped with a smart chamber top (LI-COR Biosciences, Lincoln, NE, USA). Polyvinyl chloride (PVC) rings (20 cm diameter, 12.5 cm height) were installed between the second and third crop rows in each plot, inserted 6 cm deep into the soil. Gas fluxes were measured before fertilization (baseline) and twice a week after fertilization until harvest. Cumulative N_2O emissions were calculated using trapezoidal integration of fluxes over time. The middle two rows of each plot were harvested to determine root yield. After weighing, 15–20 randomly selected beets from each plot were bagged and sent to the Western Sugar factory tare laboratory for beet sugar concentration. Treatment effects were analyzed using ANOVA in SAS at a significance level of 0.05.

RESULTS AND DISCUSSION

Table 1. Beet yield, sugar concentration, and cumulative N_2O emissions affected by N rates under deficit and full irrigation

Factors	**Beet yield** (Mg ha^{-1})	**Sugar concentration** (g kg^{-1})	**Cumulative N_2O Emission** (kg N ha^{-1})
Irrigation Level (I) (%, inches)			
Deficit (75, 14.78)	61.61	167.73	2.21
Full (18.98)	66.30	164.84	1.73
Significance level (p value)	0.119	0.316	0.241
Applied N (R) (%, kg ha^{-1})			
(0, 0)	51.43 **b***	169.55	0.26 **d**
(50, 97)	63.69 **a**	170.25	0.88 **cd**
(80, 155)	64.40 **a**	165.28	1.45 **bcd**
(100, 194)	67.91 **a**	166.74	1.92 **bc**
(125, 243)	67.38 **a**	161.81	2.85 **b**
(150, 291)	68.92 **a**	164.08	4.45 **a**
Significance level (p value)	**0.003**	0.201	**0.0001**
Interaction effect (I X R)			
Significance level (p value)	0.63	0.085	0.173

*Different letters behind mean values indicate significant treatment differences at $p \leq 0.05$.

There was no significant interaction between irrigation level and nitrogen rate for beet yield, sugar concentration, or cumulative N_2O emissions. Beet yield was not significantly affected by irrigation level (p = 0.119), with an average yield of 66.30 Mg ha^{-1} under full irrigation and 61.61 Mg ha^{-1} under deficit irrigation (Table 1). However, N application significantly influenced beet yield (p = 0.003) (Table 1). The lowest yield (51.43 Mg ha^{-1}) was observed in the control (0 % N) (Table 1). The treatments at ≥50% of the recommended N had higher root yield (63.69-68.92 Mg ha^{-1}), indicating that 50% of the recommended N rate was sufficient to achieve maximum beet yield under the tested conditions (Table 1).

However, the beet yield showed a significant positive linear relationship with the nitrogen rates (N) under both deficit (p=0.03, Figure 1.a) and full irrigation (p=0.03, Figure

1.b), suggesting that beet yield would increase with the increase in N rates. Ghimire & Maharjan (2024) also reported that fertilizer N application increased the root yield compared to the control treatment. In contrast, Ghimire et al. (2025) reported that treatments receiving ≥80% of the recommended N rate produced higher root yields than the control. In contrast, this study showed that ≥50% of the recommended N rate achieved higher root yields, likely because it also included deficit irrigation conditions. In deficit irrigation conditions, yield potential is reduced, thereby requiring less N than under full irrigation.

Sugar concentration was not significantly affected by either irrigation ($p = 0.316$) or N rate ($p = 0.201$). The mean sugar concentration was 167.73 g kg^{-1} under deficit irrigation and 164.84 g kg^{-1} under full irrigation. Across N rates, sugar concentration ranged from 161.81 to 170.25 g kg^{-1}, decreasing with increasing N application. This indicates that sugar concentration remained relatively stable despite variations in water and nitrogen supply under the tested conditions. Ghimire and Maharjan (2024) reported that fertilizer application reduced sugar concentration in most cases compared to the control treatment, consistent with the trend observed between N rate and sugar concentration in this study.

Cumulative N_2O emissions were not significantly affected by irrigation level ($p = 0.241$), with an average emission of 1.73 kg N ha^{-1} under full irrigation and 2.21 kg N ha^{-1} under deficit irrigation (Table 1). However, N application had a significant effect on cumulative N_2O emissions ($p < 0.001$) (Table 1). The lowest N_2O emissions (0.26 kg N ha^{-1}) were observed in the control (0% N), while N_2O emissions increased with increasing N rates. The cumulative N_2O emissions trend across N rate treatments was 0%≤50%≤80%=100%≤125%<150%, indicating that increasing fertilizer N beyond crop requirement substantially elevated N_2O losses (Table 1). The cumulative N_2O emission showed a significant positive linear relationship with the nitrogen rates (N) under both deficit ($p=0.02$, Figure 2.A) and full irrigation ($p=0.004$, Figure 2.B), suggesting that emissions would increase with the increase in N rates. Ghimire et al. (2025) also reported that cumulative N_2O emissions increased linearly with increasing nitrogen rates over two years in irrigated sugar beet.

Overall, irrigation did not have a statistically significant effect ($p < 0.05$) on beet yield, sugar concentration, or cumulative N_2O emissions. However, certain trends were observed across treatments. Full irrigation resulted in a higher beet yield at a near-significant level ($p=0.119$) and lower cumulative N_2O emissions ($p=0.241$). Nitrous oxide is an intermediate product of the anaerobic denitrification process, which microbes can further reduce to harmless N_2 gas. Nömmik (1956) reported that maximum anaerobic denitrification occurs when the water-filled pore space is >70%. Full irrigation may have promoted complete anaerobic denitrification, as it likely increased the water-filled pore space >70%, allowing more complete reduction of N_2O to N_2. In contrast, deficit irrigation likely maintained the water-filled pore space below 70%, favoring both aerobic/anaerobic emissions and resulting in higher N_2O accumulation.

In contrast, sugar concentration was higher under deficit irrigation, showing a trend toward significance (p = 0.316), which was farther from the tested significance level. These results indicate that although irrigation effects were not statistically significant, full irrigation tended to enhance beet yield and reduce N_2O emissions, whereas deficit irrigation slightly increased sugar concentration.

Beet Yield & Sugar Concentration

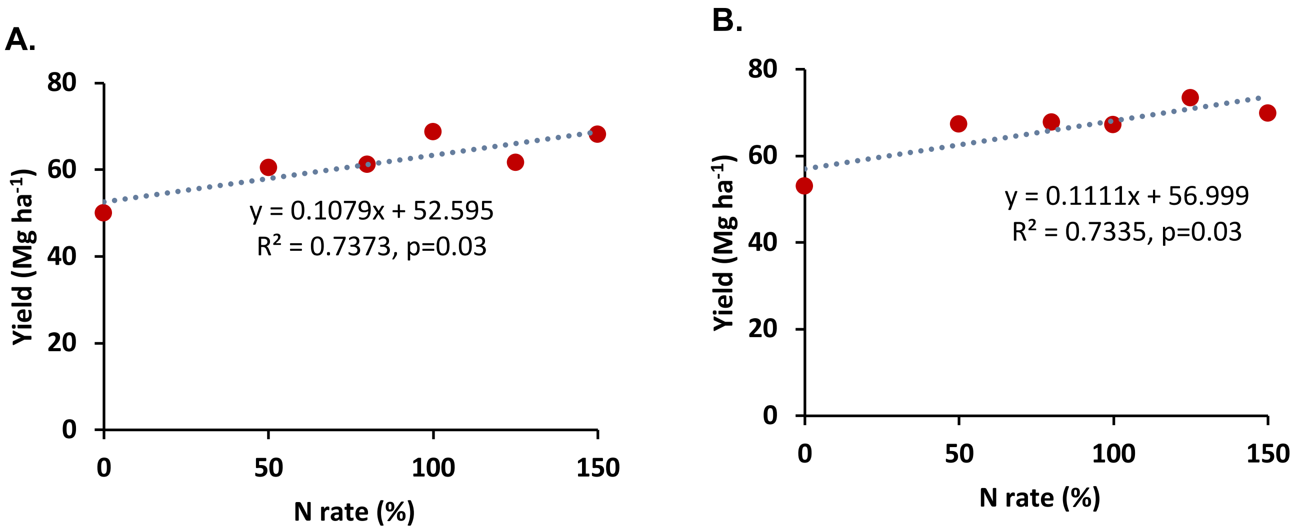

Figure 1. Relationships between sugar beet root yield and nitrogen rates under (A) deficit irrigation and (B) full irrigation.

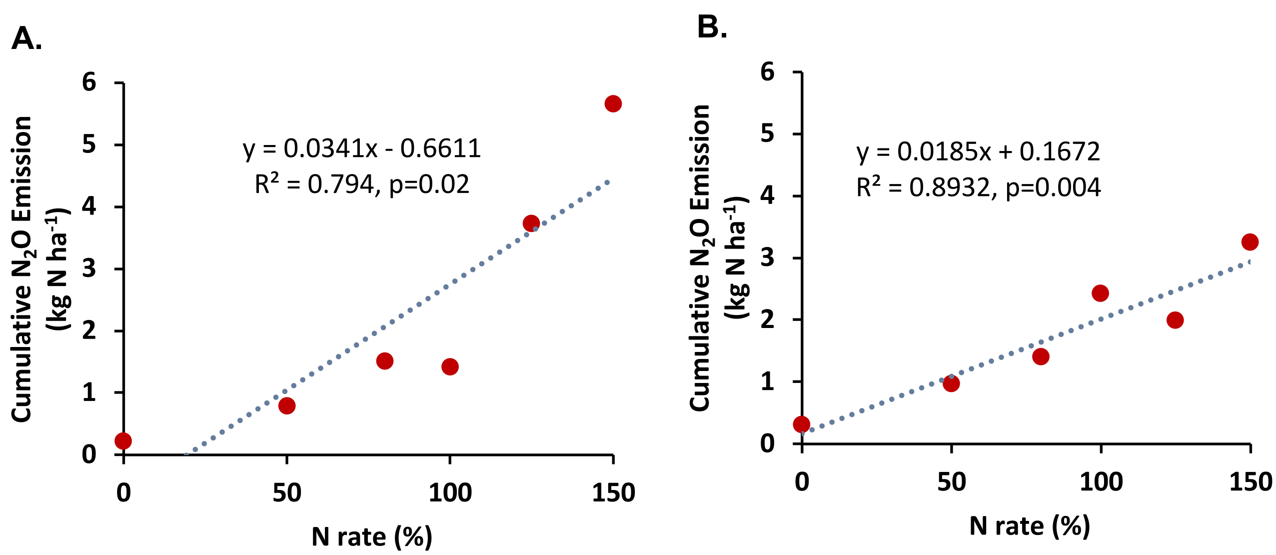

Figure 2. Relationships between Cumulative N_2O Emission and nitrogen rates under (A) deficit irrigation and (B) full irrigation.

CONCLUSIONS

This study examined the effects of irrigation and nitrogen rates on sugar beet yield, sugar concentration, and N_2O emissions in Western Nebraska. Nitrogen application significantly increased beet yield and N_2O emissions, while irrigation level had no significant effect. Full irrigation produced higher yield and lower N_2O emissions compared to deficit irrigation, likely due to greater soil moisture promoting more complete denitrification. In contrast, deficit irrigation slightly increased sugar concentration, possibly because mild water stress enhanced sugar accumulation. These results highlight trade-offs between irrigation and nitrogen management to optimize yield, sugar quality, and greenhouse gas emissions. Applying 50% of the recommended N rate under full irrigation appears to be a sustainable solution for maintaining productivity while minimizing environmental impacts in sugar beet systems of Western Nebraska.

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FROM THE GROUND UP: A FARMER-LED ON-FARM RESEARCH EVALUATING THE POTENTIAL OF A NEW FERTILIZER SOURCE FOR NITROGEN IN PASTURES FOR MISSOURI

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ABSTRACT

This research is a part of a transdisciplinary network of farmers leading on-farm research and innovation groups across Missouri, where farmers are leading the design and implementation of nitrogen (N) fertilizer treatments. The Objective of this on-farm research trial in southwest Missouri is to determine whether green lightning fertilizer technology can fulfill the N requirement of pasture in a more economical and sustainable way than the conventional sources of N.

The cost of N fertilizer is one of the important factors in the overall profitability of forage production in Missouri. Nitrogen fertilizer alone could cost 8-10% of the total operating cost for pasture establishment in Missouri. Most N fertilizers are susceptible to loss through volatilization and leaching, which could also reduce the return on investment for growers with pastureland. Almost all the fertilizer made today relies on the Haber–Bosch process for ammonia synthesis, which has a significant environmental impact. Green lighting fertilizer is based on the concept of synthesizing N-based fertilizer through humid air using plasma in a sustainable way.

The pasture plots were treated with green lighting fertilizer (20-gal ac^{-1}), a product that the manufacturer claims contain nitrate, ammonium nitrate (40 lbs N ac^{-1}), Super-U (40 lbs N ac^{-1}), and a no-N fertilizer control plot. Baseline soil sampling was done in each plot for the soil fertility analysis before the treatments were established. The treatments were applied in last week of March 2025, and all fertilizer sources were applied using a utility drone. Forage yield and quality data were collected in April and May 2025. The N treatments will be applied for the next three years, and forage sampling will continue to document any significant changes between pasture plots.

In April, there was a significant difference in yield between green lightning fertilizer and conventional fertilizer treatments ($p = 0.0021$), and a marginal difference between green lightning and the control treatment ($p = 0.0548$). Green lightning produced a 20.6% lower yield than the control, 32% lower yield than ammonium nitrate, and 39.4% lower yield than urea in April. In the May forage biomass sampling, the only significant difference was between green lightning and conventional fertilizers, where green lightning produced 28.2% lower yield than ammonium nitrate and 33.5% lower yield than Super-U. Technical issues with the machine during the first application may have limited nitrate production,

and nitrogen was below detectable levels in the GL fertilizer, possibly explaining the lower forage yield.

IMPACTS OF MANAGEMENT PRACTICES AND SOIL PROPERTIES ON FREE-LIVING NITROGEN FIXATION IN SOUTHEASTERN SOUTH DAKOTA

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ABSTRACT

The excessive use of synthetic nitrogen (N) fertilizers in modern agriculture raises economic and environmental concerns. Biological dinitrogen (N_2) fixation offers a sustainable alternative to supply N, with free-living diazotrophs playing a crucial role alongside well-known symbiotic nitrogen-fixing bacteria. Interest in free-living nitrogen fixation (FLNF) has grown due to its potential contribution to sustainable agricultural practices. In recent years, various companies have introduced biofertilizers that could boost FLNF in the Midwestern USA, but many have not considered how soil properties and conservation methods might affect this process. This study examines how crop rotations (2-, 3-, and 4-year systems), tillage practices (conventional vs. long-term no-till), and cover cropping affect potential FLNF in Southeastern South Dakota, by assessing their impacts on key soil properties and how these influence microbial N_2 fixation. Surface soil samples (0-3") were collected at pre-planting, and V5, VT, and R6 corn growth stages in 2024 and 2025 to measure the potential nitrogen fixation rate through $^{15}N_2$ incorporation. Initial findings showed that cover cropping did not significantly impact fixation rates. In 2024, the highest potential fixation was observed in the 2-year corn-soybean rotation, particularly before planting and under conventional tillage, while no-till systems maintained lower but steadier fixation rates throughout the season. Among the soil properties evaluated (potentially oxidizable carbon, cation-exchange capacity, potentially mineralizable nitrogen, exchangeable ammonium-N, nitrate+nitrite-N, and soil pH), soil pH played a mediating role in how tillage is related to FLNF. These results offer valuable insights into how free-living nitrogen fixation operates across different cropping systems and highlight the importance of conservation systems in promoting soil stability.

INTRODUCTION

Synthetic nitrogen (N) fertilization has been contributing to world's food production since the Green Revolution, and it has become a trending topic regarding N use efficiency and N losses. Before the widespread adoption of industrial N, biological dinitrogen (N_2) fixation (BNF) played a crucial role in supplying N to crops. This process remains significant today, especially in regions where soybean production is economically viable without relying on synthetic N inputs such as in the Midwestern USA (Russelle, 2008). Furthermore, N_2 can be fixed by free-living diazotrophs, which can be found in most soils. This topic has had significant interest by researchers since its discovery in the early 20th century until the Green Revolution. With the increasing consumption of synthetic N, research on free-living N fixation began to decline and has been put aside. However, in recent years, there has been a growing interest in this area, reflecting the recognition of its contribution to sustainable agriculture.

Nitrogen fixation that occurs without symbiosis between plants and microbes is known as free-living nitrogen fixation (FLNF). Unlike symbiotic diazotrophs, free-living bacteria lack a stable microenvironment and the resources provided directly by the plant. Under these circumstances, it is important to highlight the significance of soil properties, as these bacteria depend on the broader environment to regulate their activity (Smercina et al., 2019). Key factors that affect free-living N-fixing bacteria include carbon availability, oxygen concentration, soil moisture, temperature, pH, nutrient status, particularly N, phosphorus, molybdenum, and iron. As a result, the rates of N fixation are typically lower than those in symbiotic relationships, with an estimated contribution up to 54 lbs N ac^{-1} yr^{-1} (Orr, 2011). Despite their lesser contribution compared to symbiotic fixers, free-living diazotrophs are widely distributed in various environments. Given proper study and exploration, these organisms have not only the potential to significantly enhance nitrogen fixation rates (Khan et al., 2021) but also act as plant growth-promoting bacteria (Kennedy et al., 2004).

Over the past years, several companies have released biofertilizers with the potential to increase FLNF in the Midwestern USA. However, most of them have overlooked how edaphic properties and conservation practices may influence this process. In South Dakota's agricultural systems, scientific data on FLNF is limited. Therefore, my research aims to evaluate the impact of different sustainable agricultural practices, such as tillage intensity, crop rotations, and cover crops, on the ability of free-living bacteria to enhance soil nitrogen supply through fixation.

MATERIALS AND METHODS

Site description

This two-year study is being conducted at the South Dakota State University Research Farm near Beresford, South Dakota, during the 2024 and 2025 corn (*Zea mays* L.) growing seasons. The experimental plots are part of a long-term study on tillage and crop rotation. Since 1991, a no-tillage system has been in place, with consistent crop rotation for the past thirteen years and a seven-year history of cover crop planting. All plots are situated on nearly flat areas with slopes under 1%, and the soils belong to the Egan series, characterized as Fine-silty, mixed, superactive, mesic Udic Haplustolls.

Plot layout followed a split-plot arrangement in a randomized complete block design, with four replicates. Crop rotation (2-, 3-, and 4-year systems) was assigned to main plots, tillage (conventional vs. no-till) to subplots, and cover cropping (with vs. without) to sub-subplots.The 2-year crop rotation consisted of corn-soybean (*Glycine max* L. Merr.), the 3-year rotation included corn-soybean-oat (*Avena sativa* L.), and the 4-year rotation had corn-soybean-oat-rye (*Secale cereale* L.). Winter wheat (*Triticum aestivum* L.) was planted in October as the cover crop for both years. Apart from the experimental factors evaluated, all other management practices, including fertilization, were kept uniform across all the sampled plots.

Sampling and data collection

Soil samples were collected from the surface (0-3" depth) throughout both seasons during pre-plant (PP), V5, VT, and R5 corn-growth stages. A composite sample consisting of 4-5 cores was taken from each replication. Part of the sample was kept fresh for potential fixation assessment, while the rest was dried in an oven (50 °C) and ground to <2mm. To measure the potential N_2 fixation by the free-living bacteria, an assay technique involving ^{15}N-labled dinitrogen ($^{15}N_2$) was conducted following the incubation method described by Zhou et al. (2025). The soil parameters analyzed are summarized in Table 1. They included soil pH, determined for a slurry with soil/water ratio of 1:1 (Peters et al., 2015), exchangeable N (NH_4^+-, NO_3^--, and NO_2^--N) by the direct-diffusion method (Khan et al., 2000), potentially mineralizable N (PMN) by the Illinois soil N test-2 (Nunes et al., 2025), permanganate oxidizable carbon (POxC) by Culman et al. (2012), and Bray-1 P with the Ascorbic Acid method (Frank et al., 2015).

Table 1. Summary of soil sampling stages and parameters analyzed.

Sampling stage	Measurements
PP	Soil pH, Mineral Nitrogen, PMN, POxC, Bray-1 P, CEC, Potential N_2 Fixation
V5	Soil pH, Mineral Nitrogen, Potential N_2 Fixation
VT	Soil pH, Mineral Nitrogen, Potential N_2 Fixation
R5	Soil pH, Mineral Nitrogen, Potential N_2 Fixation

Data analysis was conducted with a linear mixed-effects model (LMM), considering tillage, crop rotation, and sampling stage as fixed factors. Block and their interactions were treated as random effects to account for the split-plot design. The cover crop was excluded from this model because it was not significant in the full model. Soil pH was included as a covariate (mediator) to account for chemical differences across plots. Main effects and interactions were tested using Type III ANOVA with Satterthwaite's approximation. Tukey's HSD test was employed for mean comparisons ($\alpha = 0.05$). Significant interactions were further analyzed using estimated marginal means (EMMs).

RESULTS AND DISCUSSION

Across all treatments in 2024, the potential N fixation was heavily influenced by management practices and soil chemical conditions. However, these factors did not act independently; their effects overlapped and interacted, impacting the N fixation by free-living bacteria. The presence of a cover crop did not affect the results (p>0.05), likely due to poor establishment and the harsh winter in South Dakota.

Seasonal dynamics under different tillage and rotation systems

Under conventional tillage (CT), higher potential fixation rates were generally observed early in the season, especially before planting. In contrast, under no-tillage, rates were lower but more stable throughout the growing season (Figure 1). Crop rotation influenced potential nitrogen fixation solely under conventional tillage, with the 2-year rotation showing the highest rates before planting, while the 4-year rotation peaked at R5 (Figure 2). In no-till systems, fixation stayed consistent throughout the season, and no effects from rotation were observed. Overall, these results show that tillage and rotation shape the seasonal dynamics of free-living nitrogen fixation, with conservation practices enhancing stability throughout the season.

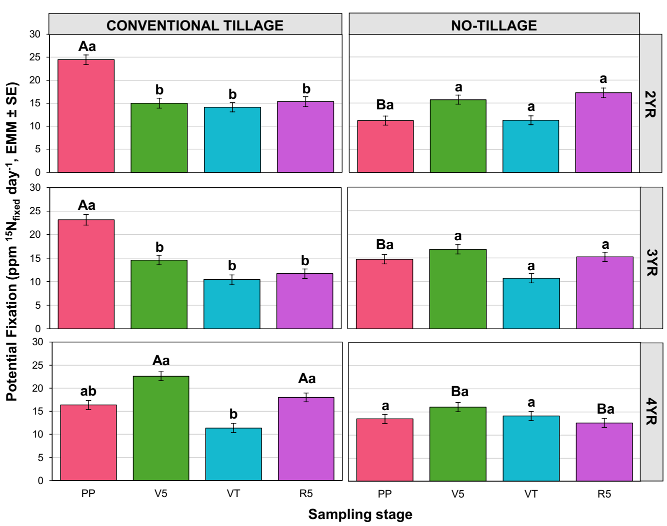

Figure 1. Potential N_2 Fixation throughout the growing season under conventional tillage and no-tillage across the three crop rotations in 2024. Bars represent estimated marginal means ± standard error (EMM ± SE). Different lowercase letters indicate significant differences among sampling stages within each tillage × rotation combination (Tukey's test, α = 0.05). Different uppercase letters indicate differences among tillage systems within each rotation × sampling stage combination (Tukey's test, α = 0.05).

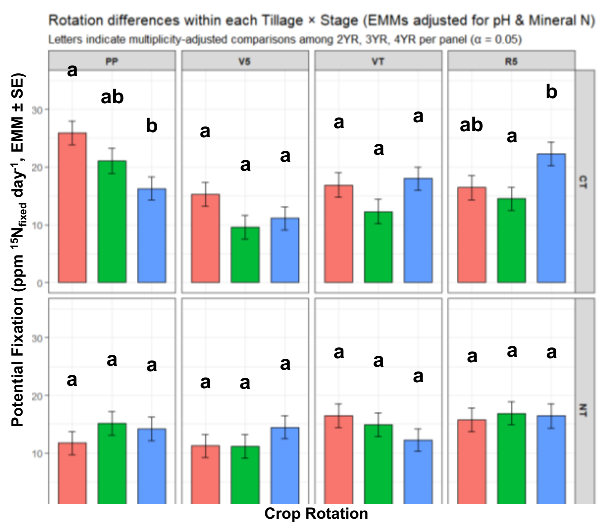

Figure 2. Rotation effects on potential N_2 fixation within each tillage × sampling stage combination in 2024. Bars represent estimated marginal means ± standard error (EMM ± SE). Different lowercase letters indicate significant differences among crop rotations (2-, 3-, and 4-year systems) within each tillage × stage panel (Tukey's test, α = 0.05). CT represents conventional tillage and NT, no-tillage.

Soil pH mediates the effect of tillage on potential N_2 fixation

Among the soil properties evaluated, soil pH played a key role as a mediator, linking tillage to potential fixation rates. Instead of acting independently, tillage interacted with pH (p=0.012), influencing how potential fixation responded across the studied pH range (~4.6-6.7). This suggests that tillage modifies the soil chemical environment in ways that affect the sensitivity of free-living nitrogen fixation to soil pH. The distribution of soil pH in categories (Figure 3), ranging from 1 (more acidic) to 5 (closer to neutral), supports this interaction, showing that soils under conventional tillage tended to have higher pH values than those under no-till. Consequently, fixation was more responsive to pH under conventional tillage, while under no-till, the relationship between fixation and pH was weaker, suggesting that this system provides a more buffered environment (Figure 4). In addition, the acidic conditions under no-till also explain the lower overall fixation rates in this system, since many diazotrophs are neutrophiles and are more abundant when soil pH > 6.0 (Martin et al., 1937).

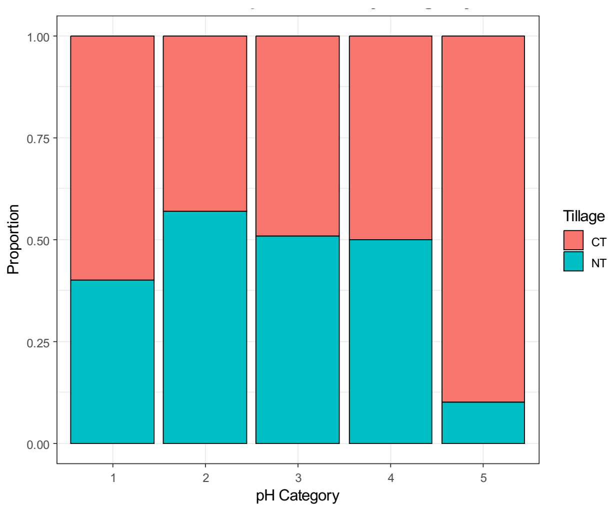

Figure 3. Distribution of soil pH categories under conventional tillage (CT) and no-tillage (NT) systems. Bars represent the proportion of

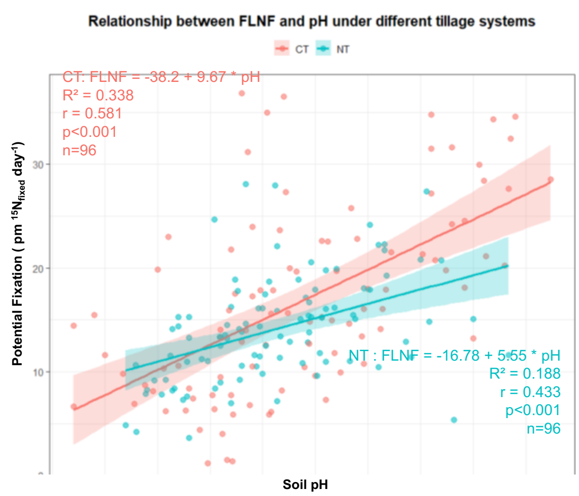

Figure 4. Relationship between soil pH and potential N_2 fixation under conventional tillage (CT) and no-tillage (NT) systems. Each point represents an individual soil sample (n = 96 per tillage system). Regression lines represent linear fits with 95% confidence intervals (shaded areas).

CONCLUSION

Considering how much reliance is placed on synthetic N fertilizer, it is crucial to explore alternatives. However, the use of biological products should take into account the entire agricultural system, and their performance might vary even at a small local scale due to interactions among management factors. This study highlights how agricultural management practices influence the potential free-living N_2 fixation for a specific location in Southeastern South Dakota; nonetheless, it emphasizes the need for proper research into how edaphic properties provide the conditions for these bacteria to thrive.

The results showed that tillage and rotation together shape the seasonal pattern of N_2 fixation by free-living bacteria, with no-tillage systems exhibiting lower but more consistent rates. Among the chemical parameters analyzed (not all results are presented here), soil pH interacted with tillage, indicating that tillage alters the chemical environment and affects the performance of N-fixing bacteria. Overall, this highlights that conservation practices help maintain stable biological N inputs over time, while conventional tillage promotes short-term N fixation during favorable seasonal conditions.

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EFFECT OF COVER CROP DIVERSITY ON NITROUS OXIDE EMISSIONS FROM CORN–SOYBEAN ROTATIONS IN CENTRAL ILLINOIS

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ABSTRACT

Nitrous oxide (N_2O) is a potent greenhouse gas primarily emitted from agricultural soils, where nitrogen (N) inputs and soil conditions interact to drive microbial processes. Cover crops are widely promoted as a climate-smart strategy to improve soil health and nutrient cycling, yet their effectiveness in mitigating N_2O emissions may vary depending on species composition and functional diversity. This study evaluated the influence of cover crop diversity on N_2O emissions in a corn–soybean rotation system in Central Illinois. Sixteen tile-drained plots were established with four treatments: cereal rye, red clover, a hairy vetch–radish mixture, and a no-cover control. With over 22 sampling dates during the 2024 and 2025 growing season, N_2O fluxes were quantified using static chamber methods, while soil nitrogen availability, moisture, and temperature were monitored to interpret emission patterns. The hypothesis guiding this work was that mixtures containing legumes and brassicas would reduce N_2O emissions more effectively than cereal rye alone by improving nitrogen use efficiency and synchronizing nutrient release with crop demand. Preliminary findings suggest that cover crop mixtures altered soil N dynamics relative to cereal rye monocultures and fallow controls, with differences in temporal emission patterns likely mediated by soil moisture and temperature interactions. Crop yield responses were also assessed, providing a critical link between environmental outcomes and agronomic performance. Collectively, these results advance understanding of how cover crop diversity can influence greenhouse gas emissions and nitrogen cycling, with implications for designing management practices that enhance both environmental sustainability and productivity in Midwestern corn–soybean systems.

INTRODUCTION

Nitrous oxide (N_2O) has a global warming potential approximately three hundred times greater than carbon dioxide over a 100-year period. Chemical reactions for nitrous oxide will take longer than what it would take to destroy and remove carbon dioxide, with the breakdown of N_2O into atmospheric N2 calculated to take approximately 121 years, as explained by the US EPA (2024). According to data from the United States Environmental Protection Agency in 2022, around 75% of nitrous oxide emissions in the United States are attributed to agricultural soils. Which is why it is crucial to explore alternative strategies to mitigate nitrous oxide emissions.

The emission of nitrous oxide from agricultural soil is a significant concern for climate change. N_2O is released primarily during the denitrification process, particularly under conditions of excess nitrogen availability and low oxygen levels in the soil. The conversion of nitrate to N_2O is more likely to occur in waterlogged soils or in fields with high organic matter, where anaerobic conditions prevail (Hanrahan et al., 2021). Factors such as soil temperature, moisture content, and pH can all influence the rate of N_2O production. For example, warmer temperatures and high moisture levels often accelerate denitrification, leading to higher emissions of nitrous oxide. Moreover, the overuse of nitrogen fertilizers increases the amount of available nitrate, thereby amplifying N_2O emissions (Bashir et. al, 2013).

Some studies have compared various agricultural systems and management practices, such as conservation tillage and traditional practices, which can include fertilization after harvest and no use of cover crops. While the benefits of some cover crops species are starting to get more recognition, challenges remain in their widespread adoption. In Central Illinois, factors such as the timing of cover crop planting, potential interference with cash crop planting, and the costs of seeds and labor can deter some farmers (Carver et al., 2021). However, programs offering financial incentives and technical support can help overcome these barriers. Extension services, government initiatives, and research collaborations can play a critical role in educating farmers about the long-term benefits of cover crops and providing resources to support their implementation. As more farmers in Central Illinois recognize the role of cover crops in reducing nitrogen losses, these practices are likely to become an integral part of sustainable agriculture (Johnson et al., 2024).

However, there remains a gap in understanding how different cover crop species, in combination with field management practices, affect nitrogen loss rates. The fluctuating rates of N_2O emissions and, therefore, nitrogen losses tend to occur due to the cover crops taking up the nitrogen in the soils (Charteris et al., 2020), which later becomes a source of nitrogen through the decomposition process. That is why this paper had the main objective to evaluate the effect of diverse cover crop species, including legumes and brassicas, compared to no cover on nitrous oxide emissions in a corn–soybean rotation system.

MATERIALS AND METHODS

This study was conducted at the University of Illinois Dudley Smith Farm located in Christian County, Illinois. The region has a temperate climate with a 30-year (1991–2020) average annual rainfall of 1083 mm. The predominant soil is a Virden silty clay loam (fine, smectitic, mesic Vertic Argiaquolls), classified as poorly drained, with 0–2% slopes. Weather data was recorded using an on-site meteorological station. Detailed descriptions of the experimental site and instrumentation were previously reported by (Preza Fontes et al., 2019; Preza-Fontes et al., 2021)) with the site's layout and instrumentation following standard procedures for tile-drained plot research.

The research site, established in 2016, contains 16 subsurface drainage plots, each measuring approximately 0.85 ha. Between 2018 and 2021, the site was in a continuous corn, strip-tillage system evaluating nitrogen management and cover cropping strategies (Preza-Fontes et al., 2021).

In the fall of 2023, a new crop rotation study began, evaluating three levels of cover crops in a corn–soybean rotation: (1) no cover crop (control), (2) cereal rye, and (3) a mixture of daikon radish and hairy vetch, and (4) red clover. The experiment followed a randomized complete block design with four replications.

In the 2023–2024 season, cover crops were planted on October 16, 2023, at seeding rates of 70 kg ha^{-1} for cereal rye, 11 kg ha^{-1} for red clover, and a mixture of 5.6 kg ha^{-1} of daikon radish with 22.4 kg ha^{-1} of hairy vetch. Cover crops were terminated on April 4, 2024, using glyphosate at 1.29 kg ha^{-1}, and soybean was planted on May 15, 2024. In the 2024–2025 season, cover crops were planted on September 19, 2024, following the same seeding rates and species composition. Termination was carried out on May 7, 2025, with glyphosate at 1.29 kg ha^{-1}, and the subsequent corn crop was planted on May 5, 2025.

Nitrous oxide emissions

N_2O emissions were measured following the USDA-ARS GraceNET project protocol. A static chamber was installed at least 48 hours before the first measurement to allow the soil to settle. The chamber remained in the field for the season and was only removed during key field operations such as planting. Chambers were accompanied by sensors measuring soil temperature and moisture at two and five inches. Nitrous oxide emissions were measured using a Gasmet GT5000 Terra Portable Gas Analyzer. Measurements were taken at increased frequency depending on the stage of the growing season, with sampling conducted twice per week after planting. A total of 24 sampling dates were collected during 2024 and 28 sampling dates during 2025.

In season soil sampling

Soil samples were collected at least once a month since before planting until harvest. Composite soil samples consisting of five cores total, divided in row and between rows to analyze for nitrate (NO3) and ammonium (NH4). All cores were collected at a depth of eight inches to be transported to the laboratory where 7 grams of soil were weighed and dried in an oven at 105°C. as the following step, 2 duplicates were weighed between 12.0 – 12.060 g and 100 ml of a solution of KCl was added to each to later shake for an hour. Samples were allowed to sit for 45 minutes after shaking and after that time had elapsed, they were filtered with 0.1mg filter paper. After going through the extraction process, samples were analyzed for ammonium and nitrate with Automated Discrete Analyzer SmartChem® 200.

Statistical Analysis

Data was analyzed using R software (version 4.5.1). A randomized complete block design was applied, with cover crop treatments considered as fixed effects. Mean differences among treatments were compared using the LSD test at a significance level of $\alpha = 0.05$.

RESULTS AND DISCUSSION

Nitrous oxide emissions

In 2024, cumulative N_2O–N fluxes showed clear differences among cover crop treatments throughout the growing season as showed in figure 1. Emissions increased steadily from April to October, with the cereal rye treatment consistently exhibiting the highest cumulative N_2O–N flux, reaching approximately 1.4 kg N ha^{-1} by October. The red clover treatment followed closely, while the no cover and hairy vetch + radish treatments produced comparatively lower emissions, both remaining below 1.0 kg N ha^{-1}. The early rise in emissions under cereal rye suggests that its residue decomposition and associated N immobilization processes stimulated denitrification, particularly under warm and moist conditions during late spring and early summer.

