



FINAL REPORT

PROJECT TITLE: Precision Irrigation and Nitrogen Management for Enhancing Water-Nitrogen Use Efficiency

PROJECT NUMBER: 6121-24DD

PRINCIPAL INVESTIGATOR AND CO-INVESTIGATOR(S): Dr. Vasudha Sharma, University of Minnesota

ABSTRACT:

This project addressed the dual challenges of nitrate leaching and inefficient water use in Minnesota's irrigated corn systems. Conducted over the 2022, 2023, and 2024 growing seasons at the Sand Plain Research Farm, the study evaluated four management strategies combining precision and conventional nitrogen and irrigation techniques. The Precision Nitrogen Management plus Variable Rate Irrigation (PNM+VRI) treatment consistently produced the highest profitability while maintaining yields, demonstrating improved nitrogen use efficiency (NUE) and reduced nitrate leaching. The outcomes provide a science-based framework to enhance productivity and sustainability in corn production systems.

INTRODUCTION:

Minnesota's irrigated agricultural systems, particularly in the Central Sands region, are facing increasing challenges from two interconnected environmental issues: nitrate contamination of groundwater and unsustainable water use. These challenges are especially acute in coarse-textured soils, which are prone to rapid drainage and low nutrient retention. As corn remains a dominant crop in the region, improving the efficiency of water and nitrogen use is critical for both agricultural productivity and environmental protection.

Traditional irrigation and nitrogen management practices, which apply water and nutrients uniformly across fields, often ignore the spatial variability of soil and crop conditions. This can result in overapplication in some zones, leading to increased nitrate leaching, and underapplication in others, leading to water stress and reduced yields. Precision agriculture technologies, particularly Variable Rate Irrigation (VRI) and Variable Rate Nitrogen (VRN) application, offer promising tools to tailor inputs based on site-specific conditions. These technologies have the potential to reduce environmental impacts while maintaining or improving crop yields and farm profitability.

Despite this promise, limited real-world data exists on the performance of these technologies in Minnesota. Most studies on VRI and VRN have been simulation-based or conducted in other

regions with different soil and climate conditions. Additionally, little is known about how these technologies interact under real field conditions or how they perform across varying rainfall years—a key concern given the increasing frequency of weather extremes due to climate change.

To address these gaps, this study was initiated in 2022 at the Sand Plain Research Farm (SPRF) in Becker, Minnesota. Over three growing seasons (2022–2024), we evaluated the agronomic, environmental, and economic outcomes of integrating precision irrigation and nitrogen management strategies in continuous corn production systems. The study was designed to capture real-world variability and operational constraints, using a factorial combination of irrigation (uniform vs. variable rate) and nitrogen (farmer practice vs. precision management) strategies.

The overarching goal of this project was to generate actionable, science-based data to inform best practices for sustainable corn production in Minnesota. By combining advanced remote sensing (UAV-based thermal and multispectral imagery), in-field sensors (soil moisture and lysimeters), and geospatial analysis, we aimed to provide a robust understanding of how integrated precision management affects yield, water use efficiency, nitrogen use efficiency, and nitrate leaching under real-world weather conditions. The results not only inform technical recommendations but also address the economic feasibility of precision agriculture adoption, a key concern for growers making long-term investment decisions.

OBJECTIVE AND GOAL STATEMENTS

1. Quantify the impact of VRI and VRN on nitrate leaching, yield, evapotranspiration, and nutrient-use efficiencies.
2. Compare economic returns of precision versus conventional nitrogen and irrigation strategies.
3. Disseminate results to farmers and stakeholders via field days, scientific publications, and Extension programming.

MATERIALS AND METHODS

The study was conducted over three consecutive growing seasons (2022–2024) at the Sand Plain Research Farm (SPRF) in Becker, Minnesota—an ideal site for irrigation research due to its coarse-textured soils, existing variable rate irrigation (VRI) infrastructure, and susceptibility to nitrate leaching. The research site encompasses approximately 10 hectares and represents the Central Sands region, where groundwater vulnerability and irrigation dependence converge to create a critical need for more efficient and environmentally sound management practices.

Experimental Design

Irrigation Strategies:

- Uniform Rate Irrigation (URI) – a conventional approach applying the same amount of water across all plots.
- Variable Rate Irrigation (VRI) – water application adjusted spatially based on real-time and model-informed management zones.