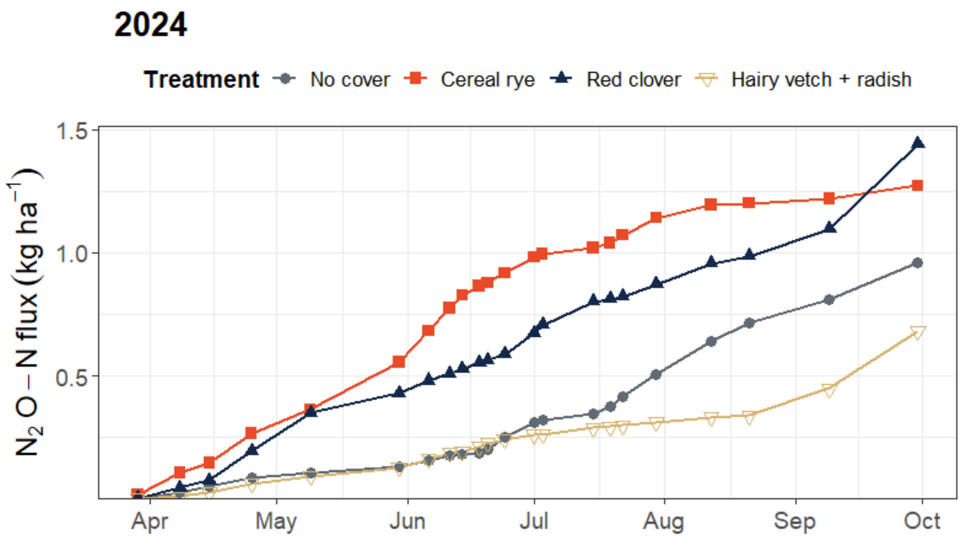

Figure 1. 2024 Cumulative fluxes

In 2025, cumulative N_2O–N fluxes were notably higher overall compared to the previous year, with pronounced differences between treatments as seen in figure 2. Emissions remained low during early spring but began to rise steadily in June, reaching a sharp increase from July to August. The cereal rye treatment showed a rapid escalation in fluxes during this period, exceeding 3.0 kg N ha^{-1} by October, while the no cover treatment reached about 2.0 kg N ha^{-1}. This sharp increase in the cereal rye plots coincided with the fertilizer application period, suggesting strong interactions between cover crop residue decomposition, available nitrogen, and favorable moisture and temperature conditions that promoted denitrification.

Although no statistically significant differences were observed, a noticeable shift in the emission dynamics was evident in 2025. Nitrogen fertilizer was applied in mid-May, which coincided with a divergence in the seasonal emission trends. Additionally, data from the weather station indicated higher rainfall accumulation in July, during which a 51.6% increase in emissions was observed for cereal rye

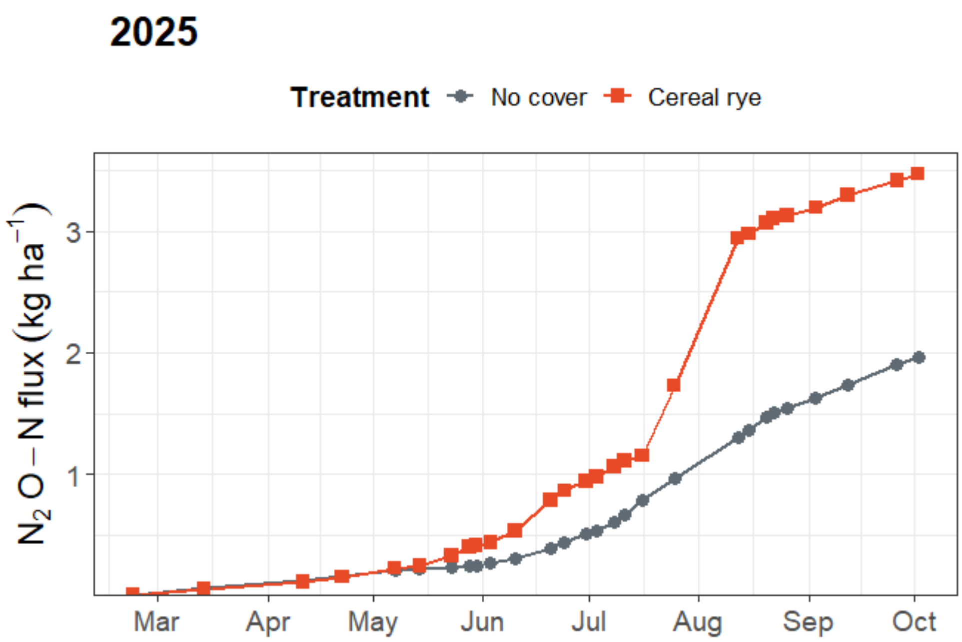

Figure 2. 2025 Cumulative fluxes

Table 1. Yield and yield scale losses summary

CC Treatment	Soybean Yield Mg/ha	cN2O_kgha	Yield-scaled N2O emissions (kg N_2O^- Mg^{-1} grain)	Corn Yield Mg/ha	cN2O_kgha	Yield-scaled N2O emissions (kg N_2O^- Mg^{-1} grain)
Cereal rye	4.4 b	1.25	0.28	13.95	3.46	0.248
No cover	5.0 a	0.958	0.19	14.78	1.11	0.075
Red clover	4.8 a	1.44	0.30			
Vetch & Radish	4.9 a	0.68	0.14			
P-value	0.012	0.59		0.21	0.49	

Soybean yield differed significantly among cover crop treatments ($P = 0.012$), with the no cover, red clover, and vetch & radish treatments producing higher yields (4.8–5.0 Mg ha^{-1}) compared to cereal rye (4.4 Mg ha^{-1}) (Table 1). Despite these differences in yield, cumulative N_2O emissions during the soybean phase were not significantly affected by cover crops ($P = 0.59$). However, yield-scaled N_2O emissions tended to be higher under red clover (0.30 kg N_2O–N Mg^{-1} grain) and cereal rye (0.28 kg N_2O–N Mg^{-1} grain) than under no cover or vetch & radish, indicating that legume-based and high-residue covers may slightly increase N_2O losses relative to grain yield efficiency.

In contrast, no significant differences were found among treatments for corn yield or N_2O emissions in the 2025 season ($P = 0.21$ and $P = 0.49$, respectively). Corn yields ranged from 13.9 to 14.8 Mg ha^{-1} across treatments, while cumulative N_2O emissions varied from 1.11 to 3.46 kg N_2O–N ha^{-1}. The cereal rye treatment exhibited higher cumulative and yield-scaled N_2O emissions compared to the no cover treatment, suggesting that the decomposition of high C:N rye residues and subsequent nitrogen fertilizer application may have stimulated denitrification. Overall, results indicate that while cover crops had limited effects on corn yield, species with contrasting residue quality influenced N_2O emissions and their efficiency relative to grain production.

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SOYBEAN RESPONSE TO TILLAGE, ROW SPACING AND NUTRIENT MANAGEMENT PRACTICES IN SOUTHERN ILLINOIS

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ABSTRACT

Conservation tillage improves long-term soil health and water quality but may reduce early soybean (*Glycine max* L.) growth due to cooler, wetter soils and limited nutrient availability. This study evaluated integrated management strategies, including tillage, row spacing, and starter nitrogen (N) and sulfur (S) fertilization, to optimize soybean performance under Illinois conditions. Field trials were established in 2024 in southern Illinois. Two split-plot experiments were conducted: (i) three tillage systems (conventional, strip-till, no-till) × three fertility treatments control, UAN (15 lb N ac^{-1}), and UAN + ATS (15 lb N ac^{-1} + 10 lb S ac^{-1}) and (ii) two row spacings (15 vs. 30 inches) × the same fertility treatments. Soil sensors monitored moisture and temperature, and plant samples were collected at V4, R2, and R8 for analysis of nutrient uptake, growth, and yield components. Preliminary findings indicate that tillage and starter fertility had limited effects on soybean establishment or yield, while row spacing significantly influenced plant population and harvest index. Soybean yields were highest when received N+S fertilization in narrow row spacing. Wider row spacing decreased soybean yield confirming growers' preference for planting soybean in 15-inch row spacings. Future research should evaluate the response of soybeans to different landscape positions under N+S fertilization and row spacings.

FERTILIZER-DERIVED NITROGEN FATE IN MINNESOTA CORN WITH RYE AND KURA CLOVER COVER CROPS

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ABSTRACT

While ideally all fertilizer nitrogen (N) is utilized by crops, much can be lost to the environment as nitrate (NO_3), nitrous oxide (N_2O), or ammonia (NH_3). To enhance agronomic systems and mitigate environmental N loss, best management practices can be utilized. Here, urea was applied to continuous corn at 250 kg N/ha or a 0 kg N/ha control, and with select cover crops (no cover, winter rye, kura clover) to assess practices that may result in optimal fertilizer N utilization. Rye and no cover crop treatments showed significantly greater yield compared to both fertilized and unfertilized kura clover treatments, suggesting kura clover competes with corn for N availability. Volatilization of NH_3 was even across rate and cover crop treatments, though these losses only accounted for a small fraction of total N applied. Greater NO_3 leaching was shown with increased N rates for no cover crop and rye treatments, though this effect was smaller for kura clover, likely due to continuous deposition of kura biomass. Greater N_2O emissions were observed with increased fertilizer rates across all cover crop treatments, with the greatest emissions coming from kura clover, likely due to strong microbial interactions. Analysis of isotopic N dispersion shows that kura clover increased the loss of fertilizer-derived N_2O relative to rye and no cover treatments. Meanwhile, rye treatments showed greater fertilizer-derived NO_3 losses relative to kura clover. There was no difference in fertilizer-derived NH_3 across cover crop treatments. In total, only 1.38, 4.00, and 2.87 percent of applied fertilizer N was lost from the system in kura, rye and no cover treatments, respectively, suggesting an idealized nutrient management system. Further isotopic analysis of corn, cover crop, and soil N pools will help determine where fertilizer-derived N disperses in a given growing season.

INTRODUCTION

As the global demand for food and commodity goods increases, so does the demand for N to enhance crop production. While fertilizer-derived N is ideally utilized by crops, much can remain in the soil or be lost to the environment in various forms such as NO_3, N_2O, and NH_3. The loss of N from soil into the environment can cause substantial economic and environmental harm as it reduces crop yield for producers, amplifies the effects of global climate change, diminishes air and water quality, and disrupts natural ecosystem processes (Kumar et al., 2018; Stark & Richards, 2008). Economically optimum N rates (EONR) have been utilized to optimize crop uptake of fertilizer N with less loss of N to the environment and minimal economic loss to crop producers (Rubin et al, 2016). By investigating optimum fertilizer N input rates producers may profit from fewer agricultural inputs while still yielding crops that satisfy consumer driven markets.

The use of cover crops has also obtained increased interest in central Minnesota as they may be useful tools in combating the water and N loss common in this area. Substantial research has been done with N scavengers, such as winter rye, and N fixers, such as kura clover to determine their potential to enhance soil health (Krueger et al., 2011; Logsdon et al., 2002; Sainju and Singh, 1997) and influence soil biogeochemistry (Alexander et al., 2019; Peterson et al., 2002). However, relatively little is known about their potential to mitigate NO_3 leaching, N_2O emissions, or NH_3 volatilization (McCracken et al., 1994; Ochsner et al., 2010), or about best nitrogen management practices when these crops are growing in combination with corn specifically (Krueger et al., 2011; Pedersen and Albrecht, 2009).

To best assess the utilization or loss of N, stable isotopes can be used to trace the movement of N in crop-soil systems. Crops commonly grown in Minnesota, such as corn, may take up naturally occurring N (^{14}N) or anthropogenically introduced isotopes of N (^{15}N) throughout the growing season. With the introduction of ^{15}N enriched fertilizers, plants may incorporate this N isotope into their biomass, thereby allowing for the detection of fertilizer-derived N in field crops. Similarly, this technique can show where in soil, water, and gas fractions fertilizer-derived ^{15}N is, and in what chemical form. While isotopically labelled fertilizers have been utilized in agricultural soils before (Tran and Giroux,1998; Walter and Malzer, 1990; Lacey et al., 2022), much remains unknown about how ^{15}N fertilizers respond in central Minnesota sandy soils with additional cover crop by N rate combinations. Overall, this study aims to leverage a ^{15}N isotopic tracing approach to better determine fertilizer-derived N loss pathways in corn to address sustainable use of fertilizers and cover crop systems in sandy soil of central Minnesota, thereby allowing for greater economic returns for producers while limiting N outputs to the local environment.

MATERIALS AND METHODS

This study was conducted starting in the spring of 2023 at the Rosholt Research Farm (Westport, MN) as part of an ongoing study. Plots of continuous corn have been in place for several years, utilizing a winter-annul rye cover crop, continuous kura clover living mulch, or no additional crop as a control since 2016. Urea fertilizer with a urease inhibitor was applied as a four-way split application administer incrementally using 90-270 lbs N/ac, with no fertilizer addition as a control. Upon application, fertilizer was incorporated into the soil with a small amount of irrigation. Treatments were replicated four times in a randomized complete block design. To trace the utilization of fertilizer N by crops or loss from the soil, a ^{15}N isotopic enrichment was utilized for a subset of plots. Microplots were established in unfertilized control plots along with 225 lbs N/ac treatment blocks which were applied with 5 atom % ^{15}N urea.

Agronomic and environmental responses were obtained for each cover crop by N rate treatment. Agronomic responses were assessed as corn grain yield. Environmental responses were assessed for NO_3, N_2O, and NH_3. Pre-established lysimeters were utilized at this site to examine the loss of N from the soil as NO_3. Installed approximately 48 inches below the soil surface and below the crop rooting zone, the lysimeters were used to collect soil water samples for NO_3 analysis and combined with water model data to obtain flow-weighted NO_3 load responses per treatment. Water samples were collected once per week and analyzed for NO_3 concentration beginning with ground thaw in April and lasting until freeze around November each year. Ammonia volatilization and nitrous oxide emissions were also measured throughout the growing season. Nitrous oxide emissions were measured two to three times a week using static chambers and a portable gas analyzer. Ammonia volatilization was measured by utilizing exchangeable acid traps 1, 4, 7, 14, and 21 days after planting and fertilizer application events. Data was analyzed with a mixed effect linear regression model using Rstudio.

RESULTS AND DISCUSSION

Preliminary results suggest that corn grain yield follows a positive relationship with fertilizer N rate. It is well known that increasing N rate to an optimum level can increase grain yield and enhance crop performance. This was observed in all cover crop treatments, with the EONR rate of 225 lb N/ac resulting in substantially higher yields compared to a 0 lbs N/ac control. At the EONR rate there were significant differences in yield between kura clover (193 bu/ac) and both rye (262 bu/ac) and no cover crop (255 bu/ac) treatments, with kura clover decreasing grain yield relative to the other treatments. This is likely due to the living mulch competing for water and bioavailable N within the growing season, thereby limiting corn to obtain essential resources needed to enhance crop performance. There was no significant difference in yield between unfertilized cover crop treatments, suggesting additional plant tissue or biological nitrogen fixation was not sufficient in supplementing crop growth (Figure 1).

From spring to fall of 2023 NO_3 was the greatest source of N loss from the soil system. Nitrate leaching load strongly correlated with water inputs into the soil system, with large precipitation and irrigation events allowing for the movement of soluble NO_3 through the soil. These losses increased with N rate, possibly due to rapid nitrification of the inorganic fertilizer upon application. Among unfertilized plots there was no difference in cumulative NO_3 leaching load between rye and no cover crop treatments. However, unfertilized kura clover showed increased leaching likely due to a small amount of biological nitrogen fixation and routine plant tissue deposition. In fertilized plots the no cover control showed the greatest leaching (122 lbs N/ac) followed by rye (90 lbs N/ac) and kura clover treatments (56 lbs N/ac). This is likely due to cover crop biomass utilizing available soil water and N that would otherwise leach from the system, especially in spring when little to no corn biomass is present (Figure 2).

Throughout the growing season both environmental gas fractions, N_2O and NH_3 remained relatively low. Nitrous oxide emissions responded to N rate, with greater fertilizer inputs resulting in increased N_2O production, likely driven by greater rates of denitrification. Among unfertilized cover crop treatments there was no difference in cumulative season-long N_2O emissions, suggesting that any additional bioavailable N from crop tissues or biological nitrogen fixation was negligible in denitrification processes. In fertilized cover crop treatments kura clover showed greater cumulative N_2O emissions (0.43 lbs N/ac) compared to rye (0.20 lbs N/ac) and no cover crop (0.21 lbs N/ac). As kura clover biomass increased with fertilizer N, the additional biomass likely provided substantially greater plant tissue that became redeposited to the soil, spurring denitrification particularly in the second half of the growing season when the crop may have been outcompeted by corn (Figure 3). Similar to N_2O, cumulative season-long loss of NH_3 was relatively low (0.82 – 0.96 lbs N/ac). There were no significant differences in NH_3 volatilization between any cover crop or N rate treatments. As this study utilizes best management practices that are intended to minimize volatilization, small losses of NH_3 are to be expected (Table 1).

The use of ^{15}N allowed for the tracing of fertilizer-derived nitrogen (FDN) into distinct environmental fractions. No cover crop plots showed no difference in fertilizer-derived nitrate ($FDNO_3$-N) compared to kura clover or rye treatments, however kura clover was significantly lower in $FDNO_3$-N compared to rye likely due to the clover's ability to take up additional FDN throughout the growing season. Kura clover also showed a difference in fertilizer-derived nitrous oxide (FDN_2O-N) compared to other cover crop systems with greater FDN_2O-N than both rye and no cover. As the clover likely incorporated ^{15}N into its biomass, subsequent tissue deposition may have been a viable source of N for denitrification processes. No differences in fertilizer-derived ammonia ($FDNH_3$-N) were observed between cover crop systems, likely due to idealized application systems (Table 1). Total season-long losses as FDN were mostly in the form of NO_3, followed by small amounts of NH_3 and NO_3, representing 1.38, 4.00, and 2.87% of total applied N in kura, rye, and no cover treatments respectively. This suggests that in corn production systems that utilize best management practices, there is a high potential to minimize FDN losses, a key strategy for enhancing environmentally responsible agriculture.

Figure 1. Corn grain yield response to cover crop and N fertilizer rate

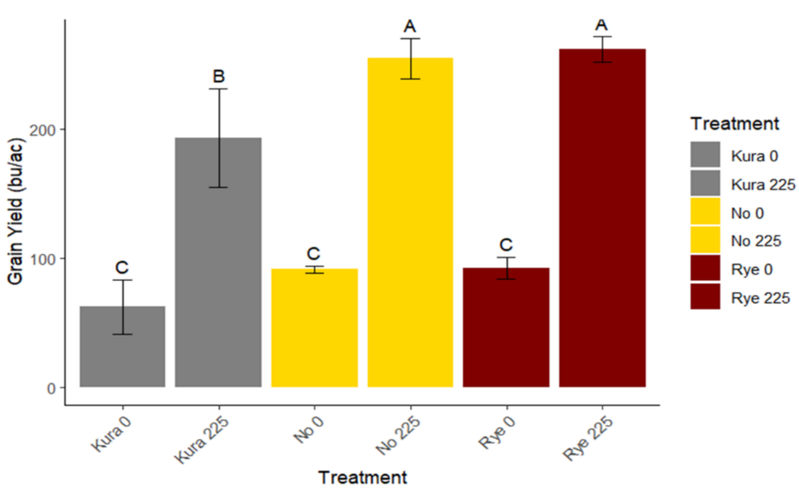

Figure 2. Cumulative soil nitrate leaching load by N rate and cover crop treatments

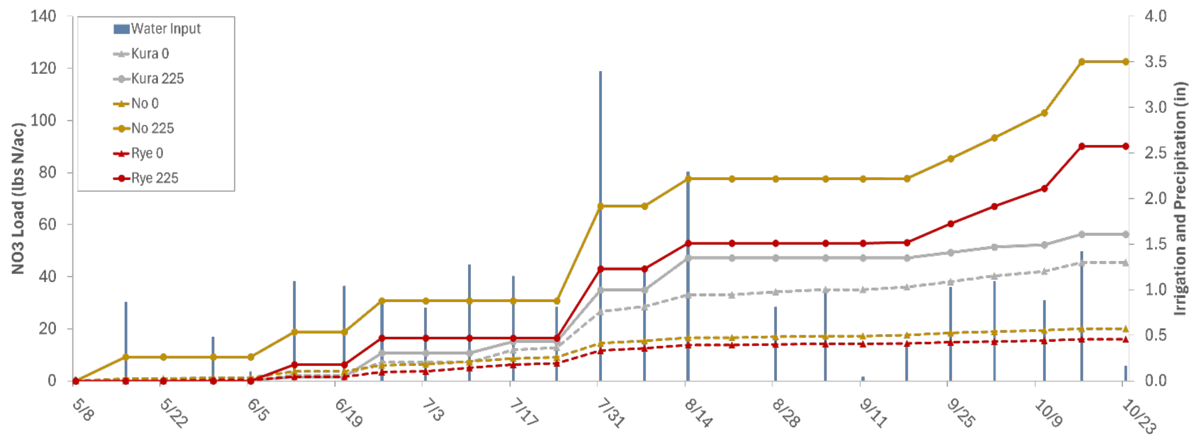

Figure 3. Cumulative soil nitrous oxide emissions by N rate and cover crop treatments

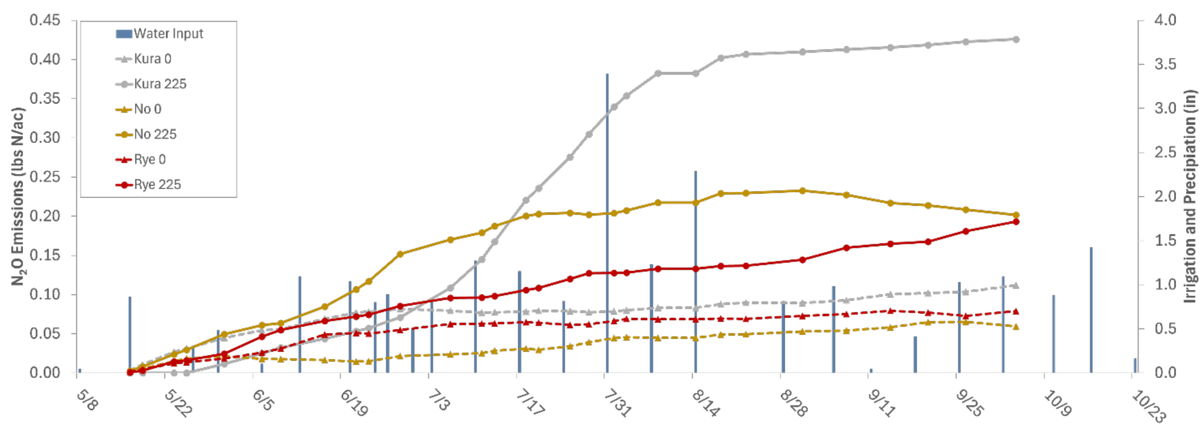

Table 1. Season long N losses and 15N fertilizer-derived nitrogen (FDN) losses in nitrate, ammonia, and nitrous oxide fractions.

Treatment	NO_3-N	FDNO$_3$-N	NH_3-N	FDNH$_3$-N	N_2O-N	FDN$_2$O-N	Total FDN Loss
	- - - - lbs N / ac - - - -						
No	122.09a	5.74ab	0.82a	0.02a	0.21b	0.01b	5.76ab
Rye	89.82b	8.00a	0.96a	0.02a	0.20b	0.01b	8.03a
Kura	55.54c	2.72b	0.93a	0.02a	0.43a	0.02a	2.76b

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SOYBEAN YIELD RESPONSE TO POLY-4 AS A SULFUR AND POTASSIUM SOURCE

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ABSTRACT

Sulfur (S) and potassium (K) play an essential role in soybean growth and metabolism, immunity against insect-pests and improving yield quality and quantity. The reduction in atmospheric deposition of S in soil over the last two decades has increased the risk of S deficiency in crops. POLY-4 is a novel S and K fertilizer source (19% S, 14% K_2O, 17% CaO, 6% MgO) that has slow nutrient release and high nutrient use efficiency properties. A two-year study was conducted at the University of Missouri Lee Greenley Jr. Memorial Research Farm near Novelty, with the objective of assessing the soybean response to POLY-4 in comparison with other common fertilizers of S and K. The treatments included rates of sulfur - 0, 9.5, 19, 27.5, and 38 lb ac^{-1} supplied through POLY-4 and sources of S (ammonium sulfate) and K (muriate of potash). The quadratic plateau curve led to the agronomic optimum nutrient rate (AONR) of S to be 18.6 lb ac^{-1}, which produced an optimum yield (YAONR) of 67.8 bu ac^{-1}. Among the S rates, the higher grain oil content (19.96%) was observed at the rate of 27.5 lb ac^{-1} and 38 lb ac^{-1}. Among the S sources, AMS supplied without any K fertilizer produced the highest oil content (19.94%) in the grains compared to POLY-4 and AMS supplied with K fertilizer. Sulfur rates significantly affected the Soil test S levels which peaked at 19.16 lb ac^{-1} under 38 lb S ac^{-1}. Overall, S rate approximately at 18.6 lb ac^{-1} achieves maximum soybean yield while preserving oil content and ensuring the optimum soil S levels and this demonstrates the effectiveness of POLY-4 in improving the soybean yield.

INFLUENCE OF SOIL AMENDMENTS AND TOPOGRAPHIC POSITION ON WINTER WHEAT HEAVY METAL UPTAKE

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INTRODUCTION

The United States Food and Drug Administration (FDA) recently introduced the Closer to Zero (C2Z) Action Plan which aims to minimize exposure to heavy metals in foods consumed by infants and young children to the lowest levels reasonably achievable. The 2021 Congressional Staff Report prompted this initiative that identified elevated concentrations of arsenic (As), cadmium (Cd), and lead (Pb) in commercially available infant foods. The FDA is expected to establish action levels for heavy metals in "baby and young children's foods," which will likely have significant economic implications for growers and food processors. To ensure a safe food supply, it is essential to understand the factors governing heavy metal uptake by crops within the soil–plant system.

Currently, limited information exists regarding heavy metal uptake by crops grown in Midwestern U.S. agricultural fields. Moreover, there are no established field experiments assessing how soil amendments influence heavy metal uptake nor studies investigating how in-field soil heterogeneity and crop growth stages affect heavy metal accumulation. Although remediation strategies for heavy metals have been extensively evaluated in contaminated environments such as urban soils, research on these issues within conventional agricultural systems remains limited.

In this project, we examined how soil amendments may reduce on-farm heavy metal concentrations in winter wheat (*Triticum aestivum* L.) and assessed the effects of topography and crop growth stages across multiple locations in Michigan.

MATERIAL AND METHODS

Study 1: Soil Amendment Strategies

Winter wheat trials were established in Lansing, MI. Among major control mitigation strategies, stabilization was found to be the quickest and most effective method. Treatments were selected in part to test different mitigation mechanisms, including pH adjustment, organic matter complexation, cation substitution, and direct element competition. A randomized complete block design with four replications was established. Treatments investigated included: 1) control, 2) pre-plant agricultural lime (2 T A^{-1}), 3) pre-plant dairy compost (5 T A^{-1}), 4) pre-plant biochar (2 T A^{-1}), 5) pre-plant gypsum (1 T A^{-1}), 6) pre-plant granular $ZnSO_4$ (10 lbs. Zn A^{-1}) and foliar $ZnSO_4$ (1 pint A^{-1}) at Feekes (FK) 9, 7) low N (50 lbs. N A^{-1}) at FK 4, 8) moderate N (100 lbs. N A^{-1}) at FK 4, 9) high N (150 lbs. N A^{-1}) at FK 4, and 10) biodegradable chelating agent ethylenediaminedisuccinic acid (EDDS) sprays with a 2 mmol L^{-1} concentration applied at FK 5, FK 5 + 1 week, and FK 5 + 2 weeks. Autumn starter fertilizer was top-dressed at a rate of 125 lbs. A^{-1} during planting except check. All treatments received a base green-up N application rate of 100 lbs. A^{-1} of urea (46-0-0) except check and N fertilizer treatments.

Study 2: Field Spatiotemporal Variability (Topography)

Winter wheat trials were established near Clarksville, MI. Linear transects (six replicates) were established across three slope positions (summit, midslope, and toeslope) resulting in 18 sampling locations per crop year.

Both Studies

<u>Sample Preparation</u>

Four random soil cores (0-8 in. depth) were sampled from each plot at Feekes 4, Feekes 9, and post-harvest followed by air-drying for 72 hours, ground, and sieved through a 2 mm sieve. Tillers at Feekes 4 and flag leaf at Feekes 9 were washed with tap water to remove soil particles followed by two washes with deionized water. At Feekes 4, tillers were separated into shoots and roots using a Teflon knife after air drying. The shoots were retained while the roots were discarded. Wheat shoots and flag leaves were dried at 158 °F for 72 hours before being ground to 1 mm (UDY Cyclone sample mill). Grain samples were manually cleaned by removing excess husk. Winter wheat grain (50g) was ground into a coarse powder using an electric coffee grinder (Hamilton Beach®, Richmond, VA) for 1 minute.

<u>Microwave Digestion and Dilution</u>

Due to variations in microwave digestion protocols, samples were processed in separate batches: (1) soil and (2) plant tissue (i.e., biomass at Feekes 4, flag leaf at Feekes 9, and grains at harvest). Soil samples were digested using a microwave-assisted acid digestion method following EPA Method 3051 (U.S. EPA, 2007) for the acid-extractable fraction. Plant tissue samples were digested at 200 °C with a ramp time of 15 min, a hold time of 15 min, 800 psi pressure, and a power range of 900–1,050 W.

<u>Elemental Analysis Using ICP-QQQ-MS</u>

Total cadmium (Cd), arsenic (As), and lead (Pb) concentrations were determined using Triple Quadrupole Inductively Coupled Plasma Mass Spectrometry (ICP-QQQ-MS; 8900 Triple Quadrupole ICP-MS, Agilent Technologies, Santa Clara, CA). Isotopes for each element were selected according to the FDA Elemental Analysis Manual, Section 4.7 ICP-MS Method. Certified reference materials (NIST 1517a tomato leaves and NIST 1515 apple leaves; National Institute of Standards and Technology, Gaithersburg, MD) and at least one analytical blank were included in each run for quality control.

<u>Plant uptake factor</u>

The plant uptake factor (PUF) indicates the winter wheat's capacity to absorb a specific element. It was calculated as the plant tissue elemental concentration divided by the soil elemental concentration, where w(plant) is the plant tissue elemental concentration (ppm) and w(soil) is the soil elemental concentration (ppm).

RESULTS

Study 1: Soil Amendment Strategies

Grain yield. Grain yield ranged from 27.1-127.5 bu. A^{-1} with a mean of 97.2 bu. A^{-1}. Low N decreased grain yield (*P* = 0.0005) by 24.5-25.9 bu. A^{-1} compared to the remaining soil amendments.

Bulk soil heavy metal concentrations. The experimental site was established on a Conover loam soil (Fine-loamy, mixed, active, mesic *Aquic Hapludalfs*) with a surface layer of 41.6% sand, 39.2% silt and 19.2% clay (National Cooperative Soil Survey, 2018). Prior to the field experiment, the average concentrations of cadmium (Cd), arsenic (As), and lead (Pb) in the soil were 0.29, 1.4, and 12.7 ppm, respectively. All soil amendments had comparable soil Cd, As, and Pb concentrations across all sampling periods except soil Pb at harvest (*P* = 0.0369). At FK 4, soil Cd ranged 0.2-0.3 ppm (avg. 0.2 ppm), As ranged 1.8-3.4 ppm (avg. 2.6 ppm) and Pb ranged 9.8-13.2 ppm (avg. 11.0 ppm). At FK 9, soil Cd ranged 0.2-0.3 ppm (avg. 0.2 ppm), As ranged 2.0-3.2 ppm (avg. 2.5 ppm) and Pb ranged 10.2-14.7 ppm (avg. 11.4 ppm). At harvest, soil Cd ranged 0.2-0.3 ppm (avg. 0.2 ppm) and As ranged 1.9-2.9 ppm (avg. 2.5 ppm). EDDS and high N increased soil Pb levels by 0.9 and 0.8 ppm compared to the check. Across sampling periods, the order of soil heavy metal concentration was Pb > As > Cd. Further, heavy metal concentrations were relatively stable across soil amendments and sampling periods (treatment × sampling interaction, *P* = 0.9997).

Plant tissue nutrient concentrations. For both Feekes 4 and 9, Pb was the most prevalent heavy metal followed by Cd and As. However, Cd was the most dominant heavy metal at harvest followed by Pb and As. All soil amendments had comparable plant tissue Cd, As, and Pb concentrations across sampling periods except flag leaf Pb. At FK 4, biomass Cd ranged 0.1-1.3 ppm (avg. 0.3 ppm), As ranged 0.1-0.4 ppm (avg. 0.2 ppm) and Pb ranged 0.3-1.6 ppm (0.6 ppm). At FK 9, flag leaf Cd ranged 0.1-0.3 ppm (avg. 0.2 ppm) and As ranged 0.01-0.02 ppm (avg. 0.01 ppm). High N increased flag leaf Pb level by 0.087 ppm (*P* = 0.0489) compared to the check. At harvest, grain Cd ranged 0.0-0.2 ppm (avg. 0.1 ppm), As ranged 0.000-0.002 ppm (avg. 0.001 ppm), and Pb ranged 0.00-0.02 ppm (avg. 0.005 ppm). All soil amendments were within the allowable limit set by the FDA (0.01 ppm).

Plant uptake factor. All soil amendments had early Cd plant uptake factor (PUF) > 1 with $ZnSO_4$ having the highest Cd PUF (2.06) while both As and Pb PUF < 1 indicated that Cd was readily translocated regardless of soil amendment. Mid-season and harvest Cd, As, and Pb PUF < 1 suggested the reduction of heavy metal uptake efficiency over time.

Cross-Element Uptake Dynamics Affecting Heavy Metal Accumulation. Using linear regression, we found that 41% of the variability in grain As uptake may be explained by variation in flag leaf Mg uptake. On the other hand, 25% of the variability in grain Cd uptake may be explained by variation in flag leaf P uptake. While 30% of the variability in grain Pb uptake can be explained by variation in flag leaf Cu uptake.

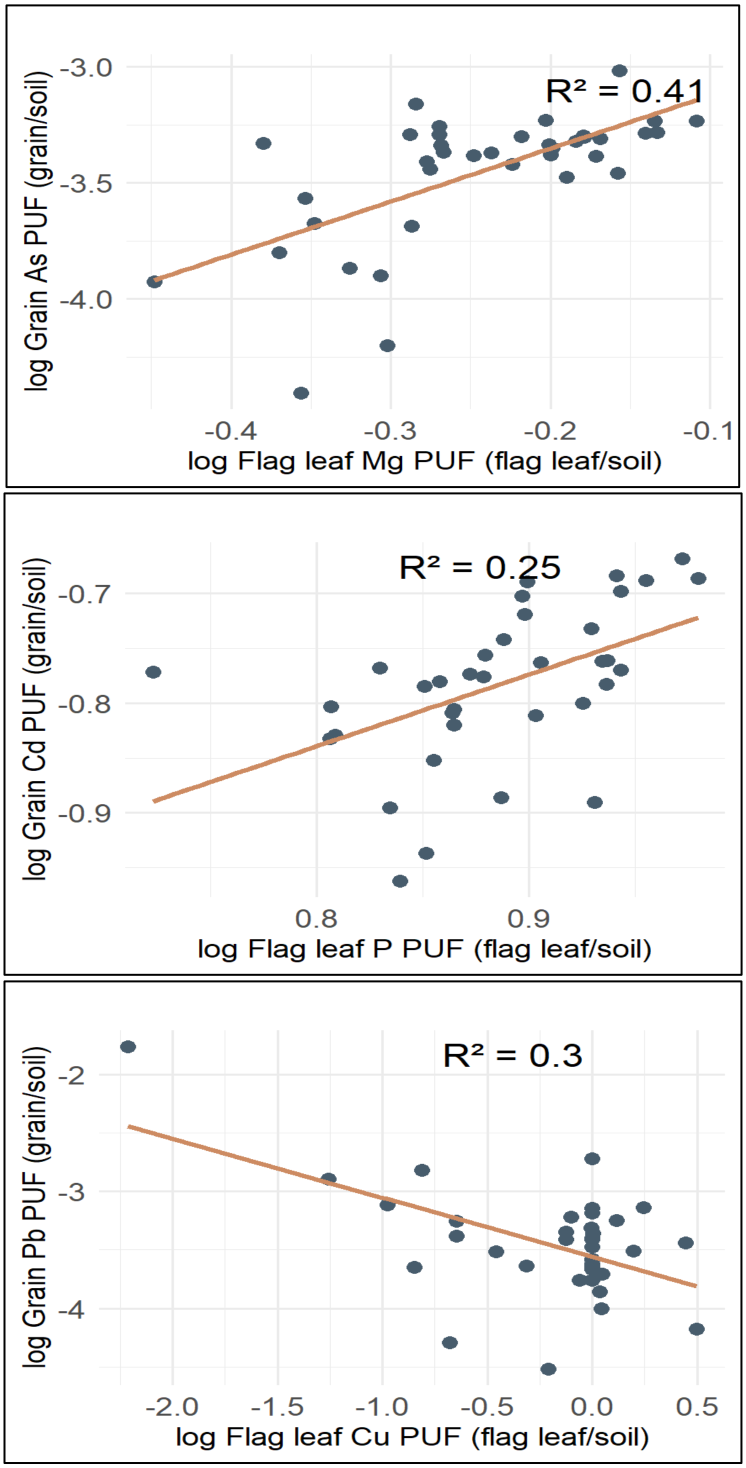

Fig. 1a–c: Linear regression of log flag leaf Mg plant uptake factor (PUF) versus log grain As PUF, log flag leaf P PUF versus log grain Cd PUF, log flag leaf Cu PUF versus grain Pb PUF.

Study 2: Field Spatiotemporal Variability (Topography)

Weather. As compared to 30-year air temperature and precipitation averages, growing conditions in 2024-25 had normal air temperatures (avg. 21.5-74.1 °F) and a dry autumn (Oct. -84%, Nov. -47%). From December 2024 to March 2025, conditions were warm (+7.5 °F) but contrasting precipitation from Dec. to Feb. (avg. -82%) and Mar. (+33%) precipitation. April to May 2025 had a warm (+8.2 °F) and dry spring (-28%). June 2025 had normal air temperature (avg. 70.4 °F) and dry summer (-37%).

Soil moisture and 4-day rainfall. The gravimetric method and 4-day precipitation data were used as contextual indicators of recent soil moisture conditions. At FK 4 (P = 0.416) (12.0-17.5%, avg. 14.7%) and harvest (P = 0.0712) (7.8-12.2%, avg. 9.8%), all slope positions had comparable soil moisture. Conversely, at FK 9 (P = 0.0096), Midslope (14.0%) had the greatest soil moisture, followed by Summit (12.3%) and Toeslope (12.0%).

Bulk soil heavy metal concentrations. The experimental site was established on a Lapeer sandy loam (coarse-loamy, mixed, semiactive, mesic *Typic Hapludalf*) with a surface layer of 64.6% sand, 25.6% silt and 9.8% clay and slope 2-6% (National Cooperative Soil Survey, 2018). Across sampling periods, soil As increased over time with lowest at FK 4 (range 1.2-1.8 ppm, avg. 1.4 ppm) and greatest at FK 9 (range 1.4-2.3 ppm, avg. 1.8 ppm), and harvest (range 1.2-2.4 ppm, avg. 1.8 ppm) (P = 5.138e-08). Meanwhile, soil Cd was lowest at FK 9 (range 0.10-0.15 ppm, avg. 0.12 ppm) with lower concentrations at FK 4 (range 0.10-0.15 ppm, avg. 0.13 ppm) and harvest (range 0.10-0.14 ppm, avg. 0.13 ppm) (P = 0.002595). Soil Pb was lowest at harvest (range 5.5-8.7 ppm, avg. 7.4 ppm) and FK 9 (range 6.0-9.1 ppm, avg. 7.5 ppm) and greatest at FK 4 (range 6.5-9.2 ppm, avg. 8.3 ppm) (P = 1.276e-06).

Across slope positions, the order of increasing soil As was Toeslope > Midslope > Summit (P = 2.644e-11); soil Cd was Midslope > Toeslope = Summit (P = 3.349e-09); and soil Pb was Toeslope = Midslope > Summit (P = 4.887e-13). The decreased acid-extractable heavy metal concentrations likely indicate that winter wheat absorbs higher levels, while greater values suggest that the crop takes up less.

Plant tissue nutrient concentrations. For both Feekes 4 and 9, Pb was the most prevalent heavy metal followed by Cd and As. On the other hand, Cd was the most dominant heavy metal at harvest followed by Pb and As. All slope positions had comparable plant tissue Pb across sampling periods. Biomass Pb ranged 0.3-1.0 ppm (avg. 0.6 ppm), flag leaf Pb ranged 0.01-0.2 ppm (avg. 0.1 ppm) and grain Pb ranged 0.0-0.01 (avg. 0.001 ppm). Grain Pb was within the allowable limit set by the FDA (0.01 ppm). Plant tissue As was consistently greatest in Toeslope with 0.3, 0.01, and 0.002 ppm during FK 4 (P = 0.0272), FK 9 (P = 0.0179) and harvest (P = 0.013), respectively. Slope positions influenced flag leaf Cd (P = 0.0053) and grain Cd (P = 0.0067) with Midslope having greatest flag leaf Cd (0.16 ppm) and Midslope (0.05 ppm) and Summit (0.05 ppm) having the greatest grain Cd levels.

Plant uptake factor. All slope positions had early Cd plant uptake factor (PUF) > 1 with Summit having the highest Cd PUF (2.71) while both As and Pb PUF < 1. Midslope and Summit had both mid-season Cd PUF > 1.0 while both As and Pb PUF < 1.0. Late-season As, Cd, and Pb PUF <1.0 however Summit remained having the greatest Cd PUF among Midslope and Toeslope.

Cross-Element Uptake Dynamics Affecting Heavy Metal Accumulation

Using linear regression, we found that 20% of the variability in grain As uptake could be explained by variation in flag leaf Mn uptake. In contrast, 69% of the variability in grain Cd uptake could be explained by variation in flag leaf K uptake, while 33% could be explained by variation in flag leaf Zn uptake. None of the elements significantly influenced grain Pb uptake in either the FK 4 or FK 9 sampling (V, Cr, Mn, Co, Ni, Cu, Zn, As, Se, Cd, Pb, Al, Ca, Fe, K, Mg, Na, P, S).

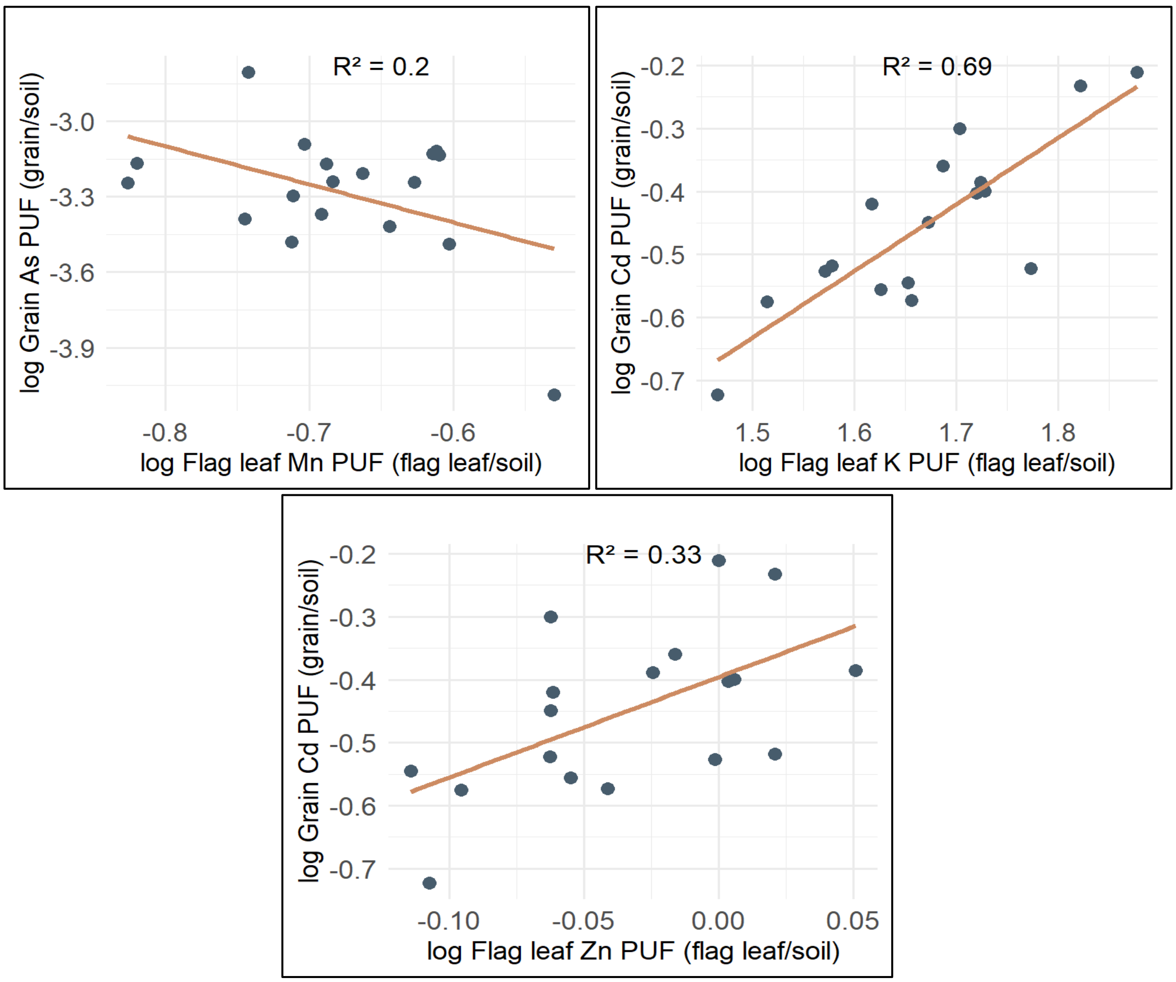

Fig. 2a–B: Linear regression of log flag leaf Mn plant uptake factor (PUF) versus log grain As PUF and log flag leaf K PUF, flag leaf Zn PUF versus log grain Cd PUF.

SOIL HEALTH RESPONSES TO INTERSEEDED COVER CROPS AND NITROGEN STRATEGIES IN THE NORTHERN CORN BELT

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ABSTRACT

Cover cropping and nitrogen (N) management are often promoted for improving soil health, yet their combined influence under interseeded systems in temperate regions remains less understood. To address this gap, a field study was conducted in South Dakota at two no-till corn–soybean rotation sites (Brookings and Beresford) established on clay loam soils. Cover crop treatments included a no cover, a single grass species, and a multi-species mixture of grass and broadleaf species interseeded at the V6 stage of corn, combined with three nitrogen (N) rates (low, medium, and high) applied 10 days after planting. Soil health was assessed at three growth stages (V6, R1, and R6) using indicators such as active carbon (Active C), aggregate stability, soil organic carbon (SOC), soil organic matter (SOM), potentially mineralizable nitrogen (PMN), nitrate-N, and ammonium-N. Cover crops produced relatively little biomass (maximum 0.9 Mg ha^{-1}, average 0.5 Mg ha^{-1}), which likely explains why no significant effects on soil health indicators were observed. In contrast, higher N fertilization rates increased PMN, nitrate-N, and ammonium-N, reflecting greater nutrient availability. Sampling time also shaped responses: Active C and SOM peaked at V6, indicating strong early-season microbial activity and fresh residue inputs, whereas SOC and aggregate stability were highest at R6, suggesting improved soil structure later in the season. Overall, short-term cover cropping had a minimal influence on soil health, while the nitrogen rate and sampling time exerted significantly stronger effects on nutrient dynamics and soil properties.

INTRODUCTION

Soil health underpins sustainable crop production by supporting nutrient cycling and environmental resilience (Davis et al., 2023; Tahat et al., 2020). However, intensive agriculture often depletes nutrients and accelerates erosion, prompting interest in conservation practices such as cover cropping and improved N management (Teng et al., 2024). While both practices independently benefit soil quality, their combined effects under temperate rainfed systems remain less understood.

The benefits of cover crops are well established in tropical regions (Farmaha et al., 2022). However, their adoption in temperate production systems is constrained by short growing seasons, cool soils, and early frosts (Blanco-Canqui et al., 2015). These factors limit biomass production and reduce potential gains in SOM, microbial activity, aggregation, and nutrient cycling (Ruis et al., 2019). Interseeding cover crops into standing crops helps overcome these challenges by extending the growing window. Research suggests that V6–V7 corn stages strike a balance between canopy openness and minimal crop competition (Brooker et al., 2020; Peterson et al., 2019). The choice of species is also critical as grasses promote SOM and aggregation through high C: N residues, legumes contribute N through fixation, and brassicas enhance rooting and reduce leaching (Blanco-Canqui & Ruis, 2020).

Additionally, nitrogen management interacts with cover crops to influence soil processes. At high fertilizer rates, grasses can reduce excess residual N, while brassicas help limit leaching losses; in contrast, at moderate rates, legumes become important contributors of biologically fixed N that complements fertilizer inputs. These dynamics mean that the soil health effects of fertilization depend not only on the rate applied but also on the functional traits of the cover crop species present (Geisseler & Scow, 2014; Finney et al., 2016).

Another layer of complexity arises from the timing of soil sampling. Soil indicators such as Active C, PMN, and inorganic N pools fluctuate across the season, with early stages reflecting microbial activity and nutrient release, and later stages capturing soil structural improvement (Hurisso et al., 2018; Kong & Six, 2010). Despite recognition of these dynamics, few studies have assessed how cover crop mixtures, N rates, and sampling times interact across a full season in temperate systems. Accordingly, the objective of this study is to assess the combined effects of cover crop composition, N fertilization rate, and sampling timing on soil health indicators in a no-till corn–soybean rotation in South Dakota.

MATERIALS AND METHODS

The study was conducted from 2021 to 2022 at two no-till corn–soybean rotation sites established in 2012 near Brookings and Beresford, South Dakota. Both sites have clay loam soils, although Brookings is primarily composed of Egan–Clarno–Tetonka, and Beresford also includes Egan–Trent silty clay loams. Average long-term precipitation is ~500 mm annually.

Both sites followed a split-plot design with four replications. The whole plot received one of the three cover crop treatments: no cover, annual ryegrass, or a four-species mixture (perennial ryegrass, crimson clover, turnip, and radish). Subplots received one of the three N rates: low (0 kg N ha^{-1}), medium (75 kg N ha^{-1} at Brookings, 100 kg N ha^{-1} at Beresford), or high (150 and 200 kg N ha^{-1}, respectively). Cover crops were interseeded at the V6–V7 stage of corn using a high-clearance planter. Fertilizer was surface-applied 7–10 days after planting as SUPERU® stabilized urea.

Pre-plant samples (0–15 cm and 15–60 cm) were collected to establish baseline fertility. In-season samples (0–15 cm) were taken at V6, R1, and R6. The indicators measured included Active C, SOM, SOC, PMN, aggregate stability, nitrate-N, and ammonium-N. Standard laboratory methods were used: POXC for Active C, loss-on-ignition for SOM, dry combustion for SOC, anaerobic incubation for PMN, wet sieving for aggregate stability, and flow injection analysis for inorganic N.

Data were analyzed in R (version 4.4.1). Linear mixed-effects models (lme4, lmerTest) were used to test the effects of cover crops, N rate, and sampling time, with site-year and block included as random factors. When significant effects ($p < 0.05$) were detected, mean separations were performed using Sidak-adjusted comparisons with the emmeans package.

RESULTS AND DISCUSSION

Seasonal temperature and rainfall patterns strongly influenced soil biological responses. At both sites, precipitation in 2021 was close to or slightly below the 30-year average; however, the distribution varied. Brookings recorded moderate early deficits followed by excess rainfall in late summer, while Beresford experienced severe June drought and wetter conditions later. These fluctuations likely disrupted synchronization between N supply and crop demand, reducing microbial activity early but increasing late-season N losses.

Cover crops had no significant effect on soil health indicators measured (Table 1). Similar short-term studies have shown that measurable improvements in SOM, SOC, or aggregation often require longer than four years of consistent cover cropping (Blanco-Canqui & Ruis, 2020; Decker et al., 2022). Low biomass production in this study (maximum 0.9 Mg ha^{-1}, average 0.5 Mg ha^{-1}) also contributed to the lack of response, as previous research suggests at least 3–5 Mg ha^{-1} is necessary for detectable improvements (Kaspar & Bakker, 2015; Nichols et al., 2020). The corn–soybean rotation may have further limited effects compared to more diverse systems that return greater organic inputs (Reisner et al., 2021). In addition, bulk sampling to 15 cm may have diluted near-surface changes, as differences in SOM and SOC are often most pronounced in the top 3–5 cm (Franzluebbers, 2002).

Table 1 F-test significance of site-year, cover crops, nitrogen rate, and sampling time, and their interactions on soil parameters, 2021–22.

Cover crop	Active C	PMN	SOM	WSA	SOC
	——— mg kg-1 ———		LOI %	——— % ———	
No Cover	436a	47a	4.2a	16.8a	2.02a
Single Species	439a	47a	4.2a	17.3a	2.01a
Mixed Species	443a	47a	4.2a	17.2a	1.99a

Note: Within each column, means followed by the same letter are not significantly different at $p>0.05$

Despite minimal treatment effects, strong interactions between site-year and sampling time were evident. Active C peaked early (V6) (Figure 1), reflecting microbial stimulation, then generally declined by R6, though patterns varied by year. PMN followed the expected seasonal declines from preplant to mid-season, with late increases in the wetter 2021 season, but continued reductions under the 2022 drought. Aggregate stability generally improved through R1 and declined by R6, again reflecting shifts in biological activity and soil moisture. SOM rose modestly in 2021 but decreased in 2022, indicating sensitivity to seasonal climate fluctuations. SOC showed both increases and declines across site-years, highlighting the importance of within-season dynamics and environmental context. Together, these results highlight the significance of sampling time as a crucial factor influencing observed soil health trends.

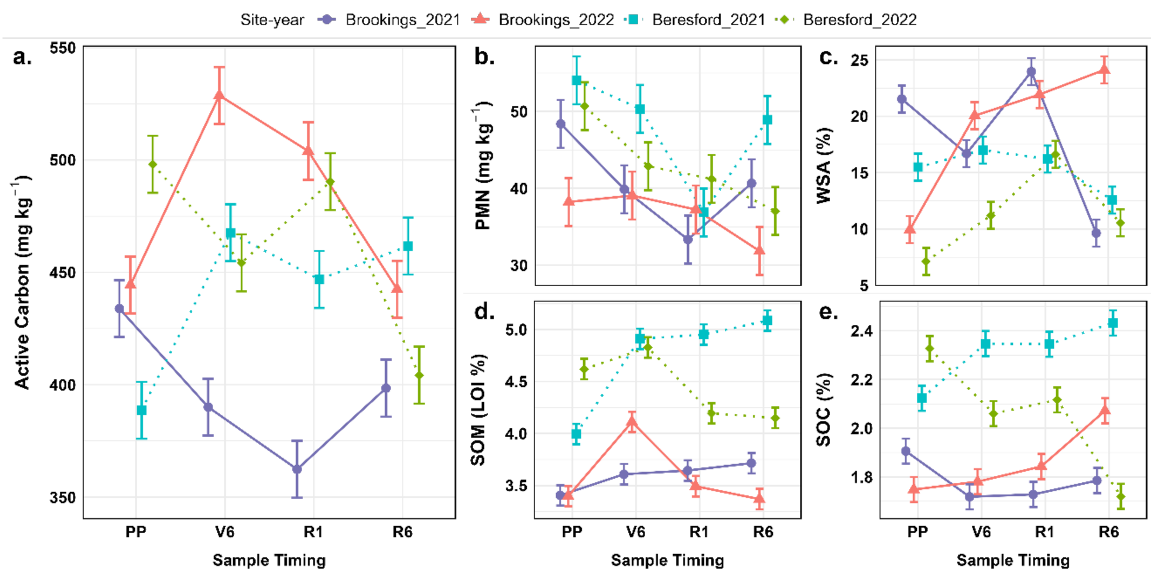

Figure 1 Seasonal dynamics of (a) active C, (b) PMN, (c) WSA, (d) SOM, (e) SOC across site-years and sample timings.
Note: Corn growth stages include V6, R1, R6 (Corn growth stages) (Abendroth et al., 2011)
Abbreviations: Active C, active carbon; PMN, potentially mineralizable nitrogen; WSA, water stable aggregates; SOM, soil organic matter; LOI, loss on ignition; SOC, Soil organic Carbon; PP, pre-plant.

Soil inorganic N responded strongly to N rate and sampling time, with nitrate-N showing more consistent changes than ammonium-N (Figure 2). In low-N plots, nitrate-N concentrations remained stable (~2–13 mg kg^{-1}), while medium and high N plots peaked at V6 after fertilization (40 and 64 mg kg^{-1}, respectively) (Figure 2a). Concentrations then generally declined with crop uptake through R1 and R6, though occasional late-season increases reflected mineralization or rewetting effects. Across all timings, nitrate-N increased predictably with the application of N.

Ammonium-N was more variable and transient (Figure 2). Levels also peaked at V6 in fertilized plots (10 mg kg^{-1} at medium N and 20 mg kg^{-1} at high N), but declined more inconsistently thereafter, often due to rapid nitrification and environmental sensitivity (Figure 2b). Overall differences across N rates were minor (4–19 mg kg^{-1}) compared to nitrate-N (20–70 mg kg^{-1}). This confirms that nitrate is the more persistent, management-responsive pool, whereas ammonium is short-lived and closely tied to microbial transformation and soil conditions.

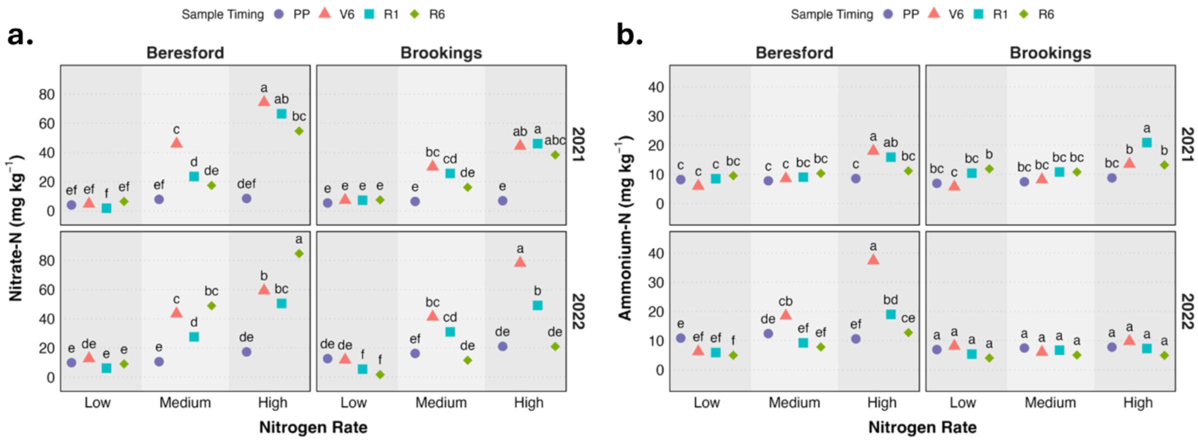

Figure 2 Inorganic soil-N concentrations across four site-years at Brookings and Beresford in 2021 and 2022.

Note: Corn growth stages include V6, R1, R6 (Corn growth stages) (Abendroth et al., 2011)
Abbreviations: PP, pre-plant.

CONCLUSIONS

Four years of interseeding cover crops had no measurable effect on soil health indicators such as active C, aggregate stability, SOM, or PMN. These results are consistent with previous findings, which report that soil health improvements often require longer-term adoption, higher biomass inputs (>3 Mg ha^{-1}), and more diverse rotations. The limited biomass (<1 Mg ha^{-1}) and use of composite 0–15 cm samples likely contributed to the absence of detectable changes in this study.

In contrast, the nitrogen rate and sampling time had a strong influence on soil health responses. Inorganic-N exhibited clear seasonal and site-specific dynamics, with nitrate-N responding more consistently and to a greater magnitude than ammonium-N. Other soil parameters (Active C, PMN, SOM, SOC, WSA) also varied across the season, with V6 capturing peak biological activity and R6 reflecting improved soil structural properties. These results highlight that sampling timing is crucial for accurately interpreting soil health outcomes.

Overall, the study demonstrates that while short-term interseeding has a limited impact on soil health, N management and sampling strategies play a central role in shaping soil nutrient pools and biological processes. Long-term trials, finer-depth sampling, and inclusion of more diverse rotations are needed to fully evaluate the soil health potential of interseeded cover crops in temperate corn–soybean systems.

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IMPROVING CORN GRAIN YIELD AND REDUCING NITRATE-N LEACHING WITH UREASE AND NITRIFICATION INHIBITORS

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ABSTRACT

Sustainable corn (*Zea mays* L.) production requires proper nitrogen (N) management to optimize yield and minimize negative impacts of N losses on water quality. Nitrification inhibitors could be a viable strategy to synchronize N availability and corn N demand and decrease N loss through nitrate-N leaching. A field study was laid out in a randomized complete block design with five replicates at the Belleville Research Center, IL, in 2023, with two fertilizer sources [urease inhibitor (U) & urease and nitrification Inhibitor (N+U)] at eight N rates (0-394 kg ha^{-1}). The objectives were to evaluate the effect of U vs N+U on corn grain yield, economically optimum N rate (EONR), nitrate-N leaching, yield-scaled leaching and N use efficiency. Corn grain yield was similar between U and N+U at lower N rates (0-283 kg ha^{-1}), with EONR of 291 and 152 kg ha^{-1} for U and N+U, respectively. Nitrate-N and yield scaled nitrate-N leaching increased exponentially with N rate, while N+U reduced nitrate-N leaching by 63% and yield-scaled leaching by 50% compared to U. The N use efficiency decreased linearly with increasing N rate for U (19 kg DM kg^{-1} N) but plateaued for N+U (28 kg DM kg^{-1} N). Overall, incorporating N+U inhibitors enhanced N retention and reduced leaching losses without major yield penalties. These findings highlight N+U as a more sustainable N management strategy in corn production systems under variable soil moisture conditions.

INTRODUCTION

Enhanced efficiency fertilizers are designed to improve nitrogen (N) use efficiency and minimize environmental losses by synchronizing N release with crop demand. Among these, urease inhibitors (U) and nitrification inhibitors are two of the most widely adopted strategies. Urease inhibitors slow the enzymatic hydrolysis of urea, thereby reducing ammonia volatilization and improving soil N retention. Nitrification inhibitors, on the other hand, delay the microbial oxidation of ammonium to nitrate, thereby reducing environmental N losses through gradual release of available N aligned with crop uptake. Previous research has demonstrated that nitrification inhibitors can enhance corn grain yield; however, the magnitude of yield response is influenced by crop type, climatic conditions, and soil characteristics (Quemada et al., 2013).The combined use of urease and nitrification inhibitors (N+U) during the corn phase may not only reduce in-season N losses but also delay N transformations, potentially increasing soil N availability. Therefore, the objectives of this study were to evaluate the effects of urease inhibitors (U) and urease + nitrification inhibitors (N+U) on corn grain yield, economically optimum nitrogen rate (EONR), leaching and N use efficiency.

MATERIALS AND METHODS

In 2023, a field experiment was initiated at the Belleville Research Center in Belleville, IL by employing a randomized complete block design replicated five times. Treatments were two fertilizer source -urease inhibitor alone and a combination of urease and nitrification inhibitors applied at eight N rates (0, 62, 117, 172, 228, 283, 339, and 394 kg N ha^{-1}).

The economically optimum rate, representing the rate of N fertilizer recommended for application was determined. A linear plateau model best fits the data. A linear plateau model can be obtained based on the N rate used:

$$y = a + bx \text{ if } x < c \quad (1)$$

$$y = p \text{ if } x \geq c \quad (2)$$

where y is the yield of corn grain (kg ha^{-1}) and x is the rate of N application (kg ha^{-1}); a (intercept), b (linear coefficient), c (critical rate of fertilization, which occurs at the intersection of the linear response and the plateau lines), and p (plateau yield) are constants obtained by fitting the model to the data (Cerrato and Blackmer, 1990).

Ion-exchange resin (IER) lysimeters were used to quantify nitrate-N leaching losses during the growing season (Langlois et al., 2003; Leon et al., 2024; McIsaac et al., 2010; Susfalk and Johnson, 2002). Lysimeters were extracted for nitrate-N using 1M KCl solution at a 1:2 resin mass-to-solution ratio and were analyzed calorimetrically, and the results were expressed on an area basis (kg nitrate-N ha^{-1}). Yield-scaled nitrate-N leaching was determined by dividing the total amount of nitrate-N leached per Mg of corn grain yield (Pittelkow et al., 2017). Nitrogen use efficiency (NUE, kg DM kg^{-1} N) was calculated as (DM yield at a given N rate – DM yield at zero N)/N applied (Ketterings et al., 2007). Data were evaluated for normality of residuals and analyzed using SAS statistical software. Results with $p < 0.05$ were considered significant.

RESULTS & DISCUSSION

Corn grain yield

Corn grain yield was significantly affected by the interaction between N sources and application rates ($p < 0.003$). A linear-plateau model provided the best fit for determining EONR for both sources, which were 291, and 152 for U and N+U, respectively (Fig.1). The lower EONR observed with N+U likely reflects limited nitrate-N availability under limited soil moisture conditions, resulting in an early yield plateau due to physiological N shortage. In contrast, the U treatment may have allowed faster nitrification and greater nitrate-N supply at higher N rates (339-394 kg ha^{-1}). At the EONR corn grain yields were 12,828 and 11,795 kg ha^{-1} for the U and N+U, respectively.

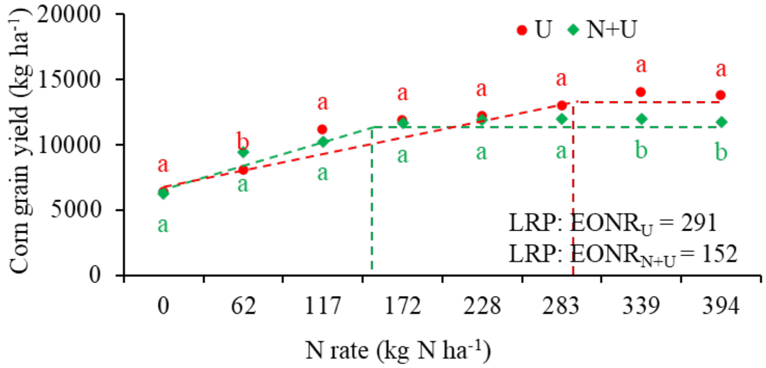

Fig. 1. Interaction of nitrogen (N) source and, N rate on corn grain yield. U: urease inhibitor; N+U: nitrification+urease inhibitor; LRP: linear plateau.

Nitrate-N leaching

Nitrate-N leaching was significantly influenced by N application rates ($p < 0.0001$), where leaching exponentially increased with increase in N rates (Fig.2). At the EONR nitrate-N leaching was 80 and 30 kg ha^{-1} for the U and N+U, respectively indicating that N+U reduced nitrate-N leaching by 63%. This reduction is likely due to the slower conversion of ammonium to nitrate, which decreases the amount of nitrate susceptible to leaching losses.

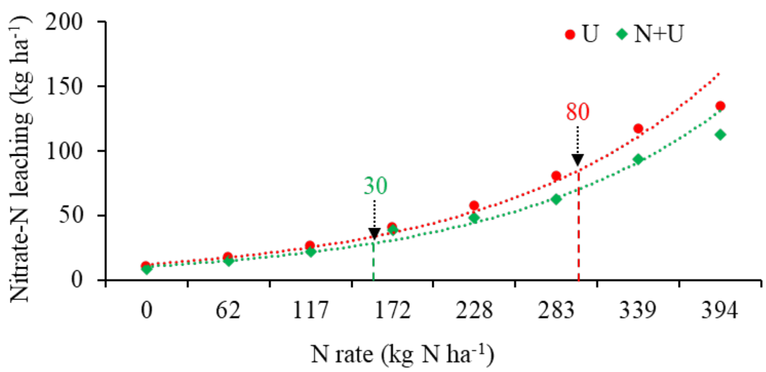

Fig. 2. Interaction of nitrogen (N) source and, N rate on nitrate-N leaching. U: urease inhibitor; N+U: nitrification+urease inhibitor.

Yield-scaled nitrate-N leaching

Exponential model was also the best fit for yield-scaled leaching losses, with significant ($p < 0.0001$) losses above the EONR. Yield-scaled leaching losses were 6 and 3 kg NO_3-N Mg^{-1} for the U and N+U, respectively, indicating a twofold decrease when switching from U to N+U (Fig.3).

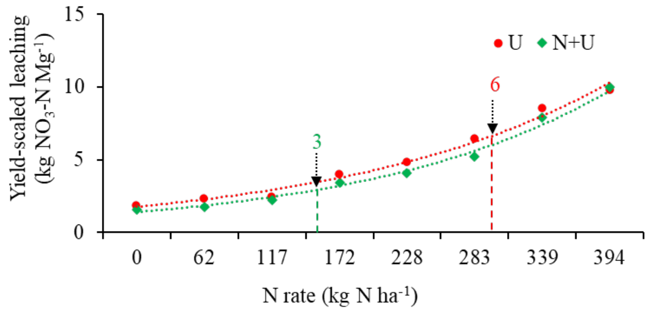

Fig. 3. Interaction of nitrogen (N) source and, N rate on yield-scaled nitrate-N leaching. U: urease inhibitor; N+U: nitrification+urease inhibitor.

Nitrogen use efficiency

Nitrogen use efficiency was significantly affected by the interaction between N sources and application rates ($p < 0.003$) (Fig.4). The N use efficiency linearly decreased with increase in N rate for U, reaching 19 kg DM kgN^{-1} at the EONR. In contrast, NUE followed a quadratic plateau response for N+U, showing the highest efficiency of 28 kg DM kgN^{-1} at EONR. This suggests that U inhibitors alone were less effective in utilizing the fertilized N compared to N+U, which showed higher efficiency at low N rates.

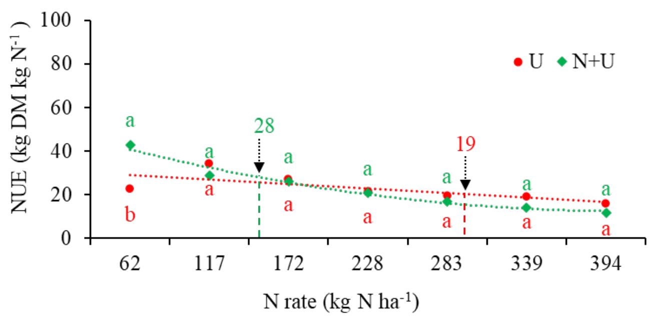

Fig. 4. Interaction of nitrogen (N) source and, N rate on yield-scaled nitrate-N leaching. U: urease inhibitor; N+U: nitrification+urease inhibitor.

Preliminary Conclusion

The combined use of N+U inhibitors improved nitrogen use efficiency and substantially reduced nitrate-N leaching compared with U inhibitors alone. These results suggest that N+U can enhance N retention and environmental sustainability without major yield penalties, particularly under conditions of limited soil moisture where nitrate losses are otherwise high.

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INTEGRATING NDVI AND PLANT TISSUE ANALYSIS AS DECISION SUPPORT TOOLS FOR NUTRIENT MANAGEMENT IN WINTER WHEAT

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ABSTRACT

Efficient nitrogen (N) management is critical for improving winter wheat grain yield and protein content while minimizing production costs and environmental risks. Remote sensing indices, such as the Normalized Difference Vegetation Index (NDVI), and physiological indicators, such as flag leaf N concentration, have been proposed as predictors of crop performance to support in-season N management decisions. This study aimed to evaluate the relationships between NDVI measured at early (Feekes 7–8) and late (Feekes 10.1–10.5.3) growth phases, flag leaf N at flowering, final grain yield, and protein content.

A randomized complete block design with four replications was established across nine locations in Kansas. Treatments consisted of seven N rates (0 to 180 lb N ac^{-1}) applied as broadcast urea at Feekes 6. NDVI data were collected using a handheld crop sensor, and grain protein was measured with an NIR spectrometer.

Results showed that NDVI was most strongly associated with grain yield at early growth stages (marginal R^2 (R_m^2)= 0.71), whereas the relationship at later stages was weaker. In contrast, NDVI showed limited predictive power for protein. Flag leaf N concentration was weakly related to both yield (R_m^2 = 0.02) and protein (R_m^2 = 0.15) across locations. These findings suggest that NDVI, particularly at early stages, can provide valuable insights for improving in-season nitrogen management decisions in winter wheat.

INTRODUCTION

Efficient nutrient management, particularly nitrogen (N) management, is essential for maintaining winter wheat productivity while reducing production costs and minimizing environmental losses. Winter wheat (*Triticum aestivum L.*) is one of the most important cereal crops in Kansas, representing approximately 20% of U.S. wheat production (Kansas Department of Agriculture, 2023). Therefore, inadequate N management strategies can lead to over- or under-application, resulting in reduced yield potential, economic losses, and increased risks of environmental pollution.

Nitrogen management in cropping systems is challenging because conventional approaches often fail to account for spatial and temporal variability in N soil supply, crop uptake, and environmental conditions (Raun *et al.*, 2002). Therefore, in-season diagnostic tools that reflect N status are needed to improve N use efficiency and guide more adaptive management decisions.

Remote sensing indices, such as the Normalized Difference Vegetation Index (NDVI), have been widely used to estimate the physiological status of plants, which is often correlated with N status (Wang *et al.*, 2012). Similarly, the N concentration in plant leaves has been shown to correlate with yield potential (Dordas, 2009). However, while both NDVI and flag leaf N concentration can indicate crop N status, limited research has directly compared their effectiveness for predicting yield and protein across multiple growth stages and environments.

The objectives of this study were to:

I. Evaluate the relationship between NDVI measured at early and late growth stages and grain yield and grain protein content.
II. Evaluate the relationship between flag leaf N concentration and grain yield and grain protein content.
III. Compare the predictive ability of NDVI and flag leaf N for supporting in-season N management decisions in winter wheat.

MATERIALS AND METHODS

The experiment was conducted across nine locations in Kansas during the 2023-24 and 2024-25 growing seasons, using a randomized complete block design with four replications. Treatment consisted of seven N rates ranging from 0 to 180 lb N ac^{-1}, applied as broadcast urea at Feekes 6. Each experimental plot measured 7 x 40ft and was managed according to local agronomic practices.

NDVI measurements were obtained using the RapidSCAN CS-45 handheld crop sensor (Holland Scientific) at early (Feekes 7-8) and late (Feekes 10.1-10.5.3) growth stages. Flag leaf samples were collected at flowering (Feekes 10.5) and analyzed for total N concentration using the dry combustion method. Grain yield was measured at harvest using a small-plot combine, and grain protein was determined with an NIR spectrometer (NIR DS3, Foss Inc.).

Data were analyzed using linear mixed models in R (lme4 package), with N rate as a fixed effect and location and replication as random effects. Relationships between NDVI, flag leaf N, yield, and protein were evaluated by calculating marginal and conditional R^2 values (MuMln package).

RESULTS AND DISCUSSION

NDVI and grain yield relationships

NDVI measured at early growth stages (Feekes 7 – 8) showed a strong positive relationship with grain yield across locations (Figure 1). It explained 71% of yield variability (marginal R^2 = 0.71), indicating a high potential for in-season yield prediction.

In contrast, NDVI measured at later stages (Feekes 101 – 10.5.3) explained only 37% of yield variability (Figure 2), suggesting it limits to predict yield.

These results align with previous findings, which show that early NDVI measurements capture canopy development and N uptake more efficiently than late-season measurements (Ali *et al.*, 2022).