Nitrogen Management Strategies:

- Farmer Practice (FP) – 220 lb N/ac split between pre-plant and sidedress at V8 stage.

- Precision Nitrogen Management (PNM) – reduced pre-plant N (20–50% of FP) with variable-rate sidedress based on crop status.

The four treatment combinations—PNM+VRI, PNM+URI, FP+VRI, and FP+URI—were replicated across field blocks (Figure 1 and Figure 2). Each plot was subdivided into 70 ft × 100–160 ft management zones for precision application and analysis. Spatial variability in soil characteristics was mapped using Veris EC sensors and high-resolution LiDAR elevation data.

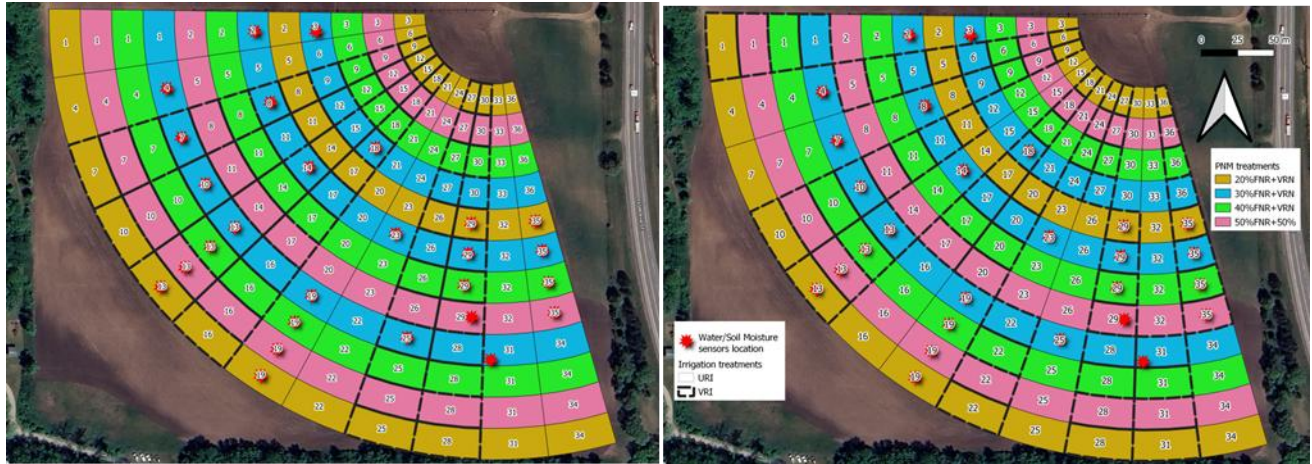


Figure 1. Experimental designs of the precision N management and variable rate irrigation study in 2022 (left) and 2023-2024 (right) at the Sand Plain Research Farm in Becker, Minnesota. Sensor locations were shown as red stars.