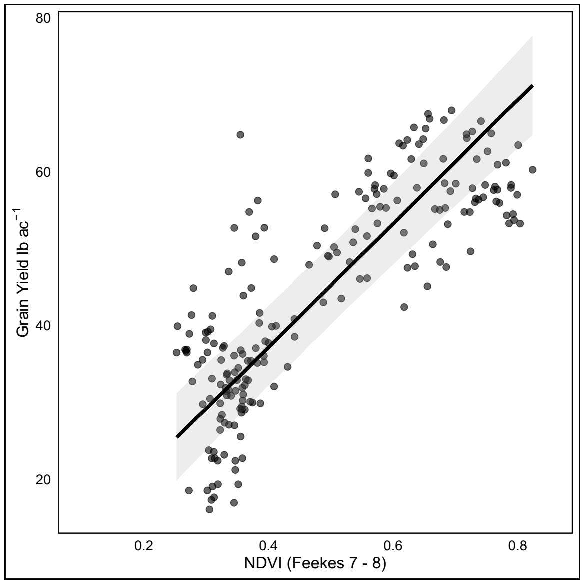

Figure 1. Relationship between NDVI measured between Feekes 7 – 8 and grain yield across nine Kansas locations. Each point represents an individual plot. The solid line shows the fitted regression from a mixed model, and the shaded area indicates the 95% confidence interval. Early-season NDVI explained 71% of yield variability (marginal ^{2} = 0.71), indicating strong potential for in-season yield prediction.

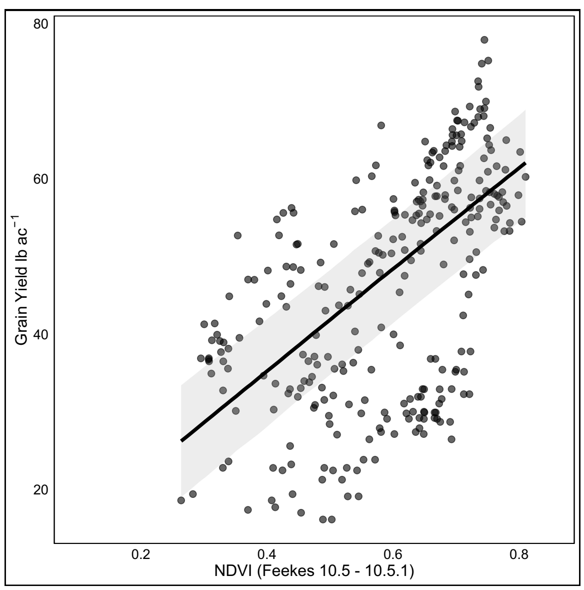

Figure 2. Relationship between NDVI measured between Feekes 10.1 – 10.5.3 and grain yield across nine Kansas locations. NDVI at these later stages explained 37% of yield variability (marginal R^2 = 0.37), suggesting reduced sensitivity due to canopy saturation at high biomass levels.

Flag leaf N and NDVI relationships woth protein

Both, NDVI and flag leaf concentration were weakly correlated with grain protein content (R^2m ≤ 0.15; Table 1). The low predictive power indicates that canopy reflectance and flag leaf N status are not strong indicators of final grain protein accumulation, which is influenced by post-anthesis N remobilization and environmental factors (Sanchez-Bragado *et al.*, 2017). Similarly, flag leaf N concentration measured at flowering showed poor relationships with yield (R^2 = 0.02).

Table 1. Marginal R^2 values from mixed-effects models relating NDVI and flag leaf N concentration to grain yield and protein across nine Kansas locations.

Predictor	Growth stage	Response	R^2m
NDVI	Feekes 7 – 8	Yield	0.71
NDVI	Feekes 10.1 – 10.5.3	Yield	0.37
Flag leaf	Feekes 10.5.3	Yield	0.02
NDVI	Feekes 7 – 8	Protein	0.02
NDVI	Feekes 10.1 – 10.5.3	Protein	0.11
Flag leaf	Feekes 10.5.3	Protein	0.15

Comparative performance of predictors

Across all predictors, early NDVI provided the strongest association with yield, while late NDVI and flag leaf N were less effective (Table 1). These findings highlight a critical window during which remote sensing can support in-season nitrogen management decisions. Early NDVI offers farmers a valuable, non-destructive tool to guide N adjustment before yield potential is determined. The limited relationship between NDVI and protein reinforces the need for complementary tools to predict grain quality more accurately in advance.

CONCLUSION

Early-season NDVI demonstrated strong potential for in-season yield prediction in winter wheat compared to flag leaf and later NDVI. These results support the use of proximal sensing as a decision-support tool to guide N management before critical growth stages. Early NDVI could be incorporated into N decision-support models for Kansas wheat. Continued research integrating multiple indicators may improve the prediction of grain protein and optimize N use efficiency across environments.

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EFFECTS OF NITROGEN RATE AND TIMING APPLIED AS ANHYDROUS AMMONIA ON CORN PRODUCTION AND PROFITABILITY

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ABSTRACT

Nitrogen (N) application timing is a critical decision for Illinois corn (*Zea mays* L.) producers, balancing operational efficiency, economic return, and environmental stewardship. We compared agronomic and economic responses to N rates applied as anhydrous ammonia (AA) in the fall and in the spring at 19 central Illinois sites from 2013 to 2020. Yield response to N was modeled to determine agronomic optimum N rate (AONR), economic optimum N rate (EONR), and maximum return to N (MRTN). Averaged across sites, EONR values for fall- versus spring-applied AA were 178 and 160 lb N ac^{-1}, respectively; yield at the EONR averaged 229 bu ac^{-1} for fall and 231 bu ac^{-1} spring N; MRTN was \$424 ac^{-1} for fall N and \$437 ac^{-1} for spring N. Of the \$13 ac^{-1} MRTN advantage to spring N, \$7 came from needing less N, and \$6 from slightly higher (2 bu ac^{-1}) yield at the EONR. When compared using a paired t-test, EONR differences between timings were statistically significant (p = 0.007), but differences in YEONR and MRTN were not (p > 0.1). Differences in N response were not consistently linked to soil or weather parameters, highlighting the complexity of N dynamics across environments. Current N rate guidelines in central Illinois (187 lb N ac^{-1} at the N and corn grain prices used in the study) would be sufficient to meet the needs of the crop whether applied in the fall or spring, these results indicate that N losses (or unavailability) tend to be higher following fall application than following spring application, with lower yield possible from fall application in fields where fertilizer N requirements are high.

INTRODUCTION

Anhydrous ammonia (NH_3, AA) is a widely used nitrogen (N) fertilizer for corn production in Illinois. In 2024, approximately 258,000 tons of AA were sold as fertilizer in Illinois, making it the single most prevalent N source used in Illinois (Illinois Department of Agriculture, 2024). While applications of AA in the spring have increased in popularity, fall applications remain common on medium-textured soils in the central Corn Belt. A retailer survey reported that 54% of fields in Illinois received some amount of AA applied in the fall (IFCA, 2024).

Few studies in the North Central Region have compared fall versus spring application with N applied over a range of rates. Touchton et al. (1979) included fall and spring applied AA at one central and one northern Illinois site in an investigation of the effectiveness of nitrapyrin, and found yield differences between fall and spring timing only at the lowest N rate (60 lb N ac^{-1}), with no yield differences at 120, 180, and 240 lb N ac^{-1}. Welch et al. (1971), using ammonium nitrate as the N source, found no differences from fall vs. spring in yield or N fertilizer efficiency above 120 lb N ac^{-1} at three Illinois locations across four years. Research in Indiana, with AA as the N source, found grain yield differences between N timing only at N rates of 130 and 180 lb N ac^{-1}, but no differences at lower N rates, although such an analysis was conducted for spring preplant versus sidedress timing and did not include a fall timing treatment (Kovacs et al., 2015).

While some previous work comparing timing of AA applications has been done, results have been mixed, and the work has not typically included a full set of N rates to allow comparisons of optimum N rates, associated yields, and economic returns to N. Thus, the rationale for this study was clear: perform and analyze on-farm N rate trials focusing on application timing differences to determine optimum N rates that could help shape management-specific N guidelines for fall or spring use of AA, as well as to evaluate whether spring-applied AA is economically advantageous.

MATERIALS AND METHODS

Field trials were conducted from 2013 to 2020 in farmers' fields across central Illinois, mostly on Mollisols with silt loam or silty clay loam textures, and included locations in Vermillion, Sangamon, Piatt, DeWitt, Logan, Douglas, Pike, and Edgar counties from 2013 to 2020. The previous crop grown was soybean [*Glycine max* (L.) Merr.] on all sites except Site 3, where corn was the previous crop. Fall AA applications were made in November, and spring applications were made before planting at fifteen sites, and as early sidedress at four sites. Additional fertilizer nitrogen was applied as base rates over the entire trial at fifteen sites, with rates ranging from 14 to 72 lb N ac^{-1}, as dry ammoniated phosphate (P source), urea-ammonium nitrate (UAN) solution applied with the planter or as herbicide carrier, or both. Trials were structured as a randomized complete block design with three or four replications. Main plots were assigned N rates of 0, 50, 100, 150, 200, or 250 lb N ac^{-1}, with application timing (fall or spring) as subplots split within N rate; there was a single 0-N strip in each block. Base N rates were added to the treatment rates. Subplots were 8 to 12 30-inch rows (20 to 30 ft) wide and ranged in length from 300 to 1200 ft. Yield data were collected by harvesting the center four to twelve rows of each subplot, with weight and moisture recorded using calibrated yield monitors on combines, or, in a few cases, using weigh wagons. Grain yields were adjusted to 15.0% moisture. Yield monitor data were cleaned based on criteria such as combine distance traveled, harvest width, and grain moisture content as described by Luck and Fulton (2015). Weather data for each site was obtained from the PRISM gridded dataset (PRISM Group, 2025). Historical AA and corn grain price information was retrieved from USDA-AMS

Economic optimum N rates were determined by setting the first derivative of the response model to an N price (\$ lb N^{-1}) to corn price (\$ bu^{-1}) ratio and solving for N rate (Equation 1 and 2). Prices of \$0.40 lb N^{-1} and \$4.00 bushel^{-1} were used for this purpose, resulting in a price ratio (PR) of 0.10 bu lb N^{-1}.

Equation 1: $QP\ EONR\ (lb\ N\ ac^{-1}) = \frac{\mathrm{PR} - b}{2c}$

Equation 2: $LP\ EONR\ (lb\ N\ ac^{-1}) = \begin{cases} X_N, & b \geq PR \\ 0, & b < PR \end{cases}$

Where c [(bu ac^{-1}) (lb N^2)$^{-1}$] is the quadratic coefficient in Equation 1, b (bu lb N^{-1}) is the linear coefficient in Equation 1 and 2, and X_N is the joint point (linear-plateau model) of the best fit response models. Once the EONR was calculated, YEONR was obtained by solving each best fit yield response function for yield. The RTN value is defined as the economic partial return received due to the increase in yield when applying nitrogen fertilizer at a certain rate (Y_N) as compared to a zero-nitrogen application (Y_0) minus the cost of the nitrogen fertilizer applied (Equation 3).

Equation 3: $RTN\ (\$\ ac^{-1}) = [(Y_N - Y_0) \times \$\ bu\ corn^{-1}] - (N \times \$\ lb\ N^{-1})$

For sites that received a base rate of N, RTN was calculated using the average of the estimated Y_0 values for each timing.

RESULTS AND DISCUSSION

Figure 1 shows the modeled yield responses to N rate and application timing at each site. The best-fitting model was chosen for each N timing combination on the basis of the R^2 values adjusted for degrees of freedom, pairwise F-tests of the model's residual sums of squares, and observation of the distribution of residuals. Those best fit models are listed in Table 1. All yield responses were best described by fitting a quadratic-plateau model, except for three instances where the linear-plateau model best fit. All N rate responses were statistically significant for both N application timings at all sites ($p \leq 0.05$) with R^2 values ranging from 0.54 to 0.96. Paired t-tests indicate that model coefficients were significantly different ($p < 0.05$) between timings. The capacity of quadratic-plateau models to explain yield responses to N rate was notably high.

Nitrogen Rate and Timing Effects on Yield

Yield response to N rate was observed for both N application timings (spring and fall) at all sites, though yield increase with incrementally higher N rates was not always consistent, even for different N application timings at the same site. As expected, the lowest N rate treatment to produce the statistically highest corn yield varied by site, ranging from 50 to 230 lb N ac^{-1}. Corn yield increases from the lowest N treatments to the statistically maxima treatments ranged from 41 to 190 bu ac^{-1} with an average of 84 bu ac^{-1} increase for both N timings. Yield response to N rate differed by site to a greater degree than by N application timing. Variance (coefficient of variation) of corn yield across N rates for individual site x N timing combinations ranged from 2.2 to 10.4%.

Effects of N application timing were inconsistent across sites and N rates. Averaged across all N rates, yield differences between fall and spring N application timing ranged from a 21 bu ac^{-1} (8%) yield benefit to fall N (Site 17 at 115 lb N ac^{-1}) to a 45 bu ac^{-1} (21%) yield benefit to spring N (Site 13 at 136 lb N ac^{-1}). Significant effects ($p \leq 0.1$) of N timing on yield were observed for at least one N application rate at ten of nineteen sites. However, N timing never affected yield at more than two N rates for any site, and when an N timing effect was significant at two N rates, no clear pattern of benefit to fall or spring application was observed in the context of yield. The general linear relationship between fall and spring yields at N rates above the lowest is strong and suggests yield differences between N timings were mostly within 10% of being equivalent. Evaluating yield at all N rates and sites in aggregate suggests that small to no yield differences would be expected between fall and spring applied AA. A significant ($p \leq 0.1$) N rate by N timing interaction was observed at two sites (16 and 17) of the nineteen. Site 16 exhibited a stronger yield response to spring-applied N as N rate increased, while spring N at site 17 optimized yield at a much lower N rate, albeit at a lower YEONR as compared to fall. No clear justification could be discerned for why fall or spring N timing affected yield response to N rate in these two sites.

Table 1. Equations describing relationships between fall or spring-applied N rate and yield for each site, optimum N rates and associated yields.

Site Index	Year	N Timing	Model	Equation Coefficients and Statistics[1]					EONR	YEONR	MRTN
				Y_0	b	c	RMSE	R^2			
									lb N ac^{-1}	bu ac^{-1}	\$ ac^{-1}
1	2013	Fall	QP	22.8	1.422	-0.0039	8.58	0.93	170	151.9	443
		Spring	QP	25.4	1.361	-0.0036	8.50	0.94	177	154.8	452
2	2014	Fall	LP	171.5	0.493		6.09	0.94	133	237.2	211
		Spring	QP	170.9	0.760	-0.0025	10.59	0.80	139	230.1	180
3	2014	Fall	QP	162.0	0.859	-0.0019	8.18	0.88	200	258.0	307
		Spring	QP	160.4	0.918	-0.0022	9.65	0.83	187	255.3	302
4	2014	Fall	QP	139.7	0.888	-0.0019	9.73	0.89	206	241.6	322
		Spring	QP	141.2	0.860	-0.0020	10.89	0.83	189	231.8	290
5	2015	Fall	QP	53.1	2.170	-0.0058	16.39	0.87	177	254.2	765
		Spring	QP	37.1	2.668	-0.0080	16.05	0.88	161	259.7	794
6	2015	Fall	LP	100.3	0.471		24.85	0.54	164	177.5	236
		Spring	LP	104.2	0.626		16.24	0.78	130	185.8	282
7	2016	Fall	QP	137.6	1.069	-0.0031	6.04	0.94	157	229.5	316
		Spring	QP	132.2	1.290	-0.0042	5.47	0.95	142	230.7	327
8	2016	Fall	QP	103.7	0.893	-0.0027	8.40	0.85	145	175.6	218
		Spring	QP	109.3	0.886	-0.0026	7.87	0.88	149	183.0	246
9	2017	Fall	QP	101.1	1.523	-0.0039	20.44	0.70	183	249.7	568
		Spring	QP	77.8	2.120	-0.0066	17.93	0.75	153	247.4	571
10	2017	Fall	QP	110.8	1.210	-0.0026	11.73	0.91	217	253.2	480
		Spring	QP	112.3	1.227	-0.0028	14.06	0.85	202	246.4	458
11	2017	Fall	QP	83.5	1.010	-0.0021	21.01	0.80	213	201.7	390
		Spring	QP	82.1	0.904	-0.0016	16.50	0.87	250	209.0	405
12	2017	Fall	QP	177.2	0.741	-0.0018	15.05	0.75	175	250.9	230
		Spring	QP	174.5	0.867	-0.0023	12.95	0.84	170	256.8	256
13	2017	Fall	QP	70.0	1.436	-0.0033	16.15	0.83	236	230.9	678
		Spring	QP	5.5	3.423	-0.0122	20.31	0.85	136	245.2	775
14	2017	Fall	QP	146.8	0.476	-0.0009	8.61	0.78	199	204.0	169
		Spring	QP	136.7	0.767	-0.0023	7.69	0.81	145	199.3	172
15	2018	Fall	QP	64.5	1.456	-0.0030	11.65	0.87	225	236.4	748
		Spring	QP	-10.4	2.877	-0.0086	8.01	0.92	162	231.4	752
16	2018	Fall	QP	90.0	1.944	-0.0042	11.56	0.96	217	308.0	795
		Spring	QP	85.0	2.105	-0.0045	14.38	0.96	223	330.8	884
17	2018	Fall	QP	171.1	1.232	-0.0054	6.50	0.90	105	240.9	270
		Spring	QP	154.7	2.573	-0.0217	5.95	0.89	57	230.9	249
18	2018	Fall	QP	109.6	1.099	-0.0024	13.95	0.80	207	233.9	448
		Spring	QP	92.8	1.531	-0.0042	13.50	0.81	171	232.3	456
19	2020	Fall	QP	100.3	1.721	-0.0057	10.84	0.92	142	229.3	460
		Spring	QP	100.0	1.787	-0.0062	8.64	0.95	137	228.9	461

[1] Coefficients for best fit models according to the general equation $Y = cx^2 + bx + Y_0$

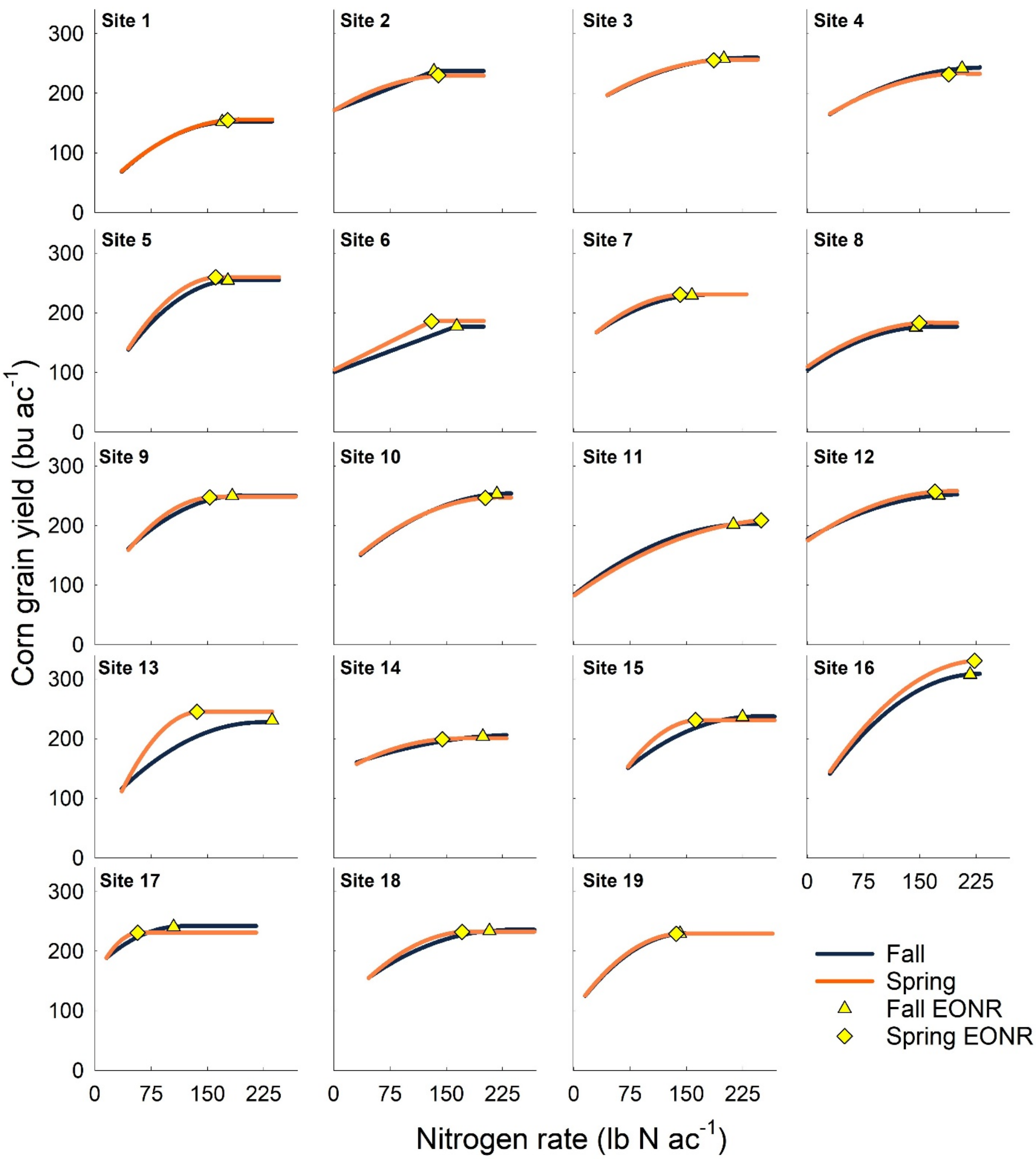

Figure 1. Relationship between N fertilizer rate and corn grain yield for both fall and spring anhydrous ammonia application timing at each site.

Economic Optimum Nitrogen Rates and Return to Nitrogen

The range of EONR values with fall application was 103 to 222 lb N ac^{-1}, with a mean of 178 lb N ac^{-1}. The range of spring EONR values was 56 to 248 lb N ac^{-1}, with a mean of 160 lb N ac^{-1}. YEONR values ranged from 151 to 331 bu ac^{-1}, with a mean of 229 bu ac^{-1} and 231 bu ac^{-1} for fall and spring respectively. Maximum return to N

(MRTN) values at the EONR ranged from \$166 ac^{-1} to \$892 ac^{-1} across the sites and timings. Across all sites, mean MRTN values were \$424 ac^{-1} and \$437 ac^{-1} for fall and spring, respectively – a \$13 ac^{-1} benefit to spring application. Of the \$13 ac^{-1} MRTN advantage to spring N, \$7 came from needing less N, and \$6 from slightly higher (2 bu ac^{-1}) yield at the EONR. When treating all sites as random, paired *t*-tests indicated the EONR for fall-applied AA was 18 lb N ac^{-1} greater (p = 0.007) compared to spring with no significant difference in YEONR. Using the same analysis on the MRTN values showed that those values were not significantly different (p = 0.133), and adjusting the PR from 50% to 150% of the PR used did not result in any significant differences.

Critics of determining N rates using maximum economic returns have suggested concerns of grain yield reductions. For all site and N timing combinations, estimated yield was on average 2 bu ac^{-1} less at the EONR compared to estimated yield at the AONR, where the maximum yield from best fit response function was determined. Furthermore, this negligible yield difference coincided with an average 18 lb N ac^{-1} lower N rate when economic returns were maximized (EONR) compared to yield maximized (AONR). We found no evidence to suggest that yield would be compromised when focusing on economic return to N to guide N rates for both N times.

Price Scenarios and Relationship with Economic Optimum Nitrogen Rate

Over the period of this study, the price ratio (\$ lb N^{-1}:\$ bu^{-1}) ranged between 0.07 and 0.13, with an average of 0.09 (USDA-AMS). This is equivalent to a range of 70% to 125% of the expected 0.10 ratio, with the average at 94% of the default ratio; a slightly lower ratio produces slightly higher EONR values. The seasonality of pricing also affects producer decisions regarding N timing. But over the period of this study, the average price ratio during the fall application months of October through December was within 0.01 of the average price ratio between the months of March through May (USDA-AMS). Such a small difference would do little to affect the decision on when to apply AA, at least compared to fall weather and application conditions.

Site Weather Characterization of Response to Application Timing

Weather is often a causal factor pointed to for observed N timing effects. The four sites with EONR values higher for fall- than for spring-applied N, were not consistently above or below the normal temperature or precipitation amounts. Additionally, they spanned four different counties, and each occurred in a different year. In fact, similar statements can be made about the sites with greater EONR values for spring N compared to fall. There were no consistent weather factors analyzed that displayed a relationship with fertilizer application timing performance.

CONCLUSION

Despite some general trends, this study's site-specific variability was considerable, and no strong relationships were observed between application timing performance and environmental parameters such as precipitation or soil characteristics. Some sites showing a greater advantage to spring applications may have had greater precipitation-induced losses after fall application, while other sites showed no such advantage. The majority of sites showed little or no difference in response to N rate between fall- and spring-applied N; most of the benefit to spring-applied N came from two sites. Across sites, yields at the economic optimum did not significantly differ, whereas the EONR was reduced by 18 lb N ac^{-1} by moving from fall to spring application. These results indicate producers can maintain optimal yields while lowering total N inputs by managing to economic return, thereby reducing input costs and the pool of nitrogen susceptible to loss**.**

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EFFECT OF BARLEY AND WINTER PEA COVER CROPS ON NUTRIENT AVAILABILITY IN NO-TILL CORN

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ABSTRACT

Cover crops are reported to have long-term soil health improvements, the first of which is reducing erosion. However, popular cereal cover crops, such as rye (*Secale cereale*), have the potential to cause a yield penalty in the following corn (*Zea mays*) crop. Legumes, such as Austrian winter pea (*Pisum sativum*), are thought to reduce this yield penalty in no-till systems. Additionally, sulfur deficiencies have been observed in some studies following cover crops. The main objective of this study is to determine if earlier termination and/or the addition of a legume will reduce cover crop competition for nitrogen. Cover crop treatments include no cover crop control, barley (Hordeum vulgare) alone (which produces less biomass than rye), and an Austrian winter pea plus barley mix. Cover crops were terminated either five weeks or two weeks before planting corn. Five nitrogen rates of 40, 170, 215, 260, and 349 lb N/A were applied, with 40 lb N/A applied at planting, and the remaining nitrogen applied as sidedress to V3 corn. An additional trial was conducted to examine the effect of sulfur on corn yields following a cover crop. Utilizing the same cover crop treatments, an additional 0 or 30 lb S/A as gypsum was applied. Agronomic data collected includes cover crop nutrient composition, cover crop biomass production, SPAD, ear leaf nitrogen content, soil nitrate and ammonium levels, and yield. Preliminary findings show that early termination of the cover crops can lead to an increase in corn nitrogen content during the growing season. Additionally, fertilizer sulfur increased corn yields following a cover crop at one site year.

INTRODUCTION

Cover crops are needed following soybean harvest to prevent erosion that occurs over the winter. Corn following these cover crops can require more nitrogen and sometimes yield less. Barley produces less aboveground biomass than other comparable cereal grains, while still providing erosion protection (Nalley, 2024). The addition of a legume, like Austrian Winter Pea, is thought to reduce the competition for nitrogen between the cover and corn crops. Early termination of cover crops, 5 weeks before planting as compared to the standard timing of 2 weeks prior to corn planting, has the potential to further reduce this competition for nitrogen due to a lower amount of aboveground biomass present.

Sulfur is classified as the fourth most important nutrient after nitrogen, phosphorus, and potassium (Aula et al., 2019). Sulfur deficiency in agricultural crops is becoming more common as the rate of sulfur deposition has declined over the past 20 years (Sharma et al., 2024). An application of sulfur has been shown to have the potential to increase corn yield in certain cases. However, there is limited research available on the demand of sulfur in a cover crop and how that affects availability of sulfur in the following corn crop. The objective of this study is to evaluate the effect of cover crop management on nitrogen and sulfur dynamics in no-till corn.

MATERIALS AND METHODS

Two studies were conducted to evaluate the outlined objectives. Both studies were conducted at the University of Kentucky's North Farm in Lexington, KY and on-farm in Glendale, KY for both the 2024 and 2025 growing seasons, resulting in four site-years per study: LEX24, GLN24, LEX25, and GLN25. Treatments, outlined in Table 1, were arranged in a split-plot randomized complete block design where the main plot is cover crop with four replications. Cover crops were terminated with 40 oz/ac of glyphosate (trade name Roundup WeatherMax). Urea ammonium nitrate was applied at planting at 40 lb N/acre. The remaining nitrogen was applied side dress at V3. When applicable, sulfur was hand applied as gypsum. Drip irrigation and soil moisture sensors were installed in Lexington both years to limit water as a limiting factor. All plots were managed so that weeds, insects, and diseases did not adversely affect yield.

Cover crop biomass samples were taken from a 1m^2 area from each cover crop replication and analyzed for biomass and nutrient composition, for the nitrogen study only. Soil Plant Analysis Development (SPAD) readings were taken at both the V10 and R1 stages as an estimation of chlorophyll and nitrogen. Soil samples were taken after V10 for analysis of soil nitrate and ammonium from the 40 and 349 lb N/ac nitrogen treatments. Ear leaves were collected at R1 for nutrient analysis. Yield, kernel weight, and kernel number were determined after harvest.

	Nitrogen Study	**Sulfur Study**
Cover Crop	Barley Barley+ Austrian Winter Pea (Mix) Fallow Control	Barley Barley+ Austrian Winter Pea (Mix) Fallow Control
Termination	5 weeks before planting 2 weeks before planting	5 weeks before planting
Fertilization Rate	40 lb N/acre 170 lb N/acre 216 lb N/acre 260 lb N/acre 349 lb N/acre	130 lb N/acre 220 lb N/acre + 0 lb S/acre 30 lb S/acre

Table 1. Treatment table for Nitrogen and Sulfur studies.

RESULTS AND DISCUSSION

Cover Crop

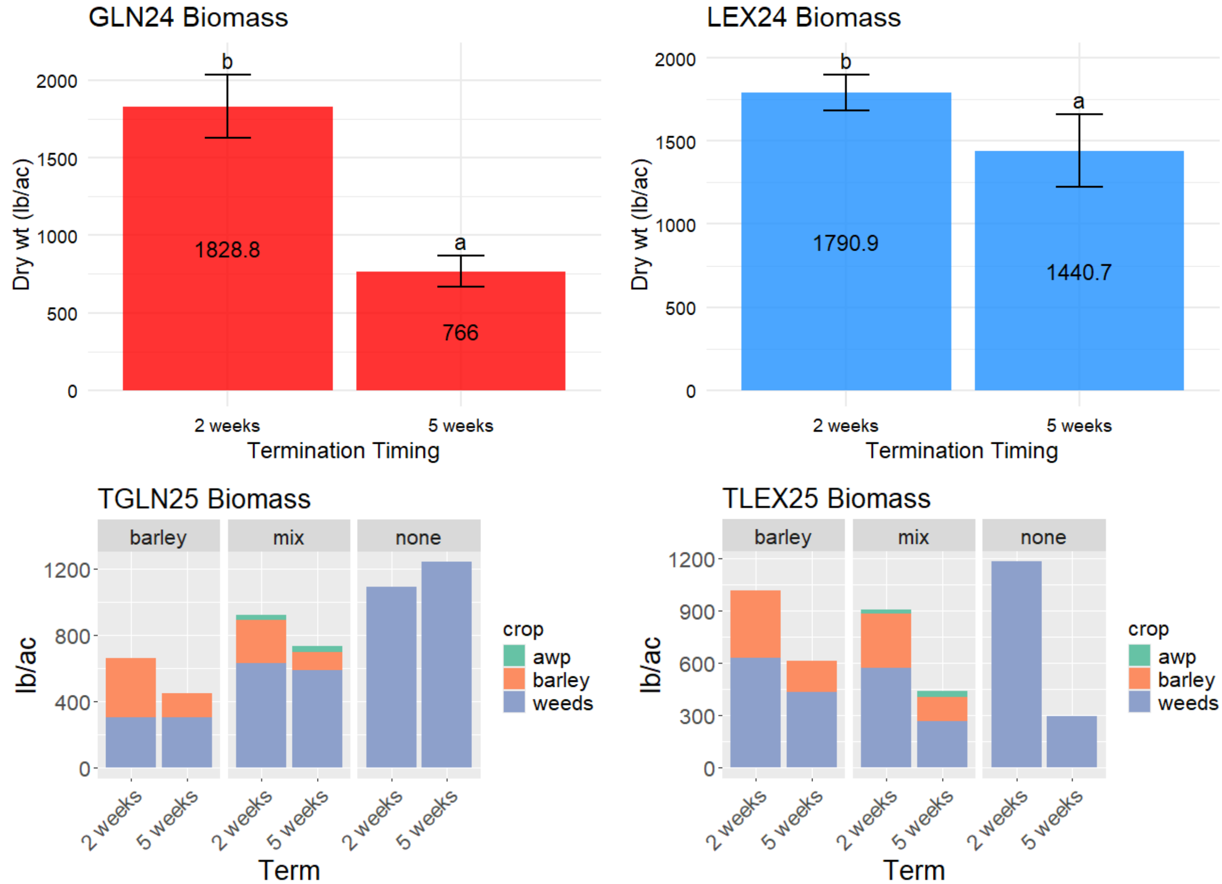

Figure 1. Cover crop biomass by site-year.

Biomass was significantly lower for the 2025 season at both locations. This can most likely be attributed to a very cold winter, limiting above ground growth. Cover crop dry biomass was statistically lower when terminated 5 weeks before planting in every site-year, except GLN24. Which still saw an 84 lb/acre increase in biomass between the 5 week and 2 week termination timings. The effect of cover crop type was variable between the site-years. Both barley and the mixture had significantly more biomass compared to the weedy fallow, but not any different from each other at both locations in 2024. Cover crop biomass was not significantly different for LEX25 while the weedy fallow had the most biomass at GLN25. Biomass was only separated in the 2025 season. At both locations, barley and winter annual weeds outcompeted the winter peas, potentially reducing their ability to offset a nitrogen penalty from the barley.

Corn Yield and Nitrogen

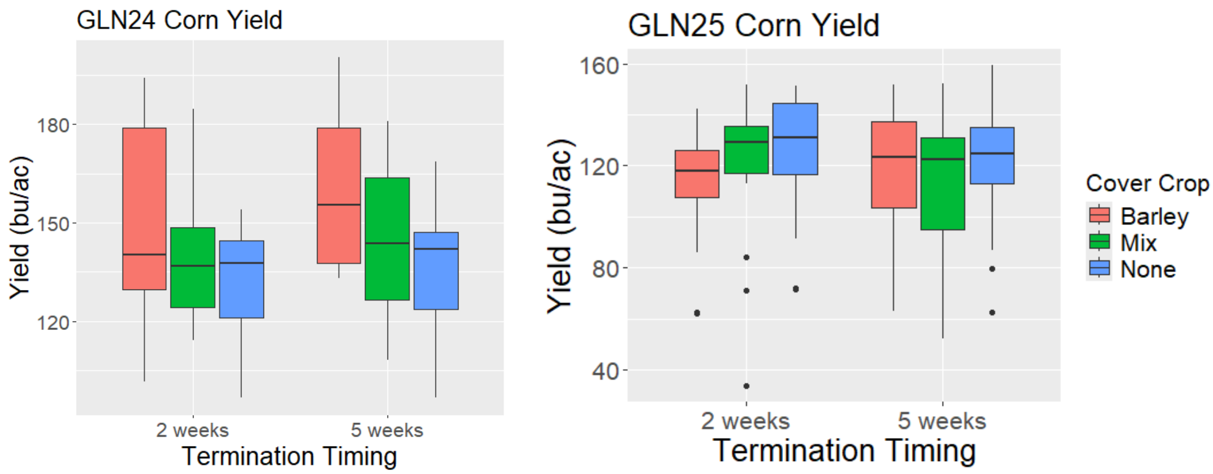

Figure 2. Corn yield by cover crop type and termination timing across all nitrogen rates.

Differences in corn yield due to cover crop was only observed at Glendale. GLN24 showed corn following barley yielded significantly higher than either the mixture or control. GLN25 revealed an inverse, with corn following barley yielding significantly lower than the fallow control. Yield was not significantly different due to termination timing.

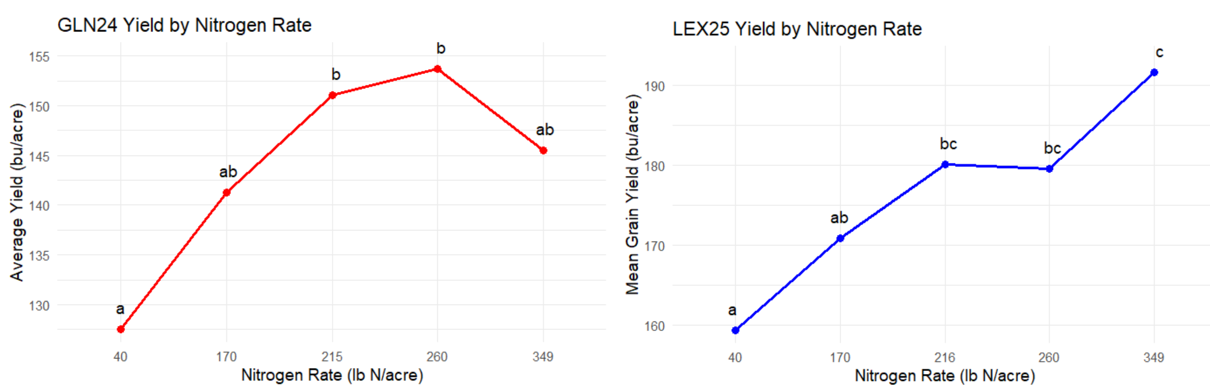

Figure 3. Corn yield by nitrogen rate across all cover crop types and termination timings for GLN24 and LEX25. (Note the differences in scale between the two graphs.)

Yield was significantly different due to nitrogen rate across all site years, except for LEX24. Corn at GLN25 (not shown) only had a yield difference at the lowest nitrogen rate, with an average yield of 70 bu/acre.

Corn Yield and Sulfur

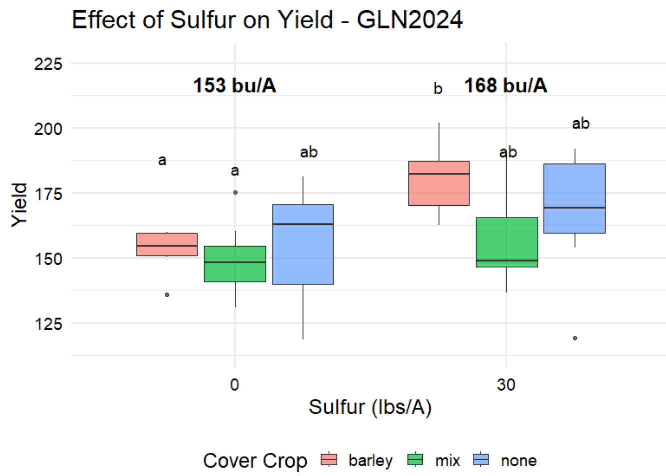

Figure 4. Corn yield following each cover crop and sulfur rates across both nitrogen rates at GLN24.

In the sulfur study, differences in yield were observed for GLN24 (Figure 4), where corn following barley showed the biggest response to sulfur. Overall, there was a 15 bu/acre increase across all cover crops and nitrogen rates, when 30 lb/acre of sulfur was applied. Yield differences were observed at GLN25 due to nitrogen rate only for this study.

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OPTIMIZING NITROGEN INPUTS IN BARLEY PRODUCTION IN NORTH DAKOTA

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ABSTRACT

Nitrogen (N) management plays a critical role in balancing yield and malting quality of two-row spring barley (*Hordeum vulgare* L.) grown in the Northern Plains. A field experiment was conducted at three locations in North Dakota to evaluate the effect of N fertilizer source on grain yield, protein, and kernel plump. Treatments included eight commercially available N sources including urea, enhanced efficiency urea, urea ammonium nitrate, calcium ammonium nitrate, sulfur enriched granular urea, and a non-fertilized check. Treatments were arranged in a randomized complete block design. All fertilized treatments received 150 lb N ac^{-1}, corresponding to 80% of the regional agronomic optimum N rate for malting barley production. Results showed N fertilization significantly increased grain yield and protein concentration compared with the unfertilized check, while kernel plump remained unaffected by N source. Despite small differences among sources, all fertilized treatments produced protein concentrations within the AMBA-recommended range (10-13%), indicating acceptable malting quality. The non-fertilized check exhibited the most desirable protein level (10%), demonstrating the typical trade-off between yield and quality. These findings highlight applying uniform N rates while varying fertilizer source can sustain yield gains without exceeding protein thresholds critical for malting quality in North Dakota barley production systems.

INTRODUCTION

Barley (*Hordeum vulgare* L.) is a major cereal crop cultivated across the Northern Great Plains of the United States, primarily for malting, food products, and animal feed (Akar, Avci, & Dusunceli, 2004). North Dakota consistently ranks among the leading barley-producing states, accounting for approximately 20% of total U.S. production in 2025 (USDA-NASS, 2025). According to the North Dakota Barley Council (2025), approximately 90% of the state's barley is marketed for malting and brewing, highlighting the strong connection between barley production and the regional malting industry.

Maintaining grain quality is essential for the malting sector, which requires kernels with plump greater than 90% and protein concentrations under 13% to ensure desirable malt extract potential and brewing performance (AMBA, 2025). Achieving this balance between yield and grain quality represents a major agronomic challenge for producers in the region. Nitrogen (N) is the most yield-limiting nutrient for barley and has a direct influence on both productivity and grain quality (McFarland et al., 2015). While adequate N supply is required to maximize yield and maintain sufficient protein content, excessive N can increase grain protein above acceptable malting thresholds and reduce kernel plumpness (Franzen, 2023). Previous studies report as N rates increase, grain protein concentration rises (Goettl et al., 2024) while kernel plumpness tends to decline (Sainju et al., 2024).

To improve N use efficiency and minimize environmental losses, enhanced efficiency fertilizers (EEFs), including urease and nitrification inhibitors and controlled release formulations, have been developed to synchronize N availability with crop uptake (Franzen, 2022). However, their agronomic performance under the cool and variable climatic conditions of the Northern Plains remains uncertain, as environmental factors such as soil temperature and rainfall patterns can strongly influence N release and uptake (Olson-Rutz et al., 2011).

Given the economic importance of malting barley in North Dakota and the sensitivity of quality parameters to N management, this study was conducted to evaluate the effect of N fertilizer source on grain yield, protein concentration, and kernel plump of two-row spring barley across multiple sites in eastern North Dakota. The findings aim to identify the most effective N sources for optimizing N use efficiency while maintaining malting quality standards.

MATERIALS AND METHODS

Field experiments were conducted during the 2025 growing season at three sites in North Dakota, near Hillsboro, Lakota, and Valley City; These sites represent distinct soil types common to barley production in the state—Fargo-Hegne (silty clay), Hamerly-Wyard (loam), and Barnes-Buse (loam), respectively (Soil Survey Staff, 2025).

The experiment was arranged in a randomized complete block design (RCBD) with nine N treatments and four replicated blocks per site. Treatments consisted of eight commercial N fertilizer sources, each applied at 80% (150 lb N ac^{-1}) of the recommended regional agronomic optimum N rate (Goettl et al., 2024) and one unfertilized check. Each fertilizer source had distinct chemical characteristics and release mechanisms (Table 1).

Prior to planting, composite soil samples (0-24 in) were collected from each site to determine baseline fertility, including nitrate-N, phosphorus (P), potassium (K), pH, and organic matter. The total known available N (TKAN) was calculated as the sum of soil nitrate (N_s), previous crop credit (N_{pc}), tillage contribution (N_t), and fertilizer N applied (N_{fert}), following the NDSU recommendation framework (Franzen, 2023). For this experiment, TKAN levels corresponded to 87±16 lb N ac^{-1} for the unfertilized check and 150 lb N ac^{-1} for all fertilized treatments.

Barley cultivars Explorer (Hillsboro) and AAC Synergy (Lakota and Valley City) were used, both two-row recognized by the American Malting Barley Association (AMBA, 2025) for malting quality potential. All fertilizers were surface applied within one week of seeding. Seeding occurred between May 7 and May 9, 2025, with in-season crop management carried out by the cooperating farmers, in accordance with regional best management practices, to control pest and disease pressure. Harvest occurred between August 13 and August 14, 2025, at physiological maturity. Grain moisture and test weight were measured using a Dickey-John model GAC500 XT grain analyzer (Dickey-John, Auburn, Illinois). Grain harvest weights were adjusted to the standard moisture content of 13.5% for yield calculations. Percent plump kernels were considered the weight of kernels which do not pass through a 6/64-inch sieve. Grain protein content was determined using near infrared spectroscopy (NIR).

Table 1. Description of nitrogen fertilizer sources used in the study.

Treatment	Analysis	Description
Urea	46% N	Granular fertilizer and the most widely used N source due to high N concentration and low cost.
CAN 27 (Calcium Ammonium Nitrate)	27% N, 4% Ca	Provides both nitrate and ammonium forms of N with added calcium, improving soil structure and reducing volatility.
Amidas (Urea + Ammonium Sulfate)	35% urea-N, 5% ammonium-N, 5.5% S	Combines rapid and stable N forms, adding sulfur to enhance protein synthesis and improve grain quality.
UAN (Urea Ammonium Nitrate)	28% N	Liquid fertilizer containing both urea and ammonium nitrate; liquid formulation allows uniform application and better soil contact, enhancing N availability.
ESN (Environmentally Smart Nitrogen)	44% N	Polymer-coated urea that provides slow N release, minimizing leaching and volatilization losses.
SuperU	46% N	Stabilized urea with both a urease inhibitor (NBPT) and a nitrification inhibitor (DCD) to reduce volatilization and nitrate losses.
Urea + NBPT	46%N	Urea treated with urease inhibitor NBPT only, slowing surface hydrolysis and reducing ammonia volatilization.
Tropicote (Calcium Nitrate)	15.5% N, 19% Ca	Provides nitrate-N and calcium to support grain filling and mitigate soil acidity.

Data analysis was performed using JMP (SAS Institute, Cary, NC). Analysis of variance (ANOVA) was carried out as randomized complete block design. Data in this study was considered statistically significant at $p \leq .05$.

RESULTS AND DISCUSSION

Grain Yield

Barley grain yield responded significantly to N source ($p < 0.0001$; Table 2). All fertilized treatments produced markedly higher yields compared to the non-fertilized check, which averaged only 47.2 bu ac^{-1}. The highest yields (59-60 bu ac^{-1}) were obtained with Can27 and SuperU, although differences among enhanced-efficiency sources were not statistically significant. These results indicate that most N sources supplied adequate plant-available N to maximize yield under the conditions of this study.

Table 2. Mean values for barley yield, grain protein content, and kernel plump averaged across three North Dakota locations.

Treatment	Yield	Protein	Plump
	bu ac^{-1}	%	%
Check	47.2 b	10.0 c	96.2 a
ESN	53.5 ab	11.1 a	95.4 a
Urea	58.3 a	11.0 a	95.1 a
Can 27	59.7 a	10.9 ab	94.9 a
Amidas	58.5 a	11.2 a	94.4 a
UAN 28	58.8 a	10.6 b	94.8 a
SuperU	59.7 a	11.0 a	94.6 a
Tropicote*	57.8 a	11.0 a	94.7 a
Urea + NBPT	58.5 a	11.0 a	94.4 a
p-value	<.0001	<.0001	NS

Note: Means with the same letter within each column are not significantly different at the .05 probability level.
Abbreviation: NS, nonsignificant; ESN Environmentally Smart Nitrogen; UAN Urea Ammonium Nitrate
*10% Tropicote + 90% Urea

Grain Protein

Grain protein concentration increased significantly with N fertilization, reflecting greater N uptake and assimilation in the fertilized plots. Protein values among N sources ranged from 10.9% to 11.2%, while the non-fertilized check produced the lowest value (10%). Although this unfertilized treatment had the lowest yield, it exhibited the most desirable protein level for malting quality, falling near the lower end of the AMBA recommended range (10-13%). Fertilized treatments remained within the acceptable threshold but trended toward the upper limit, indicating that N additions enhanced yield but also elevated grain protein concentration.

Among N sources, Amidas produced the highest mean protein value (11.2%; Table 2), which may be attributed to its ammonium-sulfate-based composition providing both N and sulfur. Sulfur can stimulate protein synthesis, potentially improving N assimilation efficiency (Adeyemi, 2023). Despite small numerical differences among N sources, all fertilized treatments delivered sufficient available N for protein accumulation while maintaining acceptable malting quality standards.

Kernel Plump

Unlike yield and protein, kernel plumpness was not significantly affected by N source (p = 0.36; Table 2). Plumpness values remained uniformly high (94-96%), indicating that kernel filling was more strongly influenced by environmental conditions-such as temperature and moisture than by fertilizer source. Similar patterns were observed in Idaho, where kernel plumpness exceeded 97% across most sites but declined under moisture stress during the grain-filling period (Adeyemi, 2023). Even the non-fertilized check showed plumpness above 96%, meeting AMBA's quality requirement (>90%). The absence of a treatment effect implies none of the N sources reduced grain size or malting potential. Thus, while N management strongly affected yield and protein, plumpness remained stable across all treatments, underscoring that N source selection can optimize yield and protein without compromising kernel quality.

CONCLUSION

N fertilization significantly improved barley yield and protein concentration relative to the unfertilized check, confirming the essential role of N in achieving optimal productivity. However, no significant differences were detected among N sources for any measured variable, indicating that all fertilizers supplied adequate available N to support yield and maintain acceptable malting quality.

Although statistical differences were minimal, Amidas tended to produce slightly higher protein values, likely due to its sulfur component enhancing amino acid synthesis and N assimilation. Conversely, the unfertilized check exhibited the most desirable protein concentration (10%), within the lower end of the AMBA-recommended (13%), representing the best malting quality among treatments.

Overall, these results suggest all N sources performed similarly under the tested conditions, but the choice of fertilizer should also account for economic return, environmental impact, and N use efficiency technologies. Balancing yield, malting quality, and sustainability remains essential for optimizing N management in North Dakota barley production systems.

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EVALUATING SOIL HEALTH INDICATORS IN RESPONSE TO TILLAGE, CROP ROTATION, AND COVER CROPPING

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ABSTRACT

Soil health is shaped by management practices that influence soil physical, chemical, and biological properties. Conservation practices such as reduced-disturbance tillage, cover cropping, and diverse crop rotations are increasingly promoted for improving soil structure, nutrient cycling, and microbial activity. However, the extent to which these practices interact and whether newly adopted no-till systems show similar benefits to long-term no-till remains unclear. This study evaluates soil health across multiple contrasting tillage and rotation contexts, ranging from a 2-year corn-soybean system to a diverse 5-year rotation including small grains. Each system is managed with and without cover crops and benchmarked against an undisturbed perennial grass control. Surface soil samples (0-2 inches) were collected in June 2025 and analyzed for a range of soil health indicators. Chemical indicators included organic C, total C and N, soil organic matter, inorganic N, available nutrients (P, K, Ca, Mg, S, and micronutrients), pH, cation exchange capacity, base saturation, and soluble salts. Biological indicators included microbial biomass and activity measures such as respiration, potentially mineralizable N, enzyme activities, and protein-based tests. We hypothesize that cover crops will enhance soil health more under no-till than under conventional tillage, and that diverse crop rotations with cover crops will accelerate soil recovery in newly converted no-till systems. This study will evaluate the benefits of cover crops and rotation diversity across tillage systems. Results will inform best management strategies to enhance soil health and promote long-term agricultural sustainability.

INTRODUCTION

Soil health is a fundamental component of sustainable agricultural production and environmental quality. It reflects the soil's capacity to function as a living system that supports plant growth, regulates water and nutrient cycling, and maintains ecological balance (Omer et al., 2024). Assessing soil health requires evaluating a combination of physical, chemical, and biological indicators that together indicate the soil's ability to function sustainably. Physical indicators include soil structure, soil texture, aggregate stability, bulk density, porosity, and water-holding capacity. These factors influence root growth, water infiltration, and resistance to erosion. Chemical indicators typically involve soil pH, soil organic matter, nutrient availability (such as N, P, and K levels), cation exchange capacity, and the presence of contaminants. These indicators provide insights into soil fertility and potential limitations to crop production. Biological indictors focus on measurements of microbial biomass, soil respiration, enzyme activity, and the diversity of soil organisms. These factors reflect the living component of the soil and its capacity to cycle nutrients and support plant growth (Biradar & Ingle, 2023).

Management practices influence soil health by altering its physical structure, chemical fertility, and biological activity (Angon et al., 2023). Conservation practices such as reduced-disturbance tillage, cover cropping, and diversified crop rotations have been widely promoted as strategies to improve soil structure, enhance nutrient availability, and stimulate beneficial microbial processes. These practices can also reduce soil erosion, increase organic matter accumulation, and improve resilience to environmental stressors such as drought (Haruna & Nkongolo, 2020). While long-term conservation benefits are well known, the rate and extent to which these benefits develop following the adoption of new conservation practices, particularly transitions to no-till systems, are less understood.

The interactions among tillage intensity, cover cropping, and cropping diversity may further influence soil health outcomes, but separating the effects of each practice remains challenging. It is uncertain whether newly adopted no-till systems can achieve the same improvements in soil structure, nutrient cycling, and microbial activity as observed in long-term reduced-tillage systems. A better understanding of these relationships is essential for improving soil health management recommendations and guiding producers in the adoption of more sustainable agricultural practices.

The objective of this study is to evaluate how tillage intensity, cover cropping, and crop rotation diversity interact to influence soil health. We aim to compare biological and chemical soil properties across long-term no-till, newly adopted no-till, and conventionally tilled systems and assess whether interactions among tillage, cover cropping, and crop rotation influence indicators of soil health. In addition, this study seeks to determine whether cover crops and diverse rotations accelerate soil recovery under no-till. Overall, this work contributes to a broader understanding of how conservation management history affects soil processes. These insights are critical for developing strategies that promote long-term agricultural productivity.

METHODOLOGY

Experimental Design

This study was conducted at the South Dakota State University Southeast Research Farm near Beresford, South Dakota. The experiment included four crop rotation systems representing increasing management complexity: a 2-year corn-soybean rotation, a 3-year corn-soybean-oat rotation, a 4-year corn-soybean-oat-rye rotation, and a 5-year corn-corn-short season soybean-hybrid rye-soybean rotation. Three tillage treatments were included: newly converted no-till systems (NT) established for two growing seasons, long-term no-till (LT-NT) systems maintained for 34 years, and long-term conventional tillage systems (LT-CT) with a continuous 34-year history of annual soil disturbance. Within each tillage treatment, plots were managed either with or without cover crops to assess their effects on soil properties. An undisturbed perennial grass area adjacent to the cropped plots served as the control, providing a benchmark for soil conditions under permanent vegetation.

The experiment followed a randomized complete block design with four replications. Soil samples were collected from each plot in June 2025, following planting and fertilizer applications. Twelve soil cores from each experimental unit were collected and aggregated from the 0-5 cm (0-2 in.) depth using a hand probe for each sample. Soil samples were sieved through an 8 mm sieve, manually cleared of visible organic matter, air-dried, and then ground through a 2 mm sieve before analysis.

The study will evaluate a broad range of chemical and biological soil health indicators. Chemical analyses include organic carbon, total carbon and nitrogen, soil organic matter, inorganic nitrogen, available nutrients (P, K, Ca, Mg, S, and micronutrients), pH, cation exchange capacity, base saturation, and soluble salts. Biological indicators include soil respiration, potentially mineralizable nitrogen, enzyme activities, and protein-based tests. Preliminary analyses were conducted on prepared samples to determine ammonium-N and Illinois Soil Nitrogen Test (ISNT-2) values.

Soil Analysis

Ammonium-N was determined using the mason-jar diffusion method. One gram of soil was placed into a mason jar with 10 mL of 2 M KCl. A petri dish containing 5 mL of boric-acid indicator solution was attached to the modified lid. Approximately 0.2 g of MgO was added, and the contents were gently swirled to mix. After allowing 15-30 seconds for the MgO to settle, the jar was sealed and placed on an electric griddle maintained at 45-50°C for 2 hours and 20 minutes to ensure complete diffusion of NH_3 into the boric acid solution. The petri dish was then removed, 5 mL of deionized water was added, and the captured ammonium-N was quantified by titration with 8 mM sulfuric acid. Ammonium-N concentration was calculated based on the volume of acid required for titration (Khan et al., 1997).

ISNT-2 was conducted to estimate potentially mineralizable nitrogen, primarily ammonium-N (~90%) and a smaller fraction of labile organic N (~10%, including amino sugars and amino acids). Two grams of soil and 10 mL of 2 M NaOH were added to a ½ pint mason jar. A pizza stand was placed in the jar to support a petri dish containing 5 mL boric acid solution. The jar was sealed and gently swirled for 10 seconds to mix the contents without spilling the boric acid. Samples were incubated at 25°C for 24 hours ± 5 minutes to allow NH_3 diffusion into the boric acid. After incubation, petri dishes were carefully removed with forceps, 5 mL of deionized water was added, and the samples were titrated with 8 mM sulfuric acid following the same protocol as the ammonium-N test (Nunes et al., 2025).

Statistical Analysis

All statistical analyses were conducted using R (version 4.4.2; R Core Team, 2024). Separate analyses of variance (ANOVA) were performed to evaluate the effects of tillage, crop rotation, and cover cropping on soil ammonium-N and ISNT-2 values. Interaction terms were initially included in the models but were not significant. The final interpretation focused on the main effects. Post-hoc comparisons were conducted using Tukey's Honest Significant Difference (HSD) test to identify differences among treatment levels, with significance determined at $p < 0.05$.

RESULTS

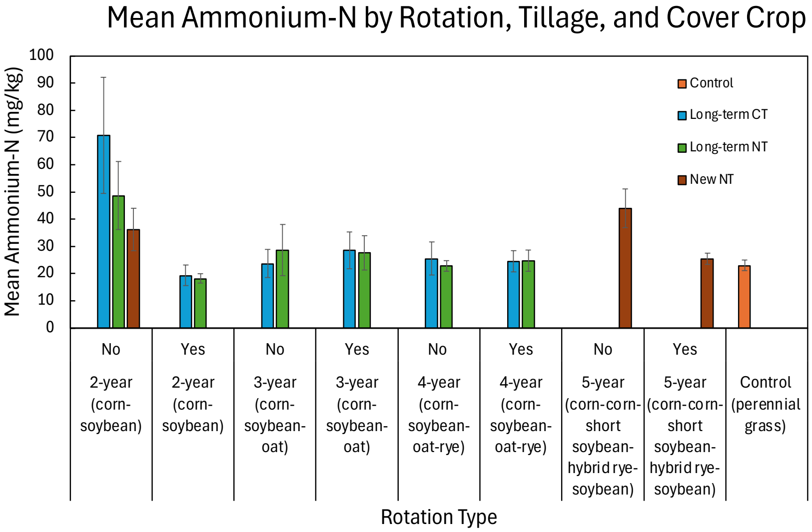

Figure 4. Effects of management on soil ammonium-N (as measured by mason-jar diffusion).

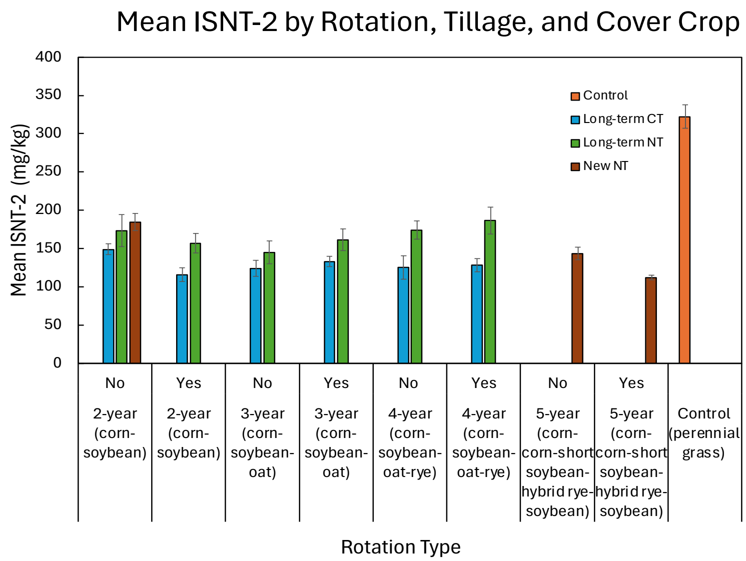

Figure 5. Effects of management on soil ISNT-2 values.

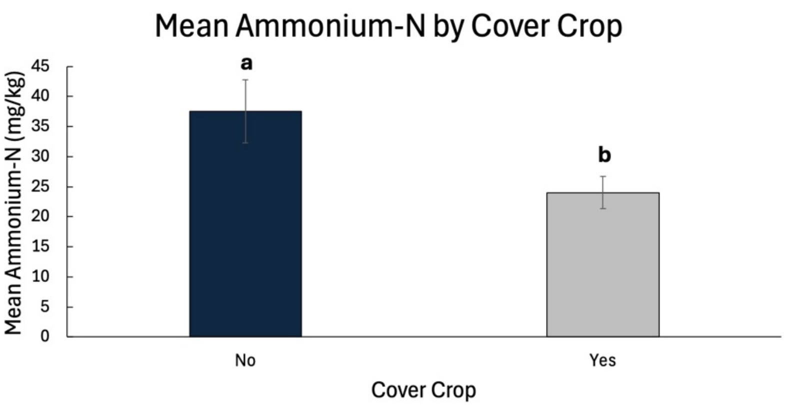

Figure 6. Mean soil ammonium-N as influenced by cover crop presence. Different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

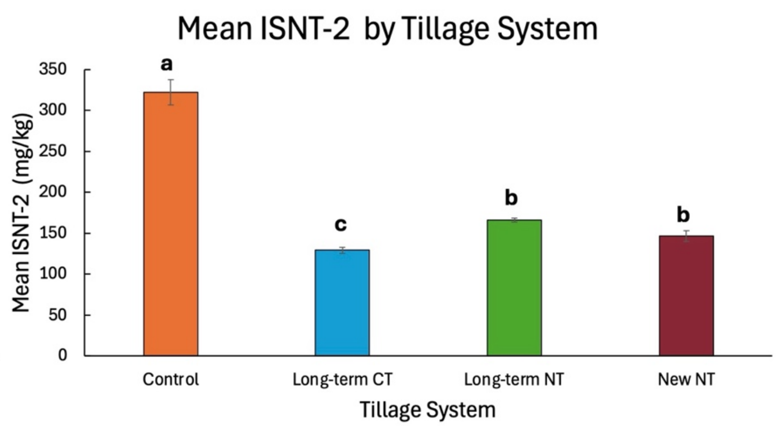

Figure 7. Mean ISNT-2 values as influenced by tillage system. Different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

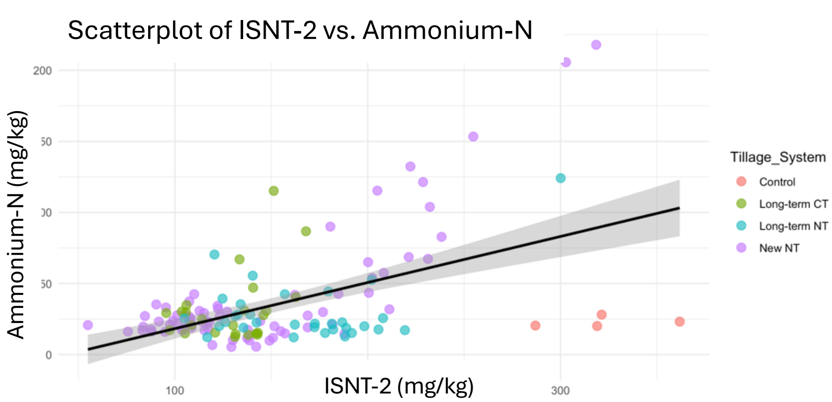

Figure 8. Relationship between ISNT-2 and ammonium-N across tillage systems.

DISCUSSION

Cover cropping consistently reduced ammonium-N concentrations across all management systems (Figure 4), suggesting that cover crops can act as a temporary nitrogen sink and reduce excess inorganic N accumulation in the soil. Crop rotation diversity influenced ammonium-N, with more complex rotations limiting the accumulation of ammonium-N compared to simpler rotations. Long-term no-till systems had relatively stable ammonium-N levels. Long-term conventional tillage and newly converted NT systems showed higher variability, likely due to differences in soil structure, organic matter content, and microbial activity associated with these management systems. Analysis of mean ammonium-N by cover crop presence (Figure 6) indicated a significant difference between plots with and without cover crops (Tukey's HSD, $p < 0.05$), confirming that cover crops significantly influence inorganic nitrogen availability.

ISNT-2 was highest in the perennial grass control and lowest in long-term conventional tilled plots (Figure 5), indicating the strong influence of long-term disturbance on the pool of mineralizable nitrogen. Long-term no-till systems maintained moderate and stable ISNT-2 values, while newly converted no-till systems showed lower values, particularly in the presence of cover crops. The effect of tillage on ISNT-2 was statistically significant (ANOVA, $p < 0.05$). The Tukey's HSD test showed that the perennial grass control differed from long-term conventional tillage, and both long-term no till and newly converted no-till were intermediate (Figure 7). These results suggest that long-term conservation practices help maintain a stable pool of biologically available nitrogen, and conventional tillage reduces labile nitrogen availability.

Soils with higher ISNT-2 values had greater ammonium-N, showing that biologically active soils support stronger microbial mineralization and increased inorganic nitrogen availability (Figure 8). This relationship varied with management history. Ammonium-N was higher in both long-term and newly adopted no-till systems. Long-term conventional tillage and the perennial grass control showed little change. These results indicate that reduced-disturbance systems enhance the accumulation of mineralizable nitrogen through improved residue decomposition and microbial activity.

CONCLUSION

These findings indicate that management practices influence different aspects of soil nitrogen dynamics. Cover cropping primarily affects short-term inorganic nitrogen pools (ammonium-N). Long-term tillage more strongly impacts labile organic N as measured by ISNT-2. Diversified crop rotations help prevent excessive ammonium-N accumulation. Differences between long-term and newly converted no-till systems suggest that soil nitrogen stability increases over time and may require several growing seasons to become fully established. The observed relationship between ISNT-2 and ammonium-N indicates that reduced-disturbance systems enhance microbial mineralization and nitrogen availability. These results provide a foundation for developing management strategies and conducting further research aimed at improving soil health stability and supporting long-term agricultural sustainability.

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OPTIMIZING NITROGEN APPLICATION IN CORN WITH AND WITHOUT A NITRIFICATION INHIBITOR

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ABSTRACT

Determining an accurate nitrogen (N) recommendation for corn production presents significant challenges due to its complexity with N transformation and losses. A careful diagnosis and decision making is required for optimizing the N management in corn. Therefore, a three-year (2023-2025) field study was conducted to evaluate the effects of varying nitrogen (N) application rates and timings with the use of a nitrification inhibitor (NI) on corn grain yield and productivity. The study was arranged in a randomized complete block design with three N application timings (fall, spring, V6 growth stage) and five N rates (0 (NTC), 60, 120, 180, and 240 lb N ac^{-1}) applied with or without pronitridine, a NI. Anhydrous ammonia (AA) was the fertilizer source for fall and spring application, whereas urea ammonium nitrate (UAN) was used for the V6 application. Results highlighted that fertilizer performance can vary substantially between years, with 2025 and 2024 generally showing higher grain yields and more favorable production metrics compared to 2023. In 2023, the highest yield was observed with 240 lb N ac^{-1} applied at V6 with NI, compared to fall AA at the rate of 240 lb N ac^{-1}. In contrast, in 2024 and 2025, 240 lb N ac^{-1} applied in spring produced the highest yield, but no differences were observed with addition of NI with this rate. Each year, the lowest N rates such as 60 and 120 lb N ac^{-1} with or without NI had the lowest yields. The findings suggested the importance of carefully selecting fertilizer sources, rates, and application strategies to optimize corn production, recognizing that optimal approaches may vary depending on specific annual environmental conditions.

INFLUENCE OF NITROGEN MANAGEMENT AND PRECIPITATION ON SORGHUM NITROGEN USE EFFICIENCY

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ABSTRACT

Grain sorghum (Sorghum bicolor L. Moench) is a key crop in Kansas which can benefit from optimized nitrogen (N) management that enhances yield while minimizing N losses. Understanding the relationships among physiological efficiency (PE), recovery efficiency (RE), and agronomic efficiency (AE), as well as their interactions with climatic factors such as precipitation, is essential for improving nitrogen use efficiency (NUE).

Experiments were conducted across five rainfed and one irrigated site in Kansas from 2021 to 2024. Nitrogen was applied as broadcast urea at planting at rates of 0, 33, 67, 101, 135, 168, and 201 kg N ha^{-1} to assess rate effects on PE. Additional management treatments evaluated RE and AE at a fixed rate of 67 kg N ha^{-1} under varying N sources (urea, UAN), timings (planting, S6, split) and placements (broadcast, coulter, streamed). Site-specific seasonal precipitation (mm) was obtained from nearby weather stations to determine climatic effects on NUE responses.

Results showed that increasing N rates above 135 kg N ha^{-1} decreased PE across all sites, likely due to nutrient imbalances caused by excessive N. Management treatments showed limited effects on RE and AE, although Split application, Coulter UAN, and the use of Super U seems to have higher RE and AE; however, these trends were not statistically significant ($p < 0.1$). Normal precipitation levels supported optimal conditions across sites, while observed in season precipitation (<468.9 mm) was associated with lower yields but not with RE or AE, emphasizing the role of water availability in sustaining production but other factors involved need to be examined.

INTRODUCTION

Grain sorghum (Sorghum bicolor L. Moench) is a key crop in Kansas cropping systems and ranks among the top five cereal crops globally. The United States is the leading producer, contributing 8.73 million metric tons—14% of world production—in the 2024/2025 season. Sorghum is a drought-tolerant, resource-efficient crop with high water and solar energy use efficiency, making it well-suited for the variable climate of the Central Great Plains. Optimized nitrogen (N) management can enhance grain yield while minimizing N losses to the environment, including nitrate leaching and nitrous oxide emissions. Understanding the relationships among physiological efficiency (PE), recovery efficiency (RE), and agronomic efficiency (AE), as well as their interactions with climatic factors such as precipitation, is essential to improve nitrogen use efficiency (NUE) and support sustainable, profitable sorghum production in Kansas.

MATERIALS AND METHODS

Experiments were conducted from 2021 to 2024 across five rainfed and one irrigated site in Kansas. Prior to fertilizer application, soil samples were collected from 0–15 cm to determine soil pH and organic matter (OM), and from 0–60 cm to quantify profile nitrogen (NO_3^- and NH_4^+). Nitrogen was applied as broadcast urea at planting at rates of 0, 33, 67, 101, 135, 168, and 201 kg N ha^{-1} to evaluate the effect of N rate on physiological efficiency (PE). Additional management treatments were applied at a fixed rate of 67 kg N ha^{-1} to assess recovery efficiency (RE) and agronomic efficiency (AE). These treatments varied by N source (urea, UAN), timing (planting, V6 stage, or split applications), placement (broadcast, coulter, or streamed), and the use of inhibitors (SuperU, ESN, and NBPT). Grain and biomass were collected at stage 9, and samples were processed through Leco N analysis to measure total N uptake. Site-specific seasonal precipitation data (mm) were obtained from nearby Kansas Mesonet weather stations to evaluate the influence of climatic conditions on nitrogen use efficiency (NUE) responses.

Table 1. Treatments description.

Trt	Kg N ha^{-1}	Placement	Source	Timing
1	**0**	Broadcast	Urea	planting
2	**33**	Broadcast	Urea	planting
3	**67**	Broadcast	Urea	planting
4	**101**	Broadcast	Urea	planting
5	**135**	Broadcast	Urea	planting
6	**168**	Broadcast	Urea	planting
7	**201**	Broadcast	Urea	planting
8	**67**	Coulter	UAN	planting
9	**67**	Streamed	UAN	planting
10	**67**	Broadcast	ESN	planting
11	**67**	Broadcast	Super-U	planting
12	**67**	Broadcast	Urea + NBPT	planting
13	**67**	Broadcast	Urea	S6
14	**67**	Broadcast	Urea	Planting/S6

Table 2. Average Soil Texture, pH, OM and N for each location.

	County	Texture	pH	OM%	NO_3^-	NH_4^+
1	Riley	Sandy	5.9	1.0	3.6	2.1
2	Ellis	Silt Loam	4.9	2.7	14.4	5.0
3	Riley	Silt Clay	6.6	2.7	7.7	22.7
4	Reno	Loam	7.5	2.7	17.1	6.6
5	Franklin	Silt Loam	6.0	3.2	9.6	16.8
6	Ellis	Silt Loam	8.3	2.7	7.7	4.9

RESULTS AND DISCUSSION

In season Cumulative Precipitation

Seasonal precipitation played an important role in supporting yield: normal precipitation levels maintained optimal conditions, while below-average in-season rainfall (<468.9 mm) was associated with lower yields. Interestingly, precipitation had minimal effect on RE and AE, highlighting the complex interactions among water availability, N management, and other environmental and physiological factors that influence nitrogen use efficiency.

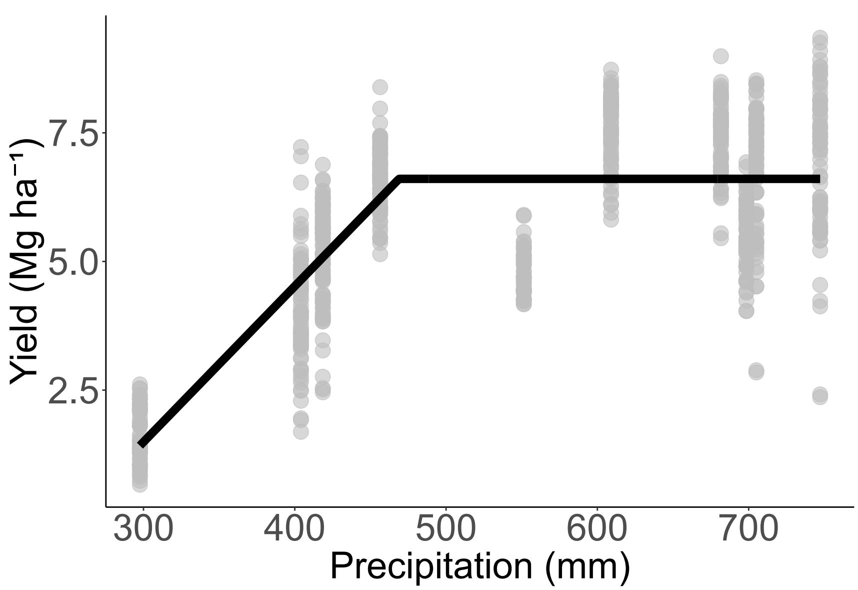

Figure 1. ***Yield response to precipitation.***

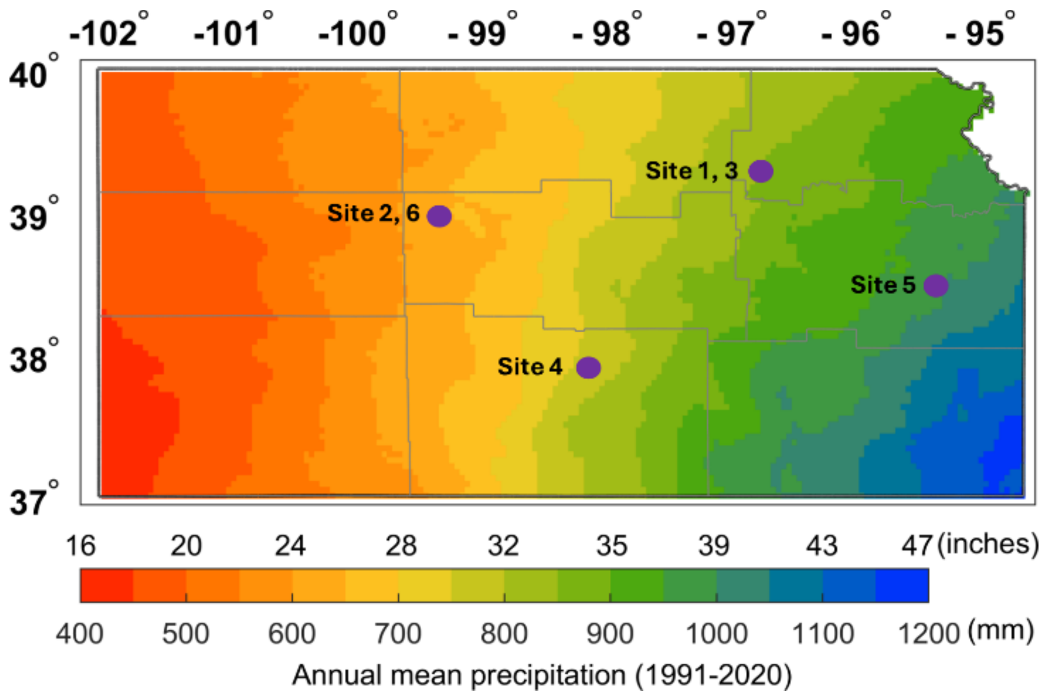

Figure 2. ***Kansas Normal precipitation map*.**

Plant Physiological Efficiency

Increasing N rates above 135 kg N ha⁻¹ consistently reduced physiological efficiency (PE) across all sites, likely due to nutrient imbalances caused by excessive nitrogen. Excessive N can negatively impact both plants and soil health: it increases water demand, can leach into groundwater or run off into surface waters, damages fine root hairs responsible for water and nutrient uptake, and raises susceptibility to pests such as sap-sucking insects. Over-application may also induce deficiencies of other nutrients (e.g., iron, manganese), excess N can promote excessive vegetative growth at the expense of panicle development and grain formation, potentially reducing yield and grain quality. In soils, excess N can disrupt beneficial microbial communities, potentially affecting water movement and overall soil function.

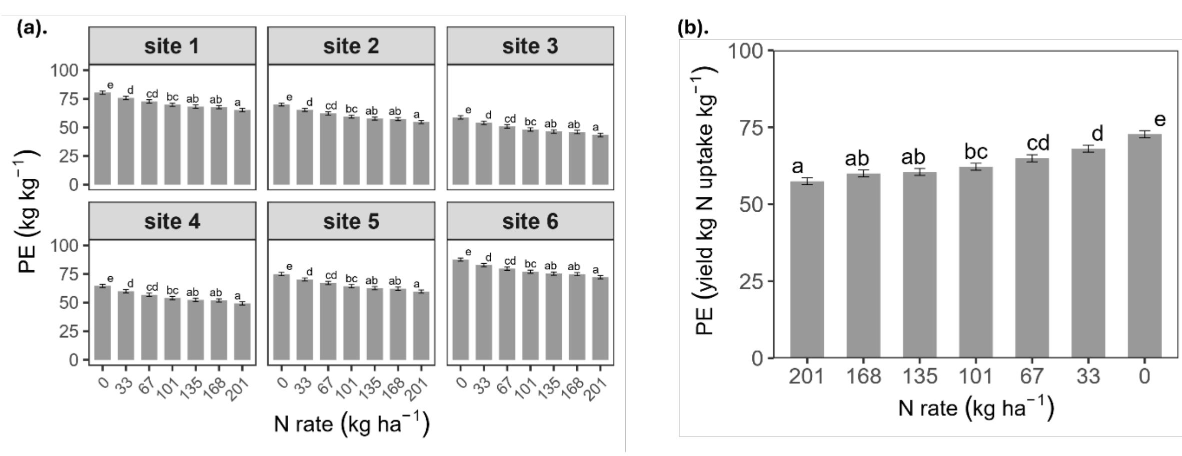

Figure 3. ***Plant PE response to increasing nitrogen rates for each site (a) and across sites (b).***
Different letters are significantly different at P<0.1.

Fertilizer Recovery Efficiency and Agronomic Efficiency

Management treatments had limited effects on RE and AE, although Split application, Coulter UAN, and the use of Super U may improve RE and AE, but these differences were not statistically significant ($p < 0.1$).

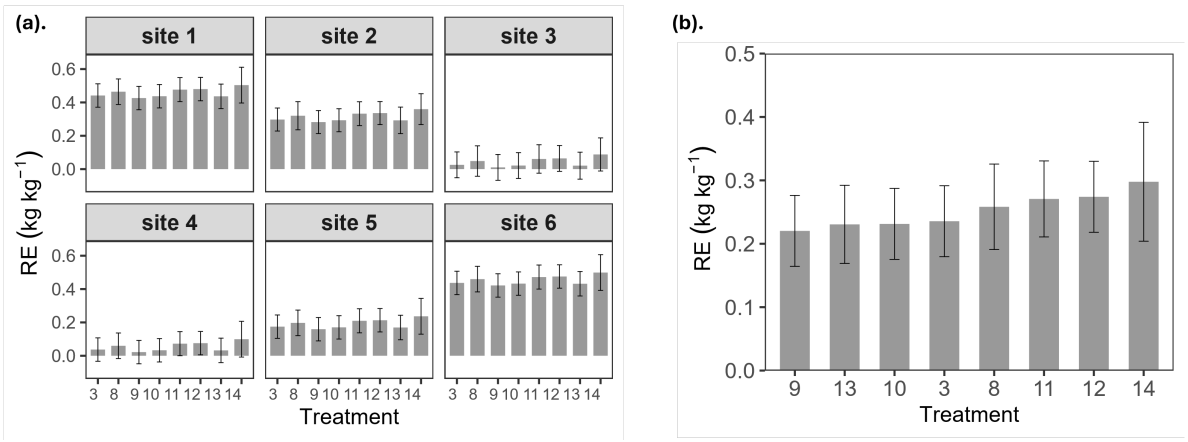

Figure 4. ***Plant RE response to increasing nitrogen rates for each site (a) and across sites (b).*** *Different letters are significantly different at P<0.1.*

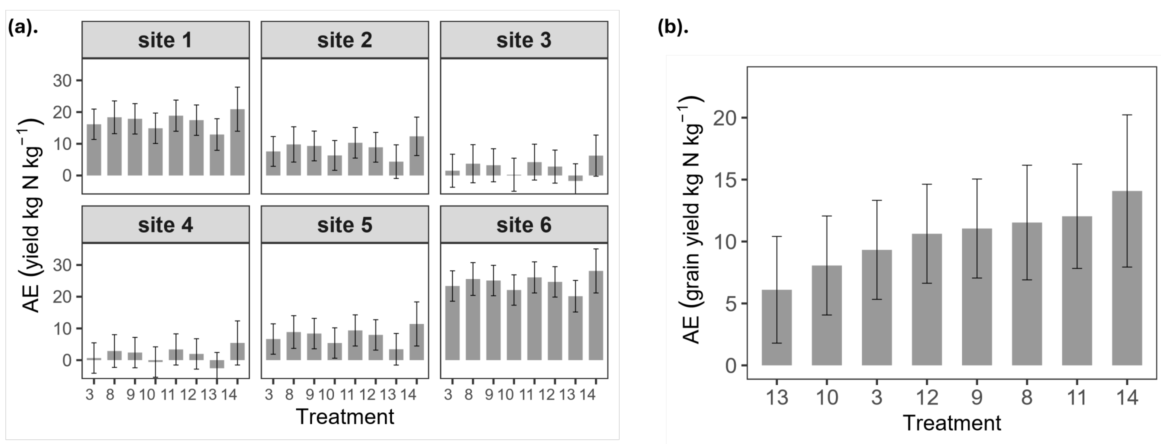

Figure 5. ***Plant AE response to increasing nitrogen rates for each site (a) and across sites (b).*** *Different letters are significantly different at P<0.1.*

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INVESTIGATING THE NEED FOR SULFUR IN KENTUCKY WHEAT PRODUCTION

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ABSTRACT

Sulfur (S) deficiencies in Kentucky wheat production are increasing due to a reduction in atmospheric S deposition, greater removal in grain and forage, and less S contamination in phosphorus fertilizers. The University of Kentucky currently does not provide S recommendations based on S soil test results. This is largely due to the Mehlich 3 soil test extractant not being correlated or calibrated for S response in Kentucky crops and the lack of S responsive fields. Surveys and studies were conducted to help develop guidance using soil testing for S fertility in winter wheat (*Triticum aestivum* L.) production in Kentucky. These will be discussed to describe the current state of S fertility in Kentucky. Tissue surveys were conducted on 70 fields in 2012 and 2013 with only one field resulting in tissue S concentrations below the reported sufficiency range of 0.15 to 0.65% S. This field was disturbed by fence row clearing, burning of bulldozer piles, and oil production - was considered an anomaly for Kentucky wheat production at that time. Large and small-plot research was conducted in wheat producing areas in 2016 using ammonium thiosulfate (ATS) in combination with UAN or UAN treated with both a nitrification and urease inhibitor. Soil samples for these studies were collected at 0 to 4 inch and 0 to 12inch depths and exhibited profile differences in S concentration between sites and depths. However, no yield differences were observed within location, only between locations. Areas at the University of Kentucky Research and Education Center (UKREC) that appeared to show S deficiency were paired with areas not exhibiting visual S deficiency symptoms and both areas were sampled. Tissue samples identified S deficient areas 75% of the time. The average yield reduction due to apparent S deficiency was 53 bu/A. Finally, a large-scale research plot at the UKREC, near the areas earlier showing S deficiency, was planted to wheat in 2024. Soil organic matter (SOM) averaged 3.01% and Mehlich 3 S (M3S) values averaged 23.2 lb S/A at the 0-to-4-inch sample depth prior to drilling wheat. Plots received either 120 or 150 lb N/A, with or without 20 lb S/A as ammonium sulfate (AMS). Wheat yields were 50 and 52 bu/A for the150 and 120 lb N/A rates and did not differ significantly. However, wheat yields were significantly different, at 37 and 64 bu/A for 0 and 20 lb S/A, respectively. The N by S interaction was not statistically significant. The yield response was purely due to S application. Although SOM and M3S levels suggested sufficient soil S to support wheat growth, wheat grain yield positively benefited from S addition. Sulfur residuality will be monitored in the following soybean crop. Additional wheat S fertility trials will be conducted to provide an understanding of S critical levels, and S fertility guidance, for Kentucky wheat production.

SOYBEAN YIELD RESPONSE TO NITROGEN AND SULFUR STARTER FERTILIZERS UNDER CONSERVATION TILLAGE AND CEREAL RYE COVER CROP

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ABSTRACT

Context: No-tillage and cover crops adoption remain limited across the U.S. North Central region due to concerns about potential yield penalties in cash crops. High residue levels can slow soil warming and mineralization and promote nutrient immobilization, often leading to limited early-season nitrogen (N) and sulfur (S) availability for soybean.

Objective: Evaluate soybean grain yield response under different tillage systems and assess the potential of N and S starter fertilization to enhance soybean yield under conservation tillage and cereal rye (*Secale cereale* L*)* cover crop systems.

Methods: Six site-years were established across Illinois and Iowa in 2024 and 2025. Experiments followed a randomized complete block design with a split-plot arrangement and four replicates. Tillage was the main-plot factor with four levels: conventional tillage (CT), strip-tillage (ST), no-tillage (NT), and NT with a cereal rye (CR) cover crop (NT+CR). Liquid starter fertilizer applied at planting was the subplot factor with three levels: unfertilized check (UTC), 15 lb N ac^{-1} (N), and 15 lb N + 10 lb S ac^{-1} (N+S).

Results: Across tillage-CR systems, starter N significantly increased V4 shoot biomass by 33 lb ac^{-1} compared to UTC, whereas no response to starter S was observed. Grain yield ranged from 64.5 to 93.5 bu ac^{-1} across site-years. No fertilizer main effect, nor a tillage × fertilizer interaction, was detected at any location or when analyzed across years. The tillage main effect was significant ($\alpha = 0.1$), with NT + CR yielding less than ST (76.2 and 78.4 bu ac^{-1}, respectively), but equivalent to CT and NT (78.3 and 77.6 bu ac^{-1}, respectively).

Conclusions: Although an early-season soybean benefit was observed from starter N, neither N nor S resulted in improved grain yield. Our overall results highlight the short-term potential to grow high-yielding soybeans under more conservative tillage–CR systems without starter fertilizers.

INTRODUCTION

The ecological benefits of no-tillage and cover crops systems are well documented. Yet, adoption of these practices remains limited across Illinois and the North Central region. Only about 4% of Illinois cropland is planted with cover crops and nearly 25% is under no-till (USDA-NASS, 2024). In soybean, a decline has been reported in no-till adoption from 51% in 2006 to 37% in 2018, based on transect survey data (IDOA, 2018). Residue accumulation under these systems faces persistent challenges in high-latitude regions. These constraints are usually linked to delayed soil drying, planting, and crop emergence, and, limited early growth caused by cooler soil temperatures and excessive residue cover early in the spring.

Nitrogen (N) and sulfur (S) availability can also be a major early-season challenge under high corn residue conditions and cereal rye (*Secale cereale* L.) cover crop. Nitrogen and Sulfur supply rely on organic matter mineralization (Carciochi et al., 2018), a process constrained by low soil temperatures. Under these conditions, N and S immobilization driven by high residue C/N ratios can exceed required C for mineralization, reducing nutrient availability for early soybean uptake. Soybean grain yield response to N fertilizer is often inconsistent (Vonk et al., 2024). This is likely due to the crop’s ability to meet approximately 60% of its N demand through biological N fixation (Salvagiotti et al., 2008), with the remainder supplied by mineralization—both processes that can be limited under cool soils. Recent investigations conducted in Wisconsin have shown a 4.1 bu ac^{-1} yield improvement in no-till soybean with pre-plant N fertilization (Kendall et al., 2025). For S, yield responses have been observed under low soil organic matter (SOM) conditions (Divito et al., 2015; Mahal et al., 2022) and were reported to disappear when SOM exceeds 3.2–3.4% (Borja Reis et al., 2021; Kaiser & Kim, 2013). However, few studies have evaluated how conservation tillage and cereal rye cover crops affect N and S early-season availability, or the potential of starter N and S fertilization to mitigate early-season nutrient limitations and improve soybean yield. Therefore, the objectives of this study were to: i) evaluate soybean grain yield response under different tillage systems, ii) determine the interactive effects of tillage and N and S starter fertilization on early-season soybean growth, and iii) assess their combined influence on final grain yield.

MATERIALS AND METHODS

Sites Description and Experimental Design.

The experiment was conducted from fall 2023 through fall 2025 across four site-years in central and northwestern Illinois. Trials were established near Fulton [F-24] (2024; 41.7680° N, 90.1989° W), Roseville [R-25] (2025; 40.7446° N, 90.6941° W), and Monticello [M-24; M-25] (2024; 39.8712° N, 88.5215° W and 2025; 39.8677° N, 88.5220° W). In 2025, two additional sites were included in Iowa near Tipton [T-25] (41.9637° N, 91.4724° W) and Hampton [H-25] (42.6877° N, 93.4742° W), where only grain yield data were collected. Composite soil samples (7-inch depth) were taken by block before planting at the Illinois sites to assess general fertility status (Table 1).

Table 1. Selected soil chemical properties at the 7-inch sampling depth, taken during early in the spring (March)

Location	pH (1:1)	OM %	CEC meq 100g^{-1}	P	K	S
				----------------	ppm	----------------
F-24	6.7	3.7	20.2	26	169	6
M-24	6.8	3.8	15.8	36	244	10
R-25	6.6	3.8	13.4	17	96	8
M-25	6.6	4.2	18.6	27	142	9

P: Bray-1 P; K: Mehlich-3 K; S: Mehlich-3 S.

The experiment was arranged in a split-plot RCBD with four replicates. The main plot factor was tillage with four levels: conventional tillage [CT; fall chisel plowing plus a field cultivator pass in the spring], strip tillage [ST; done in the fall], no-tillage [NT], and no-tillage following a cereal rye (CR) cover crop [NT+CR]. The subplot factor was starter fertilizer applied at planting with three levels: unfertilized-check [UTC], N [15 lb. N ac^{-1} as UAN 28%], and N+S [15 lb. N ac^{-1} plus 10 lb. S ac^{-1} as UAN plus ammonium thiosulfate (ATS; 12–0–0–26)]. Starter fertilizers were applied 2 × 2 inches below and to the side of the seed furrow at planting. All sites were planted in 30-inch rows at a seeding rate of 160,000 seeds acre^{-1}. In 2024 at Fulton, the NT+CR treatment was not included,.The experiment included small-plot trials (F-24, R-25, T-25, H-25) and on-farm trials (M-24 and M-25), with all plots consisting of 8 rows.

Cereal Rye Cover Crop and Soybean Management.

Soybean was grown following corn in all sites in a typical 2-yr rotation. Cereal rye was no-till drilled after corn harvest in the fall at 65 lb ac^{-1} in 7.5-inch rows. CR was terminated with glyphosate [N-(phosphonomethyl)glycine] at 1.15 lb a.i. ac^{-1} in mid- to late April. Soybeans were planted in 2024 on May 1 at F-24 and May 31 at M-24. In 2025, planting occurred on April 16 at M-25 and April 22 at R-25. In Iowa, planting at T-25 and H-25 was completed on May 6 and 18, respectively. Region-appropriate maturity groups (MG) were selected. On-farm trials were harvested using a commercial combine, collecting the entire plot, whereas only the four center rows were harvested in the small-plot trials. All yields were adjusted to 13% grain moisture.

In Season Soybean Sampling and Post-harvest Processing.

Before termination, aboveground CR biomass was sampled from two 10.7 ft^2 quadrats per plot in each NT+CR treatment, oven-dried at 70 °C to constant weight and analyzed for nutrient concentrations at a commercial laboratory (A&L Great Lakes, Fort Wayne, IN). For soybean, stand counts were taken at V3–V4 growing stage (Fehr & Caviness, 1977) by counting plants in 4–6 linear meters per plot. Whole-plant biomass was collected from 1 meter of row in small plots and from three 1-meter subsamples in on-farm plots, followed by the same procedures as CR biomass samples.

Statistical analysis

Data were analyzed using R version 4.3.3 (R Core Team, 2024). A linear mixed-effects model (lmerTest package) accounted for the split-plot structure, with tillage as the main-plot factor and fertilizer as the subplot factor. Random effects included year, location, block nested within location-year, and the main-plot error (tillage within block). Mean separation was performed using Tukey's HSD test at a significance level of α = 0.10.

RESULTS AND DISCUSSION

Cover Crop Biomass and Nutrient Analysis.

At CR termination, aboveground biomas was considerably greater in 2024 than in 2025, mainly due to higher mean spring temperatures and a later termination date (late April), and consequently, higher C/N and C/S ratios (Table 2).

Table 2. Average cereal rye cover crop aboveground biomass, nitrogen (N), carbon (C), and sulfur (S) concentration (conc.), total N, S, and C content, and C/N and C/S ratios before termination.

Location	Biomass	N conc.	C conc.	S conc.	N content	C content	S content	C/N ratio	C/S ratio
	lb ac^{-1}		%			lb ac^{-1}			
M-24	1511.8	2.4	39.9	0.18	36	604	3	17	218
R-25	653.7	3.4	42.0	0.28	22	274	2	13	152
M-25	630.2	3.6	43.7	0.27	22	276	2	12	162

M-24: Monticello 2024; M-25: Monticello 2025; R-25: Roseville 2025.
F-24: Fulton 2024, NT+CR treatment was not included.

Early-season (V4) soybean growth and nutrient response to starter fertilizer and tillage

Early-season aboveground biomass showed significant effects for the main effect of tillage and fertilizer, but no interaction (Table 3). Averaged across site-years, early-season soybean biomass was significantly greater in CT and ST than in NT and NT+CR (Table 3). Moreover, soybean biomass increased with the use of starter fertilizer compared to UTC. Starter fertilizer did not increase N shoot concentration relative to UTC. In contrast, N fertilizer significantly decreased S shoot concentration compared to UTC and N+S. The ST was the only tillage treatment that decreased S shoot concentration relative to UTC.

Table 3. Soybean plant population, aboveground biomass, and nutrient concentrations at the V4 growth stage as affected by tillage, starter fertilizer, and their interaction. Analyzed across years and locations.

	Plant population plants acre^{-1}	Plant biomass lb. acre^{-1}	N conc.	S conc.	N/S ratio
			-----------%	-----------	
Tillage					
CT	103,260 ab[1]	220.5 a	3.90	0.27 ab	14.8 ab
ST	105,728 a	202.5 a	3.84	0.26 b	15.1 a
NT	97,246 b	158.8 b	3.80	0.27 ab	14.4 b
NT+CR	97,409 b	139.7 b	3.98	0.27 a	14.6 ab
Fertilizer					
UTC	101,081	158.6 b	3.87 ab	0.27 a	14.6 b
N	100,372	191.3 a	3.95 a	0.26 b	15.3 a
N+S	101,280	191.1 a	3.81 b	0.27 a	14.3 b
P-values					
Tillage	*0.011*	*<0.001*	*0.245*	*0.060*	*0.038*
Fertilizer	*0.804*	*<0.001*	*0.004*	*0.003*	*<0.001*
Till. x Fert.	*0.119*	*0.804*	*0.555*	*0.322*	*0.277*

[1]Treatment means within a column followed by different letters are significantly different at $p < .10$ by the Tukey's HSD test.

Overall, our results showed that the additional N supply near the crop row enhanced soybean early growth across tillage systems; by an average of 33 lb ac^{-1}. Although the tillage × fertilizer interaction was not statistically significant (p = 0.804), biomass response to starter N tended to increase under greater residue accumulation treatments, averaging 19.4, 28.8, 39.0, and 42.2 lb ac^{-1} for CT, ST, NT, and NT+CR, respectively (interaction data not shown). This pattern suggests that greater N immobilization under higher residue cover may have limited mineralization and early N availability. The fact that the biomass did not differ between fertilizer treatments suggests that the increase was due to the N fertilizer alone, and that the soybean did not benefit from the combination of N+S fertilization. Sulfur concentrations remained at or near the sufficiency threshold for the V5 stage (0.27%), as reported by Kaiser & Kim (2013)

The reduced V4 biomass under NT and NT+CR (–62 lb ac^{-1}) could have been associated with lower early-season plant populations (–7,167 plants ac^{-1} on average; Table 3). The impact of missing plants is likely more pronounced at early growth stages but tends to diminish as the season progresses.

Mid-late season (R2-R8) soybean growth and nutrient response to starter fertilizer and tillage

At the R2 stage, leaf N concentration ranged from 4.99% to 5.14%, with no significant effects of tillage, fertilizer, or their interaction (Table 4). Similarly, S concentration and N/S ratios were unaffected by treatments, ranging from 0.31% to 0.33%, and from 15.5 to 16.1, respectively. Plant biomass at the R8 stage showed a significant fertilizer effect, although the response was inconsistent: biomass was greater with N as starter compared to N+S (8,032 vs. 7,505 lb ac^{-1}, respectively), but similar to UTC (7,577 lb ac^{-1}; data not shown). No significant effects of tillage or interaction were detected.

Considering both N concentration and biomass data, the initial response to starter N was not sustained as the season progressed, likely due to increased N availability from soil mineralization and biological N fixation, which becomes relatively more important during reproductive stages (Zapata et al., 1987). The lack of S response persisted through the season, with S concentrations and N:S ratios remaining above reported sufficiency thresholds for leaves at the R1–R3 stages (0.265% for S concentration and 12.18 for the N:S ratio; Divito et al., 2015).

Table 4. Soybean nutrient concentrations at the R2 growth stage, and plant biomass and population at the R8 stage as affected by tillage, starter fertilizer, and their interaction.

		R2 Stage			R8 stage	
		N conc.	S conc.	N/S ratio	Plant biomass	Plant population at harvest
		%			lb $acre^{-1}$	plants $acre^{-1}$
Tillage	***Fertilizer***					
CT	UTC	5.12	0.33	15.5	7,294	98,417 a
	N	5.14	0.32	16.2	7,920	96,958 ab
	N+S	5.16	0.32	16.0	7,365	95,401 ab
ST	UTC	5.05	0.32	15.6	7,513	100,768 a
	N	5.06	0.32	15.9	7,986	96,536 ab
	N+S	5.10	0.32	15.7	7,865	95,872 ab
NT	UTC	5.01	0.32	15.9	7,582	91,501 ab
	N	5.01	0.32	15.5	8,088	97,614 ab
	N+S	5.05	0.32	15.6	7,581	95,733 ab
NT+CR	UTC	5.05	0.32	15.9	7,947	88,027 b
	N	4.99	0.31	16.1	8,129	95,883 ab
	N+S	5.12	0.33	15.5	7,215	91,273 ab
P-values						
Tillage		*0.351*	*0.958*	*0.545*	*0.761*	*0.068*
Fertilizer		*0.282*	*0.106*	*0.307*	*0.044*	*0.222*
Till x Fert		*0.980*	*0.228*	*0.111*	*0.792*	*0.032*

Soybean grain yield.

Soybean grain yield ranged from 64.5 bu ac^{-1} to 93.5 bu ac^{-1} (data not shown). No tillage × fertilizer interaction or fertilizer main effects were detected at any location or across locations and years (Table 4). The tillage main effect was significant at M-24, where NT and NT+CR yields were significantly lower than CT (by 2.7 bu ac^{-1}, on average). At R-25 and in the combined analysis across locations and years, ST significantly outyielded NT+CR by 6.3 and 2.2 bu ac^{-1}, respectively.

Table 5. Soybean grain yield across individual site-years and combined analysis showing the main effect of tillage.

Tillage	F-24	M-24	R-25	M-25	T-25	H-25	Mean
	------------------------------------			bu ac^{-1}			------------------------------------
CT	77.4	68.3 a[2]	81.6 ab[1]	88.9	84.6	74.7	78.3 ab
ST	77.0	67.0 ab	84.6 a	92.3	83.1	72.4	78.4 a
NT	78.6	65.7 b	83.7 ab	90.6	79.2	73.7	77.6 ab
NT+CR	±	65.3 b	78.3 b	91.3	79.3	72.6	76.2 b
P-values							
Tillage	*0.683*	*0.099*	*0.073*	*0.176*	*0.184*	*0.562*	*0.065*
Fertilizer	*0.581*	*0.191*	*0.619*	*0.304*	*0.509*	*0.113*	*0.132*
Till x Fert	*0.206*	*0.313*	*0.194*	*0.845*	*0.140*	*0.300*	*0.500*

F-24: Fulton 2024; M-24: Monticello 2024; R-25: Roseville 2025; M-25: Monticello 2025; T-25: Tipton 2025; H-25: Hampton 2025; Across: across years and locations.
±NT+CR was not included in F-24.
[1]Treatment means within a column followed by different letters are significantly different at $p < .10$ by the Tukey's HSD test. [2]Only for M-24, treatment means within a column followed by different letters are significantly different at $p < .10$ by the Fisher's LSD test.

Overall, these results indicate that soybean yield was not improved by starter N or S across tillage and cover crop systems, even under high-yielding conditions. Although starter N increased early-season growth, this benefit did not result in yield increases. Across site-years, ST, NT, and NT+CR achieved yields equivalent to CT, highlighting the potential to sustain high soybean productivity under more conservative tillage and cover crop systems without yield penalties.

Additional research is needed to investigate the circumstances under which N and S starter responses occur in high-yielding soybean environments, particularly under long-term no-till, where factors such as soil compaction and soil moisture could influence nutrient availability, and under greater cereal rye biomass conditions that may exacerbate early-season nutrient constraints.

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SENSON-BASED NITROGEN MANAGEMENT AFFECTS CORN PRODUCTION AND ENVIRONMENTAL N FOOTPRINTS

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ABSTRACT

To improve air and water quality, nitrogen (N) management in corn production systems should shift from the current N decision support system [maximum return to N (MRTN)], which suggests a single rate N addition, to sensor-based (GreenSeeker) active N management (variable N rate approach). Single rate N recommendations often result in under- and over-N addition and either increase environmental N losses or cause corn yield penalty. Our objectives were to evaluate corn economic optimum N rate (EORN) and determine if sensor-based N management improves N fertilizer use, end of season N, nitrous oxide emissions, and nitrate-N leaching during a corn growing season. Our results indicated that sidedressing N improved N use by corn. A pretty simple empirical relationship (215 lb/a for 215 bu/a) can be derived across all the data. Nitrogen balances are generally positive at around 90 lbs/acre (100 kg/ha) at EONR. End of season N is generally spatially variable but always increases exponentially at rates above the EONR. Compared to flat-rate N management, sensor-based decreased N fertilizer requirement, corn yield, nitrate-N leaching, and nitrous oxide emissions. Future research should explore the effect of sensor-based N management on farm economics and environmental footprints at multi-site-years.

INTRODUCTION

The Illinois Nutrient Reduction Strategy aims to reduce nitrate-N losses to surface waters by 15% by 2025 (IEPA, IDOA, and University of Illinois Extension, 2015). Among the recommended approaches, 4R nitrogen (N) management strategies are designed to minimize nutrient losses to Illinois waterways and the Gulf of Mexico while also reducing nitrous oxide (N_2O) emissions. Applying the right N rate is one of the most effective practices for mitigating environmental N losses (Morris et al., 2018). However, determining the optimal N rate is challenging because corn N requirements depend on N responsiveness, soil N availability, and yield potential—factors that vary spatially and temporally. Precision N management has the potential to address this variability, improve N use efficiency, and reduce N losses. To address uncertainties related to variable-rate N applications, this study aimed to compare the performance of the Maximum Return to Nitrogen (MRTN) approach with a GreenSeeker-based N rate on corn grain yield and N losses including nitrate-N leaching and nitrous oxide emissions.

MATERIALS AND METHODS

Experimental Site, Design, and Treatments

This study was conducted at the Agronomy Research Center of Southern Illinois University, Carbondale, IL. Treatments were arranged in a randomized complete block design (RCBD) with five replications during the 2022–2025 growing seasons; only 2022 data are reported here. Treatments included: (i) a zero-N control, (ii) N fertilizer applied at planting using the Maximum Return to Nitrogen (MRTN) rate, (iii) N fertilizer applied at the MRTN rate at sidedress, and (iv) N fertilizer applied at sidedress based on the GreenSeeker sensor algorithm. Experimental plots measured 60 ft in length by 10 ft in width. Corn (Dekalb DKC64-35RIB) was planted using a no-till drill at a population of 32,000 seeds ac^{-1} on 18 May 2022. Sidedress N applications were made at the V8 growth stage using 32% urea-ammonium nitrate (UAN). All fertilized plots received 55 lbs N ac^{-1} as a starter application at planting, except for the zero-N control. The MRTN rate used in this study was 203 lbs N ac^{-1}.

Measurements

Soil samples (0–6 in) were collected throughout the 2022 corn growing season using a soil probe and analyzed for nitrate-N and ammonium-N. Nitrous oxide emissions were measured using custom closed, vented aluminum chambers installed between corn rows on permanently anchored bases. Gas samples were collected on 21 sampling dates using syringes at 0, 15, 30, and 45 minutes after chamber closure, and N_2O concentrations were quantified by gas chromatography (GC). Nitrous oxide fluxes were calculated from the linear change in N_2O concentration over time, and cumulative emissions were derived by linear interpolation between sampling events. Soil volumetric water content (VWC) and temperature were recorded at each gas sampling event. Corn grain yield was measured at harvest using a plot combine. Subsamples of grain and aboveground biomass were collected prior to harvest to determine N concentration and calculate plant N uptake. Yield-scaled N_2O emissions were computed by dividing cumulative N_2O emissions by grain yield. Nitrate-N leaching was assessed using resin bag lysimeters installed at 12–16 in depth, depending on the claypan layer. After retrieval, resin bags were extracted and analyzed for nitrate-N using an OI Analytical Flow Solution IV system.

RESULTS AND DISCUSSION

Corn Grain Yield

Corn grain yield was 175 bu ac^{-1} for the MRTN treatment which was 10 bu ac^{-1} higher than that of the GS treatment. However, about 80 lbs N ac^{-1} less was applied to corn based on GreenSeeker recommendation which compensated for the lower yield in 2022 (data not shown).

Soil nitrate-N trends

Soil nitrate-N was consistently higher in the MRTN-upfront treatment as compared to the no-N control and GS treatment. Soil nitrate-N reached its peak before VT stage of corn and then at R1 and any dates after that, all treatments had similar nitrate-N concentrations (Fig. 1).

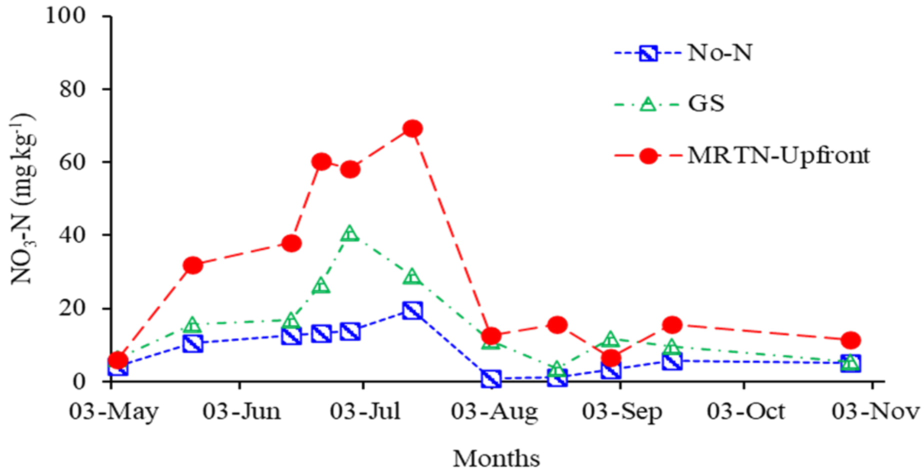

Fig. 1. Soil NO_3-N as influenced by N management in 2022. No-N is no fertilizer control, GS indicates GreenSeeker-based N rate and MRTN-Upfront is 203 lbs N ac^{-1} at planting.

Cumulative N_2O-N emissions

Cumulative N_2O-N emissions were higher in the MRTN-upfront treatment than the GS and the no-N control (Fig. 2) in line with higher N availability during the corn growing season in that treatment. Cumulative N_2O-N emissions were comparable to other reports in IL (Preza-Fontes et al., 2022; Wiedhuner et al., 2022).

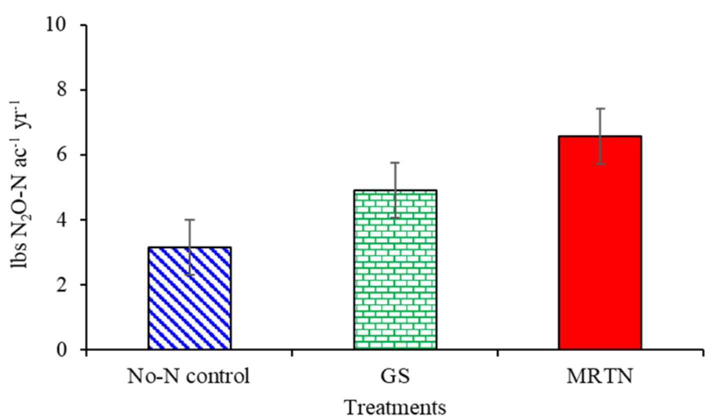

Fig. 2. Cumulative N_2O-N emissions during the corn growing season as influenced by N management in 2022. No-N is no fertilizer control, GS indicates GreenSeeker-based N rate and MRTN-Upfront is 203 lbs N ac^{-1} at planting.

Nitrate-N leaching

Nitrate-N leaching was higher in the MRTN treatment (upfront and sidedress) as compared to the GS and the no-N control. Implementing GS resulted in much lower N application that the MRTN which in turn, decreased both corn grain yield (10 bu ac^{-1}) and nitrate-N leaching. In 2022, nitrate-N leaching from the GS treatment was similar to that of the no-N control which is encouraging (Fig. 3).

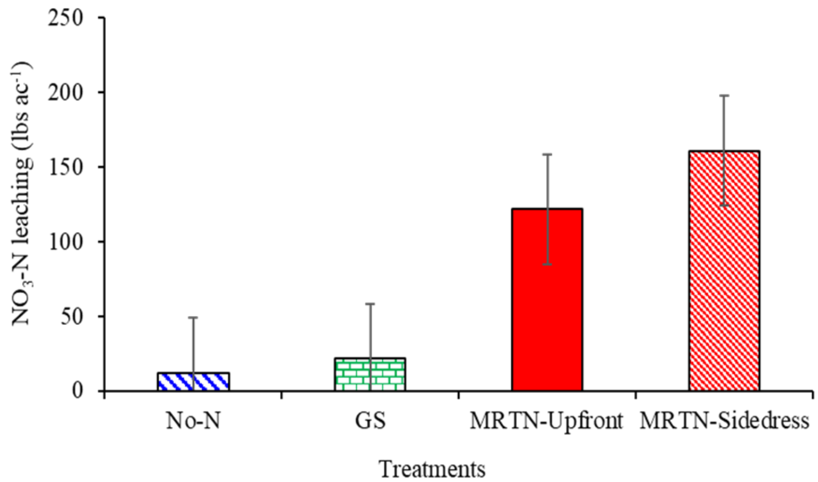

Fig. 3. Nitrate-N leaching during the corn growing season as influenced by N management in 2022. No-N is no fertilizer control, GS indicates GreenSeeker-based N rate and MRTN-Upfront is 203 lbs N ac^{-1} at planting and MRTN-sidedress is 203 lbs N ac^{-1} that was applied as 55 lbs N ac^{-1} at planting and the rest at sidedress timing.

PRELIMINARY CONCLUSION

In this preliminary trial, we observed that GS algorithm suggested 80 lbs ac^{-1} less N application to corn resulting in 10 bu ac^{-1} less yield. However, both N_2O-N and nitrate-N losses were reduced by the GS treatment compared to the MRTN. We require more site-years to confirm these results and fine tune the GS algorithm.

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EMERGING TRENDS FROM WISCONSIN'S NITROGEN OPTIMIZATION PILOT PROGRAM

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ABSTRACT

Accurately determining nitrogen (N) fertilizer requirements for crops is challenging due to the wide variability of landscapes and management across the state. Adjusting nitrogen rates comes with a high level of risk considering over-application can reduce profits and negatively affect water quality, while under-application can prevent yield targets from being reached. Conducting field-scale, on-farm research is a practical approach to better estimating optimum N rates on a field-by-field basis. In 2023, Wisconsin's Department of Agriculture, Trade, and Consumer Protection established the Nitrogen Optimization Pilot Program to provide funding for farmers to conduct their own N rate trials, in collaboration with UW-Madison. The program has supported 46 projects, conducting trials on 83 Wisconsin farms to address producer and partner driven research questions, ranging from evaluation of manure N credit to N need following a cover crop. Here, we explore trends in the dataset comparing in-season sampling with parameters of yield, economic and agronomic optimum nitrogen rate, and yield at 0 N. We also highlight the most interesting case studies to showcase how on-farm trials have shaped producer-driven decisions and demonstrate the potential of on-farm research to influence the future of nutrient management.

INTRODUCTION

Accurately predicting the N fertilizer needed for corn (*Zea mays* L.*)* during the growing season is an ongoing challenge in Wisconsin. Managing N fertilization effectively is critical to optimizing corn yield while minimizing environmental impacts and improving producer's bottom line. Current N recommendation tools provide an estimate of crop N need, but farm and field specific management may affect the accuracy of those estimates (Morris et al., 2018). Factors such as N source, timing, and placement coupled with other factors such as soil type, temperature and precipitation, and cropping history make it difficult to develop state or regional recommendations that are consistently reliable in the absence of long-term N rate trial data (Puntel et al., 2016). Winter rye (Secal cereale L.) is a commonly used cover crop due to its effectiveness in reducing soil erosion, scavenging nitrogen, and improving soil health, but can greatly impact nitrogen need for the subsequent crop. Understanding how cover crop management affects nitrogen dynamics is essential for effective nitrogen management in Wisconsin cropping systems.

To address these issues regarding N demand of crops in Wisconsin, replicated N rate studies were conducted on-farm under a variety of management conditions. Wisconsin's Department of Agriculture, Trade, and Consumer Protection established the Nitrogen Optimization Pilot Program (NOPP) to provide grants for farmers to conduct research projects aimed at answering specific N-related questions on their farms. Under 92.14(1 6), Stats., grant recipients shall collaborate with UW-Madison to implement a project that optimizes the application of commercial N and is carried out for at least two growing seasons. The objectives of these trials were to i) assess the value of early spring soil testing in accounting for available soil N, ii) to determine the economic and agronomic optimum N rate of corn, and iii) to determine the effect of a specific field variable (i.e., cover crops) on subsequent corn yield and optimum N rate.

MATERIALS AND METHODS

On-farm N rate trials were conducted across Wisconsin in 2023 and 2024. All trials in the program were N rate studies, with some including another management factor to create a split plot design (i.e. cover crop or biological product). Trials varied in project design based on the producers specific research question, field shape, and equipment capabilities, but at the basis consisted of a randomized complete block design with four replications. N rates were specific to each site with four to six rates in each trial ranging from 0 to well above grower standard rate. For each site, nitrogen response curves were chosen based on the best fitting model according to RMSE and adjusted R^2. The economic optimum nitrogen rate (EONR) was derived from the parameters of the best fitting model using a nitrogen to corn price ratio of 0.1.

Here, we highlight three sites in Lafayette County. These sites used a N rate trial (six rates) to explore N need of corn planted green following a rye cover crop. The experimental design was a randomized complete block, split plot design with four replications. The whole plot factor was a rye cover crop and the split plot factor was N rate. At all sites soil nitrate samples were collected pre-plant as a composite bulk sample of eight-twelve cores per block in cover and no cover treatment at a depth of 0-1' and 1-2'. Routine soil samples at a depth of 0-6" were also collected at this time. Cover crop biomass was collected in spring before termination to be analyzed for C:N. Yield was harvested and measured on a plot basis using a weigh wagon or yield monitor. Site 3 had a manure application of 12 ton/ac dry beef manure. Manure was spread on the growing cover crop in early spring.

RESULTS

Agronomic and economic optimum nitrogen rates had great variation from site to site across the state, with EONR varying from 0 to 193 lb-N/ac. The farmer "business as usual rate" is the N rate farmers would have applied to the trial area under normal conditions. Out of rate trials in 2023 and 2024, 19 sites did not reach a plateau within the nitrogen rates applied while 35 sites reached a peak or plateau within the applied rates.

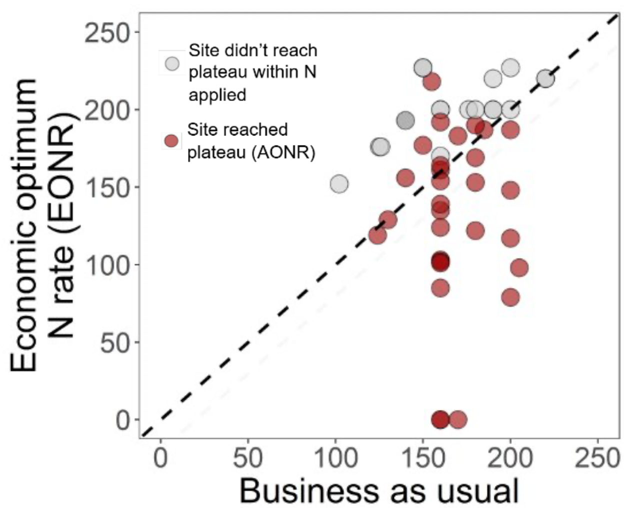

Figure 1. Economic optimum nitrogen rate (EONR) of nitrogen rate trials across the state by the farmer "business as usual" nitrogen rate in lb-N/ac. The black dashed line is the 1:1 line.

Cover crop trial- Site 1

Total biomass of the rye cover crop was 2355 22 and total nitrogen uptake of 48 lb/ac. The no cover control treatment had greater soil nitrate than the rye cover crop at both soil depths (Table 2), an indication of this nitrogen uptake by the cover crop. Quadratic plateau was the best fit curve for both the rye cover crop and no cover treatment. Corn yield was consistently lower following a cover crop than no cover, with the largest difference at lower N rates (Figure 3). EONR was 204 lb-N/ac following the cover crop and 179 lb-N/ac without cover.

Table 1. Pre-plant soil nitrate for all sites at the depth of 0-2'.

Pre-plant soil nitrate (NO_3-N)		
		lb/ac
Site 1	No cover	45
	Cover	15
Site 2	No cover	43
	Cover	18
Site 3	No cover	63
	Cover	20

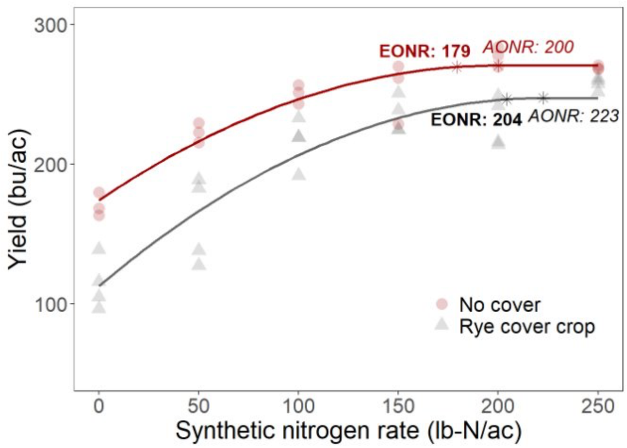

Figure 2. Site 1 quadratic plateau nitrogen rate yield response curve of corn following a cover crop treatment and bare control across six nitrogen rates. EONR was calculated using the parameters of the curve and a nitrogen to corn price ratio of 0.1.

Cover crop trial- Site 2

Total biomass of the rye cover crop was 967 lb/ac across the field, with a C:N of 15 and total nitrogen uptake of 26 lb/ac. The no cover control treatment had greater soil nitrate than the rye cover crop (Table 1), an indication of this nitrogen uptake by the cover crop. Quadratic was the best fit curve for both the rye cover crop and no cover treatment. Corn yield was consistently lower following a cover crop than no cover across all N rates (Figure 3). EONR was 236 lb-N/ac following the cover crop and was not reached within applied N rates following the rye cover crop.

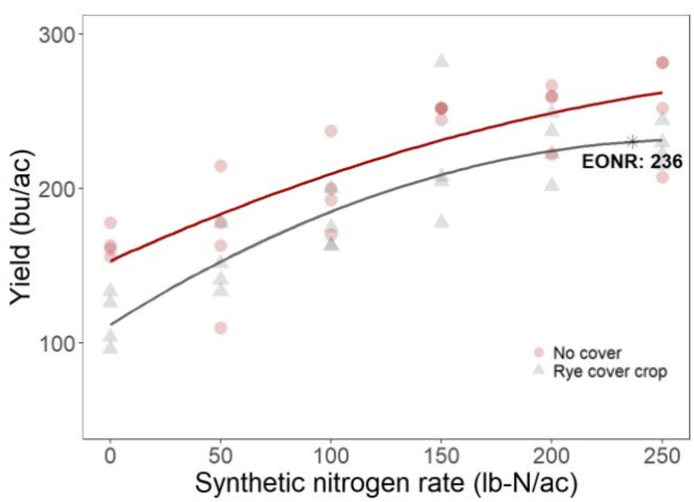

Figure 3. Site 2 quadratic nitrogen rate yield response curve of corn following a cover crop treatment and bare control across six nitrogen rates. EONR was calculated using the parameters of the curve and a nitrogen to corn price ratio of 0.1.

Cover crop trial- Site 3

Total biomass of the rye cover crop was 6275 lb/ac across the field, with a C:N of 18 and total nitrogen uptake of 168 lb/ac. The no cover control treatment had greater soil nitrate than the rye cover crop at both soil depths (Table 1), an indication of this nitrogen uptake by the cover crop. Corn yield was not significantly different at any N rate or between cover and no cover. This lack of response of yield to applied synthetic nitrogen indicated all necessary nitrogen was supplied to the field by the manure.

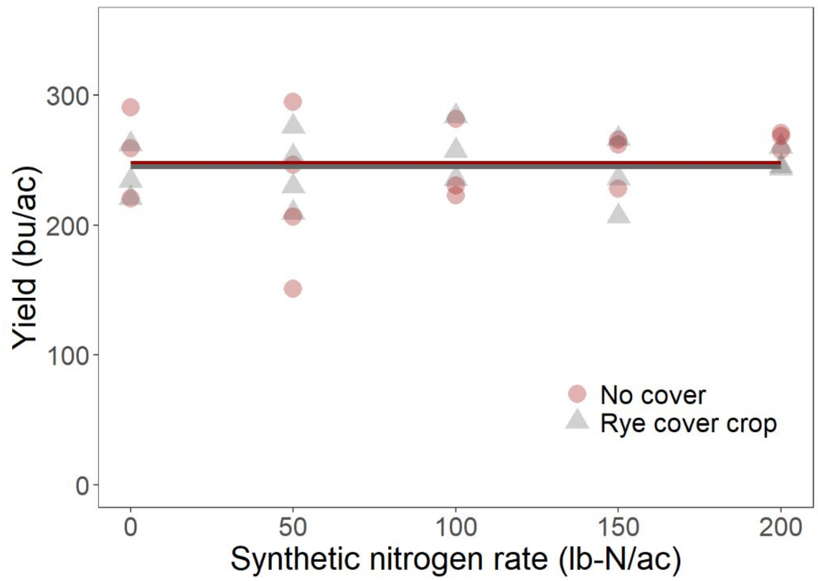

Figure 4. Site 3 yield of corn following a cover crop treatment and bare control across six nitrogen rates.

CONCLUSION

The cover crop case study demonstrates the importance of providing farmers with the tools to conduct their own trials to gain practical knowledge on nitrogen management on their farm. Rye successfully established as a cover crop on all sites and effectively scavenged soil nitrogen that may have otherwise been prone to leaching, but a yield drag occurred on two out of the three sites. Yield drag did not occur when the field had a manure application (site 3). Further research is necessary to better understand how cover crop management can be tweaked to avoid yield drag of corn following a rye cover crop.

Participating in on-farm nitrogen rate trials gave agronomic insight and provided value for both university researchers, farmers, and other project partners. Data generated from these on-farm studies has generated much interest from other local farmers as the data continues to be shared at field days and webinars. On-farm trials continue to highlight variability across the Wisconsin landscape and farming systems, proving the need for more local farmer generated data.

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EFFECT OF MANURE SOURCES ON SOIL PHOSPHORUS DYNAMICS

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ABSTRACT

This study evaluated the effects of different organic fertilization strategies on soil P pools across two sites in Ohio. Treatments included two manure-amended sites, one receiving dairy manure (Northwest) and the other receiving swine manure (Western), with a history of a hog farm at the site. Soil samples were collected from the 0-20 cm depth in summer 2024. Samples were analyzed for inorganic P pools using a sequential extraction procedure. Phosphorus saturation (P-sat), determined using acid ammonium oxalate extraction, remained below the environmental risk threshold (11.8%) under dairy manure, while swine manure increased P-sat above the threshold, indicating enhanced risk of P loss. Total phosphorus (TP), measured using EPA 3051A acid digestion, varied with treatments. Swine manure increased TP by 3 to 4 times as compared to controls, whereas dairy manure showed no significant effect on P pools. Inorganic P pool analysis revealed calcium (Ca-P) and iron-bound P (Fe-P) as dominant fractions. The results underscore that manure type, rate, and historical management could influence soil P dynamics differently. Understanding these interactions is key to balancing agronomic and environmental goals in nutrient management planning.

INTRODUCTION

Phosphorus (P) is vital for crop production, but also contributes to water quality issues when it enters water bodies through leaching or runoff. In Ohio, runoff and subsurface leaching of P from agricultural soils are major causes of nutrient enrichment in Lake Erie (Watson et al., 2016). While manure applications can improve soil fertility, repeated use may lead to P buildup and greater loss risk, depending on the manure source and management history. Understanding how different manure types affect soil P pools is essential for balancing productivity with environmental protection. This study evaluated the effects of dairy and swine manure on soil P distribution and P saturation across two field sites in Ohio to identify how manure source and site history influence soil P dynamics.

MATERIALS AND METHODS

Soil samples were collected from two locations in Ohio, USA: Northwest (Hoytville; 41°12'46"N, 83°45'50"W) and Western (Clark County; 39°51'39"N, 83°40'45"W), which had a history of hog farming. At the Northwest site, treatments included two dairy manure applications: 8,000 gallons acre^{-1} and 12,000 gallons acre^{-1}, and a control treatment receiving urea ammonium nitrate solution (UAN 28%) at 67 gallons acre^{-1}. At the Western site, two primary treatments were imposed: swine manure application and no-manure control. Each treatment was further subdivided into two nitrogen (N) rate levels. Plots receiving swine manure were fertilized at high (200 lb N acre^{-1}) and medium (150 lb N acre^{-1}) nitrogen rates, while no-manure plots received high (200 lb N acre^{-1}) and low (100 lb N acre^{-1}) nitrogen rates. UAN 28%

served as the N source for all treatments. Treatments started in 2013 and 2023 at Northwest and Western sites, respectively, with corn-soybean rotations.

Laboratory Analysis

Fractionation of inorganic soil phosphorus pools

Inorganic P sequential fractionation was performed according to Zhang & Kovar (2002). The procedure identified five P fractions: (i) soluble or loosely bound P (Sol-P), extracted with 1 mol L-1 NH_4Cl; (ii) Al-P associated with aluminum (hydr)oxide surfaces, extracted using 0.5 mol L-1 NH_4F; (iii) Fe-P associated with iron (hydr)oxide surfaces, extracted with 0.1 mol L-1 NaOH; (iv) Reductant or occluded P defined as P trapped within mineral matrices, extracted using a solution of 0.3 mol L-1 sodium citrate, 1 mol L-1 sodium bicarbonate, and sodium dithionite, and (v) Ca-P, extracted using 0.25 mol L-1 H_2SO_4. Between each extraction step, samples were washed and centrifuged twice with saturated NaCl to remove residual P from the previous fraction. The NaCl wash solutions were combined with their corresponding extracts to ensure complete recovery of P associated with each phase. All extracts were diluted 10 times using 3% HCl, except Sol-P, and analyzed for P using inductively coupled plasma-atomic emission spectrometry (ICP-OES; Agilent Technologies 700 Series, Santa Clara, CA, USA).

Oxalate Extractable Phosphorus

The soil samples were analyzed for oxalate phosphorus saturation (P-sat) as outlined by McKeague and Day (1966). The samples were extracted with 0.2 M ammonium oxalate solutions. The oxalate [(NH4)2C2O4] extractable fraction identifies P adsorbed to amorphous, non-crystalline, or poorly ordered Al and Fe oxides, unlike the inorganic P sequential fractionation method, which is assumed to primarily extract P bound to crystalline Al (hydr)oxide surfaces (Bayley et al., 2008). Following extraction, all solutions were centrifuged, decanted, diluted 10x using 3% HCl, and analyzed for P using ICP-OES. Phosphorus saturation was calculated using extractable P, Al, and Fe concentrations obtained from acid ammonium oxalate extraction (Equation 1):

$$[\text{Ox-P (mol)}/ (\text{Ox}(\text{Al(mol)} + \text{Fe(mol)}))] \times 100 = \text{P-sat\%} \quad (1)$$

Total phosphorus

Total phosphorus (TP) was determined using the microwave-assisted acid digestion procedure outlined in U.S. EPA Method 3051A (U.S. EPA, 2007). In this procedure, soils were digested using concentrated hydrochloric and nitric acids. The digestion process was conducted under controlled temperature conditions of 175 °C using a MARS 1600-watt microwave to complete the dissolution of phosphorus-bound mineral and organic matrices. After digestion, the resulting extracts were diluted to appropriate concentrations using deionized water. These liquid extracts containing the released phosphorus were then analyzed for TP content using ICP-OES.

Statistical Analysis

Statistical analyses were performed using R version 4.4.2 (R Core Team, 2024). Assumptions of parametric testing were evaluated using the Shapiro-Wilk test for normality and Levene's test for homogeneity of variance. When these assumptions were violated, non-parametric Kruskal-Wallis tests were used. Significant treatment effects were followed by pairwise Wilcoxon rank-sum tests, with adjusted p-values using the Benjamini-Hochberg method.

RESULTS

Dairy manure

Dairy manure amendments did not affect TP concentrations. Despite the application of 12,000 gal acre^{-1} (D1) and 8,000 gal acre^{-1} (D2) of dairy manure, TP remained statistically similar to the inorganic fertilizer treatment of UAN 28% at 67 gal acre^{-1} (D3), which received no manure-derived P. Mean TP concentrations in D1 (711.05 mg kg^{-1}) and D2 (710.20 mg kg^{-1}) were statistically similar ($p > 0.05$) to those in the control treatment (D3; 741.50 mg kg^{-1}) (Figure 1A). Across all soil inorganic P pools, dairy manure treatment effects were not statistically significant, suggesting that manure inputs at the applied rates did not alter the distribution of soil P. Phosphorus saturation levels ranged from 6.5% to 11.15% across all treatments (Figure 1B), with all values remaining below the Ohio environmental threshold of 11.8%. This suggests a low potential risk of P loss via runoff or leaching under the dairy manure management evaluated in this study.

Swine Manure

Swine manure treatments resulted in significantly higher TP concentrations compared to the no-manure control plots at Western (Figure 1C). Mean TP values were 1161 mg kg^{-1} and 1411 mg kg^{-1} under swine manure with high and medium nitrogen application, respectively, while no-manure plots averaged 370 mg kg^{-1} (high N) and 379 mg kg^{-1} (low N). TP concentrations under swine manure treatments were approximately 3 to 4 times greater than those under no-manure treatments.

Similarly, P-sat levels were elevated with swine manure. Phosphorus saturation levels ranged from 16.64% up to 29.89% under both swine manure treatments; in contrast, no-manure treatments remained below the Ohio environmental threshold, ranging from 6.2% to 9.31% (Figure 1D).

Swine manure treatments significantly affected all soil P fractions (Figure 2). All P fractions showed higher concentrations under swine manure treatments compared to no-manure controls. The observed differences were primarily between the manure treatments (swine vs. no manure), while nitrogen rate within each major treatment had no significant effect.

DISCUSSION

The effects of dairy and swine manure on soil P dynamics were evaluated at two sites that differed in soil type and management conditions. As these sites contrasted in manure type, application history, rate, and intrinsic soil properties, the results were interpreted within each site. Therefore, no direct statistical comparisons were made between these two experiments or sites. Two different rates of dairy manure compared with control manure plots did not affect any of the soil P pools. Among all pools, Ca-P was the dominant fraction at the dairy manure site. As the dominant soil series at NW was Hoytville clay soils, these soils commonly contain residual limestone fragments that might create Ca-rich conditions within the 0-20 cm soil depth, favoring Ca-P accumulation (USDA-NRCS, 2025a).

In swine manure-treated plots, TP concentrations were approximately 3 to 4 times greater than those in control plots (Figure 1A). Moreover, P-sat percentages at the swine site exceeded the Ohio environmental threshold, whereas values at the dairy site remained below this limit (Figure 1B). The higher P content in swine treatments could be from the legacy effect of swine manure, as the area was used for raising hogs about 2 decades ago (J. Davlin, personal communication, 2025). The higher P accumulation under swine manure can be attributed primarily to the larger application rates used in the swine manure treatments and the inherently greater P content of swine manure (Rayne & Aula, 2020). Li et al. (2014) reported that P content in swine manure is approximately 4.4 times higher than in dairy manure. The primary factor responsible for this difference in P content is how P is supplied in their feed. In cereal grains, P occurs predominantly as phytic acid (Leytem et al., 2004), and swine generally have lower phytase activity than cattle, thus limiting their ability to hydrolyze phytic acid (Rayne & Aula, 2020). Thus, swine are often fed with supplemental phytase to improve the breakdown of phytate and increase P digestibility. Without adequate phytase, more phytate-bound P is excreted, contributing to higher manure-P loads.

Excessive P buildup in soils receiving manure applications is also linked to the inherently narrow nitrogen-to-phosphorus (N:P) ratio in manure compared with the N:P ratio in crop demand. To meet crop N requirements, manure is often applied at rates that far exceed the crop’s P needs, resulting in P accumulation over time (Sharpley et al., 1993). Further, the timing of manure application might have influenced these outcomes. Soil samples at the swine manure site were collected roughly six months after the most recent application, whereas at the dairy manure site, samples were collected nearly twelve months after application. According to Kleinman and Sharpley (2003), P loss to runoff is greatest immediately after application and declines over time as applied P becomes more stabilized in the soil, suggesting that the shorter interval since application at the swine manure site could have contributed to the elevated P saturation observed. Overall, these findings highlight that manure type, nutrient composition, application rate, and timing interact to shape soil P dynamics. Future work should compare swine and dairy manures side by side at the same site, using matched application rates under both N-based and P-based regimes to minimize site effects.

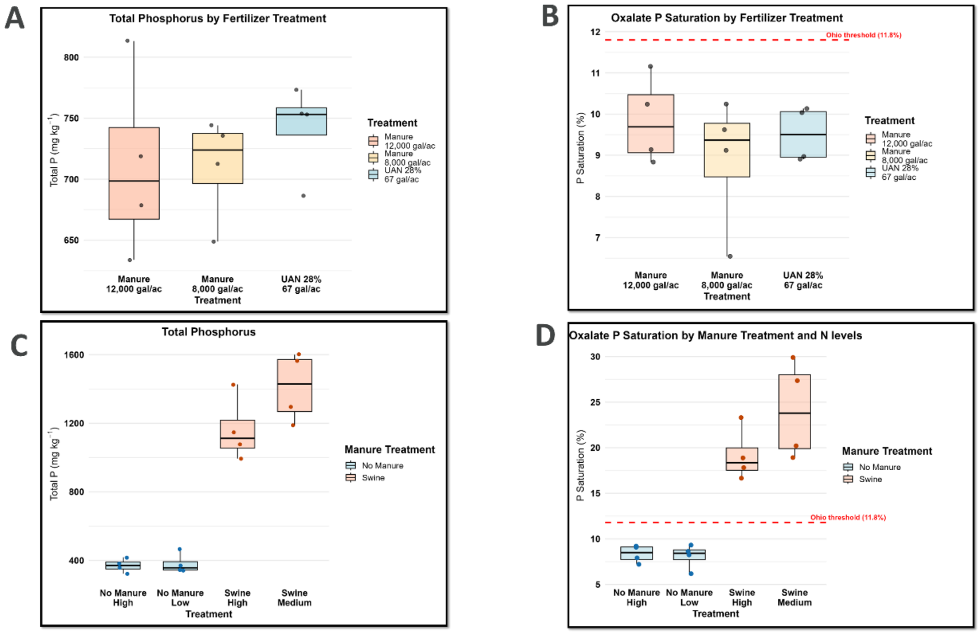

Figure 1. Effect of different manure amendments on total phosphorus (TP) and oxalate phosphorus saturation across the two sites in Ohio: Western (Clark County) and Northwest (Wood County). (A) and (B) represent the TP and P saturation under two dairy manure treatments and one no-manure treatment at the Wood County site. (C) and (D) shows TP and P saturation under swine manure and no-manure treatments with different nitrogen levels at the Clark County site. The red dashed lines in (B) and (D) represent the Ohio environmental threshold for P saturation (11.8%).

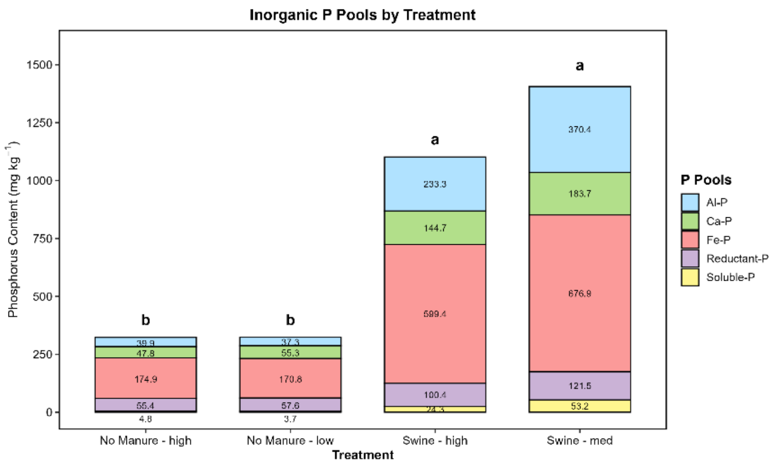

Figure 2. Five different soil phosphorus (P) fractions under different swine manure and no manure treatments. The distribution of inorganic P pools (Soluble-P, Reductant-P, Fe-P, Ca-P, and Al-P) under swine manure and no-manure treatments with varying N rates at the Clark County site. Different letters above bars indicate statistically significant differences among treatments (Tukey HSD, $p < 0.05$).

CONCLUSION

This study demonstrated that manure source plays a critical role in shaping soil P dynamics. Dairy manure applications did not significantly alter total or inorganic P pools and maintained P saturation below the environmental risk threshold, suggesting low potential for P loss. In contrast, higher P accumulation and saturation were observed under swine manure. However, these results should be interpreted with caution, as site-specific factors such as past management history and time since manure application may have contributed to the elevated P levels. Overall, the findings emphasize that differences in manure composition, rate, and site legacy can shape soil P behavior, underscoring the need for site-specific and P-based manure management strategies to sustain productivity while minimizing environmental risk.

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INTERPRETING SOIL HEALTH TEST RESULTS TO GUIDE MANAGEMENT FOR MISSOURI ROW CROPS

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ABSTRACT

Soil health testing provides an integrated measure of the physical, chemical, and biological properties that determine a soil's capacity to function as a living ecosystem. This study summarizes the interpretation framework developed by the University of Missouri Soil Health Assessment Center (SHAC) to help Missouri farmers understand their soil health test reports. Data are based on over 13,000 soil samples collected statewide, providing benchmarks for key indicators such as Total Organic Carbon (TOC), Permanganate Oxidizable Carbon (POXC), Soil Respiration, Wet Aggregate Stability (WAS), ACE Protein, Potentially Mineralizable Nitrogen (PMN), and soil texture. The SHAC soil health scoring system enables producers to assess biological activity, nutrient cycling, and soil structure while identifying management practices that improve soil function over time.

INTRODUCTION

Soil health is the foundation of productive and sustainable farming systems. Unlike conventional soil fertility tests, which focus on nutrient availability, soil health testing evaluates the physical, chemical, and biological functions that support long-term productivity (Zuber et al., 2020, 2021). In Missouri, variable soil types, climate conditions, and management histories impact soil function. The Soil Health Assessment Center (SHAC) developed a comprehensive soil health test and interpretation guide to support management decisions. This proceeding summarizes key indicators and interpretation methods used by SHAC and outlines management recommendations based on measured soil health categories.

MATERIALS AND METHODS

Soil samples were analyzed at the University of Missouri Soil Health Assessment Center following standardized laboratory protocols. Indicators measured included Total Organic Carbon (TOC), Permanganate Oxidizable Carbon (POXC), 3-Day Soil Respiration, Wet Aggregate Stability (WAS), ACE Protein, and Potentially Mineralizable Nitrogen (PMN). These indicators were scored from 1 to 5 and categorized as Very Low, Low, Medium, High, or Very High based on percentile rankings of over 13,000 soil samples representing Missouri's major soil regions (Table 1). A composite soil health score was calculated as the mean of individual indicator scores.

RESULTS AND DISCUSSION

Total Organic Carbon: It measures the amount of carbon in soil organic matter (SOM). It's a key indicator of long-term soil health, affecting nutrient cycling, soil structure, water-holding capacity, and biological activity. A higher TOC indicates better soil fertility and resilience.

Permanganate Oxidizable Carbon: POXC represents the active, easily available portion of soil organic carbon for microbes. This fraction responds quickly to management changes and serves as an early indicator of changes in soil health. Higher POXC values typically reflect better biological activity, nutrient cycling, and soil structure.

Soil Respiration: Soil respiration quantifies CO_2 released from soil over a short incubation period. It reflects microbial activity and the breakdown of organic matter. Higher values indicate the presence of active microbes and healthy soil processes. Practices such as reduced tillage, cover crops, and organic amendments enhance soil respiration.

Wet Aggregate Stability: WAS indicates the ability of soil aggregates to resist breakdown when exposed to water. Higher WAS means better soil structure, improved water infiltration, and lower erosion risk. Increasing SOM and microbial activity through cover crops and reduced tillage improves WAS.

ACE Protein: It measures easily extractable organic nitrogen (amino acids and peptides) that feed soil microbes. It reflects the soil's ability to supply nitrogen through SOM decomposition. Practices that build SOM—like cover crops and manure—boost ACE Protein levels and overall soil nitrogen cycling.

Potentially Mineralizable Nitrogen: PMN estimates the amount of organic nitrogen that can be converted to plant-available forms by microbes. High PMN signals strong microbial activity and potential for natural nitrogen supply, without requiring heavy fertilizer inputs. Influenced by SOM, moisture, temperature, and management practices such as cover cropping, reduced tillage, and organic amendments.

Soil Texture: Soil texture reflects the relative proportions of sand, silt, and clay present in a soil sample, which determines its textural classification. This classification affects important soil characteristics, including porosity, water-holding capacity, drainage, root penetration, and nutrient retention. Information on soil texture helps inform decisions about crop selection, nutrient and water management, and tillage practices. Soil texture is measured only once at a given location, as it changes very slowly over time, in the order of decades or centuries, under natural conditions.

The statewide database revealed wide variability in soil health indicators across Missouri regions. Total Organic Carbon (TOC) ranged from less than 1% in degraded systems to over 3% in well-managed soils. Biological indicators such as POXC, ACE Protein, and PMN were highly responsive to management practices like reduced tillage, cover cropping, and manure use.

Table 1. Summary of six soil health indicator interpretation ranges, soil health status/implication, and percentile of Missouri (MO) soils under five different soil health categories.

Soil Health Category	Health Test Ranges	Soil Health Status/Implication	MO Soil* Percentile
Total Organic Carbon (%)			
1. Very Low	< 0.75	Severely depleted soil organic matter; limited nutrient retention, microbial life, and structure. High risk of erosion and compaction. Requires major restoration	0-5
2. Low	0.75 – 1.5	Reduced biological and physical functioning, suboptimal productivity. Indicates recent degradation or low input history.	6-25
3. Medium	1.6 – 2.5	Adequate carbon level for moderate productivity. Needs improvement for long-term sustainability.	26-80
4. High	2.6 – 3.5	Well-structured, fertile, and biologically active soil. Supports resilient cropping systems.	81-95
5. Very High	> 3.5	Exceptional soil quality may support ecosystem services beyond crop production (e.g., carbon sequestration). high microbial and nutrient potential.	96-100
Permanganate Oxidizable Carbon (POXC) (ppm)			
1. Very Low	< 200	Poor biological activity; depleted microbial food base. Often compacted or over-tilled soils, low fertility.	0-5
2. Low	200 – 400	Microbial activity and nutrient cycling are limited. Needs organic inputs and cover crops.	6-25
3. Medium	401 – 600	Moderate microbial function. Can support productivity with balanced management.	26-80
4. High	601 – 800	High biological activity and potential nutrient turnover. Indicates active soil management.	81-95
5. Very High	> 800	Very active microbial system; strong indication of biological soil health and carbon inputs.	96-100
3-Day Soil Respiration (mg CO_2 kg soil^{-1} 3-day^{-1})			
1. Very Low	< 300	Microbial dormancy indicates biological inactivity, possible compaction or low organic matter.	0-5
2. Low	300 – 550	Limited microbial turnover may indicate stress or need for organic inputs.	6-25
3. Medium	551 – 950	Functioning microbial system; moderate nutrient cycling and soil life.	26-80
4. High	951 – 1300	High biological activity and good organic matter decomposition.	81-95
5. Very High	> 1300	Very active system: excellent biological health but must be balanced to avoid rapid soil organic matter depletion.	96-100
Wet Aggregate Stability (%)			
1. Very Low	< 10	Very unstable soil structure; high erosion risk and poor water retention.	0-15

2. Low	10 – 25	Weak structure; likely surface crusting and low porosity.	16-50
3. Medium	26 – 45	Moderately structured; can support crops but is sensitive to disturbance.	51-75
4. High	46 – 70	Stable structure; good infiltration and microbial habitats.	76-95
5. Very High	> 70	Excellent aggregation; supports soil aeration, root growth, and resilience to stress.	96-100
Autoclaved Citrate-Extractable (ACE) Soil Protein (g kg^{-1})			
1. Very Low	< 2.5	Poor soil N mineralization potential: microbial biomass is limited.	0-5
2. Low	2.5 – 4.0	Low microbial nutrient access; needs OM input and less disturbance.	6-25
3. Medium	4.1 – 7.0	Moderate soil protein availability; balanced biological N cycling.	26-80
4. High	7.1 – 10.0	Good protein and nutrient cycling potential; resilient system.	81-95
5. Very High	> 10.0	High N mineralization and biological activity. May support N credits in management.	96-100
Potentially Mineralizable Nitrogen (ppm)			
1. Very Low	< 30	Very low N availability: likely N deficiency unless supplemented.	0-5
2. Low	30 – 60	Suboptimal N cycling: reliance on synthetic N expected.	6-25
3. Medium	61 – 100	Moderate potential for organic N release; supports partial N supply.	26-80
4. High	101 – 140	High N supply potential; supports reduced N fertilization.	81-95
5. Very High	> 140	Excellent N mineralization; may allow crediting N in recommendations.	96-100
*Based on over 13,000 cover crop cost-share data across different soil textures in Missouri			

Management Recommendations

The management recommendations based on the overall soil health score are provided.

1. **Very Low Soil Health (overall score <1.76)**
   - Adopt no-till immediately to reduce erosion and preserve remaining topsoil.
   - Use cover crops intensively, ideally every year, with diverse species mixes to build organic matter and provide winter protection.
   - Apply high rates of manure, if nutrient tests indicate a need, to jump-start biological activity.
   - Diversify rotations with legumes and deep-rooted crops to improve aggregation and nitrogen cycling, avoiding monoculture systems.
   - Avoid bare fallow — maintain soil cover year-round.
   - Be patient, improvements may take several years, but erosion control and soil cover offer immediate benefits.

2. **Low soil health (overall score 1.76 – 2.75)**

- Maintain no-till and cover cropping; positive trends are beginning, but more improvement is needed.
- Maximize living roots year-round to enhance soil biology and structure.
- Ensure adequate fertility for both cover crops and cash crops to support biomass production.
- Diversify rotations with legumes and deep-rooted crops to improve aggregation and nitrogen cycling, avoiding monoculture systems.
- Incorporate organic amendments, like manure, to build soil carbon and nutrients.
- Minimize compaction via controlled traffic and cover crop roots.
- Avoid bare fallow — maintain soil cover year-round.
- Soil tests every 3-4 years to track progress and guide inputs.

3. **Medium soil health (overall score 2.76 – 3.75)**
    - Continue core practices: no-till, cover crops, and diverse rotations.
    - Introduce multi-species cover crop mixes (legumes + grasses + brassicas).
    - Optimize cover crop management, allowing more spring growth if it doesn't interfere with planting.
    - Continue organic inputs, focusing on manure for stable carbon. Consider adding carbon-rich amendments (e.g., biochar) if erosion or leaching is a concern.
    - Enhance nutrient cycling with practices like precision fertilization and split applications.
    - Manage crop residues in place to reduce disturbance and retain carbon.
    - Keep improving diversity above and below ground.
    - Avoid setbacks, such as deep tillage or long bare fallow periods.
    - Soil tests every 3-4 years to track progress and guide inputs.

4. **High soil health (overall score 3.76 – 4.75)**
    - Maintain current practices, no-till, cover crops, with continued diversity and minimal disturbance to preserve soil function.
    - Select cover crops strategically (e.g., legumes for nitrogen, grass for carbon) to support biological processes.
    - Monitoring nutrient levels, higher organic matter may support nutrient supply but also increases removal from high yields.
    - Fine-tune nutrient management using soil health data (e.g., credit more nitrogen if respiration, ACE protein, and PMN are high). Avoid over-application of synthetic nitrogen to maintain microbial balance.
    - Monitor long-term trends and weather-induced variability.
    - Trial innovative practices like companion cropping or biological amendments to further optimize.
    - Begin to document carbon sequestration gains if considering carbon markets.
    - Use flexible practices cautiously, allowing only occasional intensive tillage when necessary for weed and pest management.

- Stay proactive to maintain gains; soil can decline quickly without consistent management.

5. **Very High soil health (overall score >4.75)**
    - Continue all core soil health practices; these fields are high-performing assets.
    - Explore innovative practices like precision nutrient management, inter-seeding cover crops, or livestock integration.
    - Prevent degradation: watch for overuse of inputs, overgrazing, or tillage creep.
    - Monitor soil health metrics regularly (e.g., aggregate stability, microbial activity) to ensure continued success.
    - Educate and share: These soils could serve as benchmarks or demonstration plots.
    - Experiment carefully with new practices, documenting impacts.
    - Consider ecosystem service monetization (e.g., carbon credits, water quality credits).
    - Avoid complacency; high-functioning soils can degrade rapidly with mismanagement.
    - Protect long-term productivity by treating these fields as models of conservation and resilience.

CONCLUSIONS

The Missouri Soil Health Assessment provides a comprehensive framework for evaluating the biological, chemical, and physical health of soils. Interpreting soil health results in relation to statewide benchmarks enables producers to identify constraints and select suitable management practices. Practices such as reduced tillage, cover cropping, organic amendments, and crop rotation diversity are crucial for enhancing soil function and long-term productivity.

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THE EFFECTS OF PHOSPHORUS AND POTASSIUM APPLICATION ON A 14-YEAR-OLD MISCANTHUS × GIGANTEUS STAND

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ABSTRACT

Miscanthus × giganteus (miscanthus) is a perennial C4 grass grown for renewable bioenergy and bioproducts. While miscanthus is often considered to have low nutrient requirements, the need for fertilization remains poorly understood, particularly in mature stands. This study aims to provide insight by evaluating for potential phosphorus (P) and potassium (K) limitations in a 14-year-old miscanthus stand in central Iowa that had received no prior fertilization. The experiment followed a randomized complete block design with four blocks and plots measuring approximately 800 ft². Treatments included fertilization of P (100 lb/a), K (130 lb/a), and combined P+K, with all plots receiving nitrogen (N) at 200 lb/a to eliminate potential N limitation. Baseline soil testing showed low to moderate P (5–13 ppm) and K (73–181 ppm) levels, and pre-treatment measurements of stem height, density, and yield revealed positive correlations between soil nutrient levels and biomass production, with K showing a slightly stronger relationship. In response to fertilization, P did not significantly increase soil test P ($p = 0.33$) or plant tissue P concentrations among treatments ($p = 0.193$). This suggests poor incorporation or rapid fixation of applied P. Conversely, K application led to significantly higher soil test K ($p < 0.001$) and plant tissue K ($p = 0.038$), though without corresponding yield increases indicating sufficient baseline K and possible luxury uptake. Average yield increased across all plots post-treatment, including controls, likely due to N fertilization or favorable weather. This work contributes to a deeper understanding of nutrient requirements in mature miscanthus and will enhance the ability to make informed fertilization recommendations.

BIOLOGICAL NITROGEN SUPPLIERS FOR SOYBEANS

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ABSTRACT

Soybeans are known to require more N than most crops, largely due to the high N levels found in their seeds. The most important source of N for soybean plants is the biological N fixation process. However, high yields (above 70 bu acre^{-1}) could limit the capability of this process to supply the plant's N demand. This study aims to investigate the use of non-rhizobial biological N suppliers, their ability to provide N to the soybean plants and potentially fill the N demand gap. The study was conducted at three sites in Indiana with different fertility characteristics: high fertility (West Lafayette), intermediate fertility (Wanatah), and sulfur-deficient (LaCrosse). At each site, two non-rhizobial biological N suppliers, Envita® (*Gluconacetobacter diazotrophicus*) and Utrisha-N® (*Methylobacterium symbioticum*), were applied under four fertility regimes: no fertilizer; 40 lb acre^{-1} of N; 20 lb acre^{-1} of S; and 40 lb acre^{-1} of N plus 20 lb acre^{-1} of S. The experimental design followed a 4 x 3 factorial arrangement with an additional untreated control resulting in 13 treatments. The treatments were replicated five times in each location, resulting in 65 experimental plots per study site. The evaluated parameters were plant nutrient content at R2 and R4 growth stages, yield, seed weight, and grain oil and protein concentrations.

INTRODUCTION

A large amount of nutrients is demanded for high-yield crops, and since its importance for the composition of enzymes and other proteins needed for photosysnthesis, a large amount of N is required (Sinclair and Horie, 1989 as cited in Salvagiotti et al., 2009). It is known that soybeans usually require more N than other crops, largely due to high N levels found in their seeds (Sinclair and de Wit, 1975 as cited in Ciampitti et al., 2021). The most important source of N for soybean plants is the biological N fixation process (Ciampitti et al., 2021), however, high yields (above 70 bu acre^{-1}), could limit the capability of this process to supply the plant's N demand (Ciampitti & Salvagiotti, 2018). This context makes it interesting to improve the N supply for the soybean plants utilizing different biological N sources. This study investigates two non-rhizobial biological N suppliers, which are Envita® and Utrisha-N®.

Envita® is a biological product produced by Azotic that consists of *Gluconacetobater diazotrophicus* bacteria. According to the manufacturer the bacteria are able to enter the plant both through the root zone, when applied in-furrow, or leaf stomata, when applied as a foliar spray. Once inside the plant, the bacteria colonizes the plant cells and create small vesicles or "air pockets" that have the ability of capturing nitrogen from the atmosphere. The bacteria then repopulates within the cell.

Utrisha-N® is a biological product produced by Corteva that consists of *Methylobacterium symbioticum* bacteria. Acording to Corteva, the bacteria enters the plant through the stomata and enters the leaf cells. Once in the plant cells, the bacteria converts N_2 from the air into ammonium, which results in a constant supply of amino acids to the plant.

This study aims to evaluate the efficiency of the two non-rhizobial biological nitrogen suppliers in providing nitrogen to soybean plants and their subsequent impacts on crop yield under contrasting environmental conditions. Specifically, the research investigates their performance in both low nitrogen supply environments, where additional N input may enhance plant growth, and high-yield environments, where greater nitrogen demand is expected. It is hypothesized that these products will improve soybean yield, with a stronger effect in high-fertility soils due to increased crop nutrient demand, while also demonstrating the potential to supply nitrogen effectively in low-N environments, contributing to overall nitrogen-use efficiency.

MATERIALS AND METHODS

The study followed a 4 x 3 factorial structure and was arranged in a randomized complete block design (RCBD) having 4 fertility regimes and 3 biological treatments, plus the addition of 1 extra untreated control, resulting in a final number of 13 total treatments. The 13 treatments were replicated 5 times in each experimental site, resulting in a final number of 65 small scale (10ft x 50ft) plots per location. Field trials were established in 3 locations within the state of Indiana with different fertility characteristics and were conducted throught the 2023 and 2024 seasons. Soybeans were planted in 15 in wide rows at a 140,000 seeds/acre seeding rate. Fertilizers were hand broadcasted on the small plots after planting. Biological treatments were sprayed at V6 growth stage with CO_2 backpack sprayer.

Locations

- **West Lafayette – IN:** high fertility environment
- **Wanatah – IN:** intermediated fertility environment
- **LaCrosse – IN:** sulfur deficient environment

Table 1. Locations of experimental sites.

Soybean varieties and planting dates

Location	2023		2024	
	Variety	Planting date	Variety	Planting date
West Lafayette	P31A73E-Illevo	May 6th	P31A73E-Illevo	May 4th
Wanatah	P28A65E-Illevo	May 18th	P28A65E-Illevo	May 22nd
LaCrosse	P18A73E	May 2nd	Becks 3300E	May 7th

Table 2. Soybean varieties and planting dates.

Fertility regimes

- **No fertilizer**
- **Nitrogen** = 40.0 lb.acre^{-1} via Urea
- **Sulfur =** 20.0 lb.acre^{-1} via Pelletized gypsum

•	**N + S =** 40.0 lb.acre^{-1} + 20.0 lb.acre^{-1} via Urea + Pelletized gypsum

Table 3. Fertility regimes with application rates and fertilizer sources.

Figure 1. Fertilizer spreading.

Biological treatments

•	**No biological**
•	**Utrisha-N® (Corteva):** *Methylobacterium symbioticum* – 5.0 fl.oz.acre^{-1}
•	**Envita® (Azotic):** *Gluconacetobacter diazotrophicus* – 0.18 fl.oz.acre^{-1} + 5.0 fl.oz.acre^{-1} of NIS (Activator 90)

Table 4. Biological treatments with application rates.

Figure 2. Biological spray application.

Data colection

For both the 2023 and 2024 seasons soil fertility was determined by soil sampling the study sites before the fertilizer application at 0-8 in depth. Yield was determined by harvesting the center of the plots using a combine harvester and then adjusting yields to 13% grain moisture. Grain subsamples were collected to dermine protein and oil contents through NIR analysis and also grain weight. For the 2023 season, plant nutrient content was determined for both the R2 (full bloom) and R4 (full pod) growth stages through leaf sampling of the most recent mature leaves.

Statistical analysis

SAS 9.4 was used to run proc GLM with main level factors, and interactions were tested with appropriate error terms. Interactions are reported and means separated according to Fisher's Protected $LSD_{0.1}$.

RESULTS AND DISCUSSION

The only analyzed parameter in which the biological products had a significant positive effect was the 2023 R4 nitrogen leaf content at a high fertility environment, West Lafayette – IN, where treatments that received Utrisha-N had a higher leaf N content on the pooled results.

%	None	Envita	Utrisha-N	Pooled	
None	4.7	4.6	5.1	4.8	**b**
Nitrogen	4.9	4.9	4.9	4.9	**b**
Sulfur	5.7	5.5	5.5	5.6	**a**
N + S	5.4	5.5	5.7	5.5	**a**
Pooled	5.2	5.1	5.3		
	B	**b**	**a**		

Table 5. R4 nitrogen leaf content at West Lafayette in 2023.

Sulfur was the biggest contributor factor for yield gains in all locations and years. With an emphasis on the low fertility environment, LaCrosse – IN, where a gain of 10.9 bushels per acre was observed in 2024.

$bu.acre^{-1}$	None	Envita	Utrisha-N	Pooled	
None	57.5	56.6	57.7	57.3	**c**
Nitrogen	58.9	54.9	54.2	56.0	**c**
Sulfur	67.4	66.9	70.2	68.2	**b**
N + S	72.6	70.0	73.9	72.2	**a**

Table 6. Grain yield at LaCrosse in 2024.

Preliminary conclusions

The results show that S was the responsible for the fertility effects observed. The biologica N suppliers were not able to overcome the limited supply of N at LaCrosse, which is the S deficient and low biological N fixation soil. There was no biological effect or interaction effect at Wanatah, which is the moderate fertility soil. The biological N suppliers were able to increase the N supply in a high yield environment.

Considerations

It is important to further study what drives the efficiency of the biological products, their working mechanisms and how they are impacted by other sprays during the season.

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DOES TWO-SIDED BANDING OF NITROGEN AND SULFUR FERTILIZERS IMPROVES CORN YIELD IN MIDWESTERN CROPPING SYSTEMS

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ABSTRACT

Efficient fertilizer management is essential for improving corn (*Zea mays* L.) productivity while reducing environmental risk. Fertilizer timing and placement help synchronize nutrient availability with crop demand. In Midwestern corn systems, fertilizer is traditionally banded on one side of the row. This study evaluated two-sided banding of nitrogen (N) and sulfur (S) using a split-application strategy in an Iowa corn production system. Fertilizer timing and placement did not significantly affect grain yield but did increase stover biomass ($p < 0.05$) relative to the unfertilized control. Results suggest that applying all fertilizer as a starter, particularly in a wet growing season, may reduce field operations compared with split application, though potential N loss from early-season leaching remains a concern. These practices may be considered for Midwest corn–soybean systems depending on seasonal conditions and management priorities.

INTRODUCTION

Nitrogen management remains a major component of achieving high and sustainable corn yields in Iowa and the greater U.S. Midwest, where N is typically the most limiting nutrient. Although required in smaller quantities, sulfur plays an important role in N assimilation and crop growth. Declines in atmospheric S deposition have increased the occurrence of S deficiency in cropping systems. Previous research has highlighted the benefits of S fertilization in corn across diverse agroecosystems (Kovar, 2021).

Traditional fertilizer placement in corn often involves banding nutrients on one side of the row, which may limit uniformity in early nutrient uptake. Two-sided banding, placing fertilizer on both sides of the seed furrow, may enhance nutrient accessibility and improve early plant growth. Liquid N fertilizers that also supply S such as UAN + ATS which can influence both N assimilation and crop vigor (Liu et al., 2020).

This study assessed the effects of two-sided banding of liquid N and S fertilizers (UAN + ATS) and spring fertilizer timing on corn performance. The objectives were to:

1. determine whether split application (starter + side-dress) improves crop response compared with applying all fertilizer as a starter or solely as a side-dress.

2. evaluate whether two-sided starter banding provides agronomic or operational advantages such as reducing equipment passes.

MATERIALS AND METHODS

The study was conducted at the Iowa State University Agricultural Engineering and Agronomy Farm in Boone, Iowa. Six fertilizer treatments were arranged in a completely randomized design (CRD) with four replications (24 plots total). Plot dimensions were 15.24 m × 4.57 m. The two treatment factors were fertilizer timing (starter vs. side-dress) and placement method (one-sided vs. two-sided banding). Treatments were:

1. 0-0_0-0: no starter and no side-dress (control).
2. ST1-0_202-0: one-sided banding of 202 kg N/ha at planting; no sidedress.
3. ST1-SD2_56-146: one-sided banding of 56 kg N/ha at planting and two-sided side-dress of 146 kg N/ha.
4. ST2-0_202-0: two-sided banding of 202 kg N/ha at planting; no side-dress.
5. ST2-SD2_56-146: two-sided banding of 56 kg N/ha at planting and two-sided side-dress of 146 kg N/ha.
6. 0-SD2_0-202: no starter and two-sided side-dress of 202 kg N/ha.

Corn was planted at 36,000 seeds/ha. Liquid fertilizer was applied as UAN + ATS at rates totaling 202 kg N /ha, corresponding to the treatment design. Biomass and grain yield were collected at R6. Data were analyzed using R version 4.3.1 (R Core Team, 2023), and treatment means were separated with Tukey's test at $p \leq 0.05$.

RESULTS AND DISCUSSION

Grain Yield

Corn grain yield showed minimal response to fertilizer placement–timing treatments (Figure 1). All fertilized treatments produced similar yields, indicating that neither two-sided banding nor split N application improved grain production compared with the one-sided starter or side-dress-only treatments. These results suggest that total N availability across the season was sufficient for achieving maximum grain yield, and that placement method did not restrict root access to N.

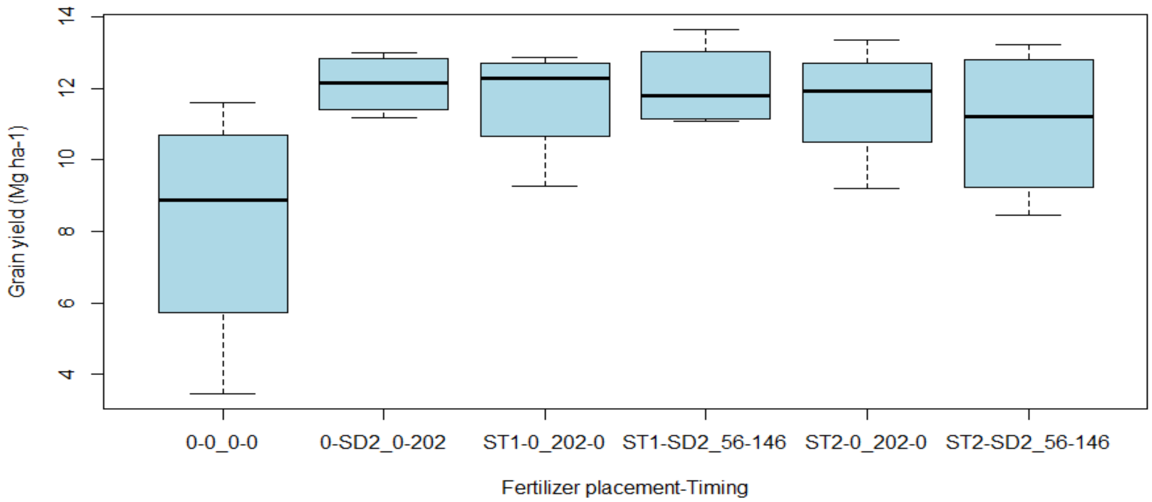

Figure 1. Corn grain yield response to fertilizer placement-timing treatment

The lack of yield differences also suggests that corn compensated for early-season variability in nutrient placement as long as adequate N was supplied later. The wet growing season may have further reduced the advantage of starter versus side-dress timing by enhancing soil N mobility.

Stover Biomass

Stover yield was significantly affected by fertilizer treatments (Figure 2). All fertilized treatments produced greater biomass than the control, demonstrating the importance of N availability for vegetative growth. Two-sided banding tended to increase stover biomass similarly to one-sided banding at comparable N rates.

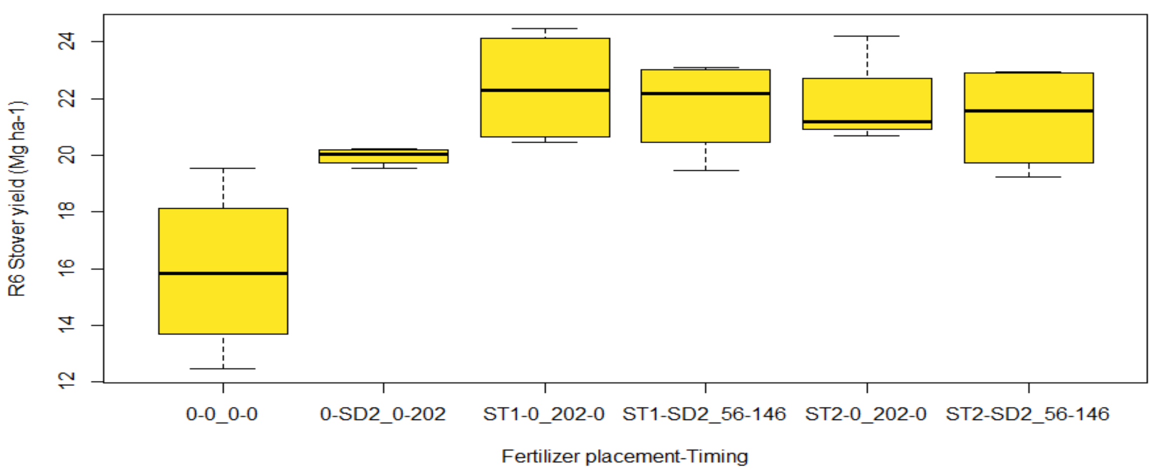

Figure 2. Effect of fertilizer placement–timing on corn stover yield.

The increased biomass under two-sided banding may reflect improved lateral nutrient distribution around the root zone, supporting more uniform early growth. However, applying all fertilizer as a side-dress did not enhance biomass relative to the control, while applying all N upfront with one-sided banding resulted in the highest stover production. Despite differences in vegetative growth, the increased biomass did not translate to grain yield improvements, a trend consistent with other N–S studies (Kovar et al., 2021; Crespo et al., 2025).

Implications

These results indicate that fertilizer placement and timing influence vegetative growth but may not impact grain yield when total N is adequate. Applying all fertilizer as a starter using a one-sided band may offer economic advantages by reducing field passes, fuel use, and labor: an important considerations in Midwestern corn production systems.

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INDUSTRIAL HEMP RESPONSE TO NITROGEN APPLICATIONS IN MISSOURI

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ABSTRACT

Industrial hemp (*Cannabis sativa* L.) is gaining attention as a multipurpose crop for fiber, grain, and cannabinoids, but region-specific guidelines on nitrogen (N) management are limited. Field experiments were conducted at two locations (Albany, Novelty) in northern Missouri in 2024 & 2025 to evaluate the effects of N applications on industrial hemp production. Experiments were laid in a randomized complete block design with a split-plot arrangement and four replications. Main plots included four varieties (Futura 83, Orion 33, Puma, and Yuma), and subplots consisted of five N rates (0, 40, 80, 120, and 160 lb N ac-^{1}). In 2024, the plant population at Novelty was highest in the control and decreased with increasing N, while in 2025, N did not affect population. Puma and Yuma consistently produced the tallest plants and thickest stems across both locations, with plant height and stem diameter increasing with N rate up to 160 lb N ac^{-1} at Novelty (2024-2025) and up to 80 lb N ac^{-1} at Albany in 2025. At Novelty (2024), maximum biomass was recorded at 80-120 lb N ac^{-1}. In 2025, biomass increased to 160 lb N ac^{-1} at Novelty. At Albany (2025), biomass yield increased from 40-160 lb N ac^{-1} but was comparable. Puma constantly produced the highest biomass yield, followed by Yuma. At Novelty, grain yield increased with N up to 120 lb N ac^{-1} in 2024 and 160 lb N ac^{-1} in 2025. At Albany, grain yield was maximum at 160 lb N ac^{-1}. The linear-plateau model fit the 2024 Novelty data best (R^2 = 0.59), whereas at Albany, yield showed no response to N (R^2 < 0.01). This research emphasizes the importance of optimizing nitrogen (N) and variety selection to maximize yield potential under variable soil and climatic conditions in Missouri, while underscoring the need for site-specific nutrient management approaches to ensure sustainable hemp production.

INTRODUCTION

Nitrogen (N) management in industrial hemp (*Cannabis sativa* L.) production remains difficult due to variations in soil properties, climatic conditions, and cultivar-specific nutrient demands. Nitrogen is essential for chlorophyll synthesis, enzymatic activity, and photosynthetic activity, and influences crop growth and yield (Campiglia et al., 2017). Previous studies have reported that N supply strongly affects hemp productivity (Aubin et al., 2015; Yang et al., 2021; Kaur et al., 2023). The optimal N rate varies significantly across different environments. Campiglia et al. (2017) observed a 35-40% increase in fiber yield when N rates increased from 0 to 110 lb ac^{-1} under Mediterranean conditions, while Aubin et al. (2020) reported diminishing returns beyond 90 lb N ac^{-1} for Canadian dual-purpose hemp cultivars.

Excessive N application usually delays flowering, enhances vegetative growth, and reduces fiber quality (Prade et al., 2011; Yang et al., 2021). In contrast, inadequate N supply limits canopy development and reduces grain and biomass accumulation.

Papastylianou et al. (2023) reported that AE and apparent N recovery efficiency in dual-purpose hemp increased up to 110 lb N ac^{-1} but declined at higher rates due to reduced recovery and excess nitrate accumulation. Similarly, Vera et al. (2010) and Aubin et al. (2015) reported yield plateaus and declining efficiency beyond 110-135 lb N ac^{-1}.

These findings highlight the complex interaction between variety, N, and environmental factors, suggesting that uniform fertilizer recommendations are impractical. Region-specific studies are needed to identify the agronomic optimum nitrogen rate (AONR) for maximizing yield and NUE under local soil and climatic conditions. Therefore, this study was conducted to evaluate the response of industrial hemp to five N rates across two locations in Missouri, having different soil properties and rainfall patterns, to determine optimum N rates and assess varietal responses under Missouri's production systems.

MATERIALS AND METHODS

Field experiments were conducted in 2024 and 2025 at the University of Missouri's Lee Greenley Jr. Memorial Research Farm near Novelty, MO, and the Hundley-Whaley Extension and Education Center near Albany, MO. The dominant soil series at Novelty and Albany was Leonard silt loam and Grundy silt loam, respectively. The Leonard silt loam is a poorly drained soil with a slope ranging from 1% to 6%. The Grundy silt loam is somewhat poorly drained, with high runoff properties, and has a slope ranging from 2% to 5%.

The experiments were designed as a randomized complete block with a split-plot arrangement and four replications. The main plots were four industrial hemp varieties, including 'Puma', 'Yuma', 'Orion 33', and 'Futura 83'. The subplots included N application rates (0, 40, 80, 120, and 160 lb N ac^{-1}) applied using SuperU® fertilizer source. The sub-plot size was 10 x 20 ft. Each plot had four rows of industrial hemp planted at a row spacing of 30 inches, with a seeding rate of 20 lb ac^{-1} at Novelty and 40 lb ac^{-1} at Albany in 2024. Seeding rate was 40 lb ac^{-1} at both locations in 2025. Plant measurements included plant population, plant height, and stem diameter. At physiological maturity, hemp plants were hand-harvested from a 10-ft length of the second row in each subplot, and fresh biomass weights were recorded. Plants were threshed (ALMACO BT-14 belt thresher, Nevada, IA) to separate seeds from stalks. Subsamples of the stalks were air-dried to determine their moisture content and calculate the dry biomass yield. Seeds were dried, cleaned, and weighed to determine grain yield. The grain yields were adjusted to 8% moisture before data analysis. The data were analyzed using the GLIMMIX procedure in SAS, and means were compared at a significance level of $p = 0.05$. Nonlinear regression was performed using linear and Quadratic plateau models to fit grain yield responses to N using RStudio v4.5.1.

RESULTS AND DISCUSSION

Plant Population: In 2024 at Novelty, control (0 lb N ac^{-1}) produced the highest population, statistically comparable to 40 and 80 lb N ac^{-1}. Futura 83 had the highest plant population, which was significantly higher than Yuma and Puma (Table 1). At Albany, plant population was affected only by variety in 2024, and Futura 83 had the highest plant population among all other varieties (Table 2). In 2025, N did not affect plant population at either location. , 'Puma' had the best establishment of other varieties at Novelty (Table 3). The plant population did not vary significantly by variety or N at Albany in 2025 (Table 4).

Plant Height: In 2024 and 2025, Puma and Yuma varieties produced the tallest plants at Novelty, whereas Puma reached to maximum height at Albany in both years. Plant height increased with N rate and was maximum at 120 lb N ac^{-1} at Novelty in 2024. Maximum height was observed at 160 lb N ac^{-1} at Novelty and 80 lb N ac^{-1} (statistically similar to 120 & 160 lb N ac^{-1}) at Albany in 2025.

Stem Diameter: Yuma produced the thickest stems at Novelty, while Puma and Yuma had bigger stem diameters at Albany in 2024 and 2025 (Tables 1-4). A significant variety x N interaction was observed at Novelty in 2024, where 'Puma' and 'Yuma' showed maximum stem thickness at 120-160 lb N ac^{-1} (data not presented). N application increased stem thickness up to 160 lb N ac^{-1} at Novelty in 2024 & 2025 (Table 1 & 3) and 80 lb N ac^{-1} at Albany in 2025 (Table 4).

Biomass and Grain Yield: In 2024 at Novelty, the highest biomass yield was recorded at 120 lb N ac^{-1}, statistically similar to 80 lb N ac^{-1}, while 160 lb N ac^{-1} reduced biomass yield. Puma produced the highest biomass at Novelty, about 50% greater than Futura 83 and Orion 33 in 2024. At Albany, Puma, Yuma, and Futura 83 had similar biomass yields, with 'Orion 33' yielding about 50% less biomass in 2024. In 2025, variety and N significantly influenced biomass yield at both locations. At Novelty, Puma and Yuma produced the highest biomass yield, and the highest biomass yield was recorded at 160 lb N ac^{-1} (Table 3). At Albany in 2025, maximum biomass was recorded at 120 and 160 lb N $ac^{-1,}$ which was greater than the non-treated control but statistically comparable to the 40 and 80 lb N ac^{-1}. Puma again outperformed all varieties in biomass production by giving 2–3 times more biomass yield than 'Futura 83' and 'Orion 33' (Table 4).

In 2024, grain yield increased with N up to 120 lb ac^{-1} at Novelty (Table 1). At Albany, Futura 83 had higher grain yield, nearly double to Orion 33 in 2024 (Table 2). In 2024, Linear Plateau (LP) provided a good fit (R^2 = 0.59) compared to QP (R^2 = 0.58), defining the agronomic optimum nitrogen rate (AONR) near 120 lb N ac^{-1} at Novelty. The yield at AONR was 1,621 lb ac^{-1} at Novelty in 2024. Fiber-type varieties ('Puma' and 'Yuma') did not produce grains due to late maturity in Missouri. In contrast, grain yield showed no significant response to N fertilization at Albany (Figure 1b). Both the LP and QP models exhibited very low coefficients of determination ($R^2 < 0.01$), suggesting that the N rate had a minimal influence on grain yield.

In 2025, grain yield was significantly affected by N at Novelty (Table 3). Yield increased with N rate, reaching a maximum of 704 lb ac^{-1} at 160 lb N ac^{-1}, about five times higher than the control and double to the yield obtained at 80-120 lb N ac^{-1}. Models did not converge for the 2025 data.

Table 1. Main effects of variety and nitrogen rate on plant population, height, stem diameter, aboveground biomass, and grain yield at Novelty in 2024. Means within a column followed by different letters are significantly different at $\alpha = 0.05$. Underlined p-values indicate significant fixed effects.

Variety	N rate	Plant Population	Plant height	Stem diameter	Aboveground Biomass	Grain yield
	lb ac^{-1}	Plants ac^{-1}	in	mm	lb ac^{-1}	lb ac^{-1}
Futura 83		117394 a	37 b	8.5 c	6134 c	1316
Orion 33		109989 a	32 c	7.6 c	4855 d	1153
Puma		62257 b	52 a	15.7 b	10421 a	-
Yuma		40075 c	51 a	17.4 a	9070 b	-
	0	96304 a	39 c	9.5 d	5402 c	723 c
	40	89329 ab	42 b	11.9 c	7768 b	994 bc
	80	84670 ab	44 ab	12.7 bc	8056 ab	1212 b
	120	75413 bc	45 a	13.3 b	9221 a	1623 a
	160	66429 c	44 a	14.6 a	7655 b	1619 a
Source of Variation		---*P-values*-----------------------				
Variety		<.0001	<.0001	<.0001	<.0001	0.0910
N		0.0018	<.0001	<.0001	<.0001	<.0001
N*variety		0.3031	0.6053	0.0494	0.9260	0.0341

Table 2. Main effects of variety and nitrogen rate on plant population, height, stem diameter, aboveground biomass, and grain yield at Albany in 2024. Means within a column followed by different letters are significantly different at α = 0.05. Underlined p-values indicate significant fixed effects.

Variety	N rate	Plant Population	Plant height	Stem diameter	Aboveground Biomass	Grain yield
	lb ac^{-1}	Plants ac^{-1}	in	mm	lb ac^{-1}	lb ac^{-1}
Futura 83		48134 a	45 c	16.2 b	8835 a	1015 a
Orion 33		37272 b	49 ab	13.4 c	5782 b	569 b
Puma		29403 bc	51 a	28.6 a	11469 a	-
Yuma		24829 c	48 bc	28.4 a	10887 a	-
	0	37026	47	21.9	9232	777
	40	37571	48	20.0	9179	739
	80	36209	49	21.6	9882	827
	120	35209	48	22.8	8142	943
	160	28533	47	21.8	9783	673
Source of Variation		---*P-values*----------------------------				
Variety		<.0001	0.001	<.0001	0.0004	0.0004
N		0.2291	0.5564	0.0521	0.8092	0.6242
N*variety		0.6659	0.3935	0.5801	0.5349	0.2970

Table 3. Main effects of variety and nitrogen rate on plant population, height, stem diameter, aboveground biomass, and grain yield at Novelty in 2025. Means within a

column followed by different letters are significantly different at α = 0.05. Underlined p-values indicate significant fixed effects.

Variety	N rate	Plant Population	Plant height	Stem diameter	Aboveground Biomass	Grain yield
	lb ac^{-1}	Plants ac^{-1}	in	mm	lb ac^{-1}	lb ac^{-1}
Futura 83		83417 b	76 a	6.7 bc	3698 bc	390
Orion 33		54885 c	61 b	5.1 c	2636 c	301
Puma		122839 a	84 a	8.4 ab	6791 a	-
Yuma		40293 c	78 a	10.1 a	5168 ab	-
	0	71329	53 c	4.7 c	1771 c	137 c
	40	72963	61 c	5.7 c	2359 c	168 bc
	80	71874	77 b	8.1 b	4852 b	368 b
	120	75686	82 b	8.2 b	5742 b	351 b
	160	84942	99 a	11.3 a	8143 a	704 a
Source of Variation		------------------------------------*P-values*-----------------------------------				
Variety		<.0001	0.0007	<.0001	<.0001	0.1741
N		0.5889	<.0001	<.0001	<.0001	<.0001
N*variety		0.1975	0.4692	0.7377	0.4547	0.7520

Table 4. Main effects of variety and nitrogen rate on plant population, height, stem diameter, aboveground biomass, and grain yield at Albany in 2025. Means within a column followed by different letters are significantly different at α = 0.05. Underlined p-values indicate significant fixed effects.

Variety	N rate	Plant Population	Plant height	Stem diameter	Aboveground Biomass	Grain yield
	lb ac^{-1}	Plants ac^{-1}	in	mm	lb ac^{-1}	lb ac^{-1}
Futura 83		51375	59 c	6.7 b	3326 b	266
Orion 33		65050	55 c	5.3 b	2498 b	238
Puma		61855	96 a	11.9 a	8582 a	-
Yuma		33106	80 b	12.5 a	5042 b	-
	0	46101	48 b	6.3 b	2079 b	76
	40	49335	63 b	8.5 ab	4750 ab	214
	80	52998	87 a	10.7 a	4764 ab	242
	120	64977	85 a	10.2 a	6763 a	319
	160	50820	80 a	9.7 a	5955 a	407
Source of Variation		---*P-values*----------------------				
Variety		0.0652	<.0001	<.0001	0.0002	0.7286
N		0.7180	<.0001	0.0042	0.0334	0.1260
N*variety		0.9679	0.4803	0.3578	0.6216	0.9243

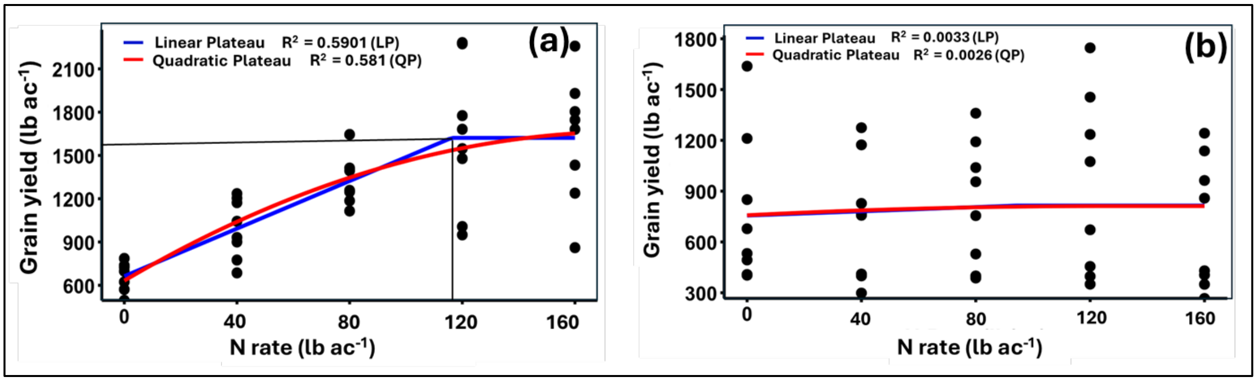

Figure 1. Relationship between nitrogen (N) rate and grain yield of industrial hemp at Novelty (a) and Albany (b) in 2024, fitted using Linear Plateau (LP) and Quadratic Plateau (QP) models.

CONCLUSION

Our results demonstrated clear varietal and N rate differences in industrial hemp growth and yield under Missouri conditions. Nitrogen significantly enhanced plant growth up to 160 lb N ac^{-1} at Novelty and 80-120 lb N ac^{-1} at Albany. Nitrogen application at a rate higher than 160 lb ac^{-1} may result in increased growth and yield at Novelty. Among the tested cultivars, Puma and Yuma consistently produced the tallest plants, thickest stems, and highest biomass, while ‘Futura 83’ excelled in grain yield across both locations and years. Puma and Yuma performed best for fiber and biomass production, whereas Futura 83 proved most suitable for grain yield. Adopting moderate N rates within the identified optimum range offers a balanced strategy for maximizing yield potential and nitrogen efficiency across Missouri’s diverse growing environments.

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