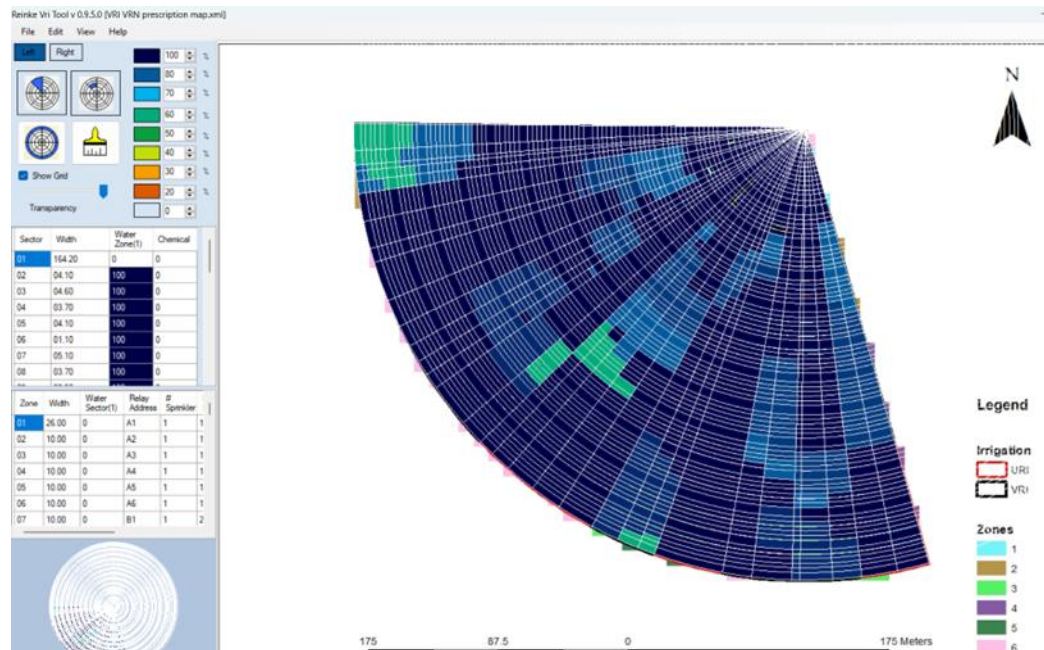


Figure 2. Irrigation prescription map created using Reinke VRI tool. The uniform rate irrigation (URI) plots will get 100% uniform irrigation. The VRI plots will get irrigation based on the management zones. Zone 1: 100% irrigation, Zone 2: 80% irrigation, Zone 3: 95% irrigation, Zone 4: 89% irrigation, Zone 5: 60% irrigation and Zone 6: 100% irrigation. (2024)

Instrumentation and Data Collection

Soil Moisture Monitoring:

Neutron access tubes and capacitance sensors were installed at multiple depths to continuously monitor volumetric soil moisture. This data informed both irrigation scheduling and water balance calculations.

Lysimeter Installation:

Suction cup lysimeters were placed at 1.2 m depth in selected plots to capture nitrate-N leachate below the root zone. Water samples were collected weekly throughout the growing season and analyzed for nitrate concentration.

Remote Sensing and UAV Flights:

UAV flights were conducted 6–8 times each season using SENTERA 6X multispectral and thermal sensors. Imagery was processed to derive crop water stress indices (CWSI), NDVI, and other vegetation indices used for both irrigation decision-making and nitrogen status assessment.

Nitrogen Application Strategy:

For FP plots, N was applied at standard rates (50% pre-plant and 50% sidedress). For PNM plots, pre-plant applications ranged from 20–50% of FP, and in-season variable rate nitrogen (VRN) applications were guided by UAV imagery and growth stage diagnostics (typically V8–V10).

Plant and Soil Sampling:

Plant samples were collected at V8 and R6 stages to measure total nitrogen uptake. Soil samples were taken before planting and after harvest at 0–30 cm and 30–60 cm depths to assess nitrate concentrations. Grain yield and grain nitrogen content were determined via plot combine harvest and laboratory analysis.

Water and Nitrogen Use Calculations:

- **Evapotranspiration (ET)** was calculated using a water balance approach integrating soil moisture, rainfall, and irrigation inputs.
- **Water Use Efficiency (WUE)** was computed as grain yield per inch of water used.

$$WUE = Y/ET \text{ (kg mm}^{-1}\text{)}$$

where Y is grain yield, and ET is evapotranspiration calculated from water balance method

- **Nitrogen Use Efficiency (NUE)** was calculated as yield per unit of nitrogen applied.

$$NUE = Y/N \text{ (kg kg}^{-1}\text{)}$$

where Y is yield and N is the total N rate applied

Economic Analysis:

Input costs for nitrogen (based on annual price) and irrigation (based on per-acre-inch cost) were recorded. Gross returns were calculated from grain yield using market prices (\$6/bu in 2022, \$5.50/bu in 2023–24), and net profitability was determined by subtracting total input costs. Economic comparisons were made between treatments and against the baseline (FP+URI).

Weather Monitoring and Rainfall Events

On-site weather stations provided rainfall and temperature data. The three years exhibited contrasting conditions: 2022 was a moderate rainfall year (16.6 in), 2023 was dry (10.6 in), and 2024 was abnormally wet (24.8 in) (Figure 3). These conditions enabled evaluation of treatment performance under varied climate scenarios.

RESULTS AND DISCUSSION

Across three years, VRI consistently reduced irrigation volumes and costs, while PNM improved nitrogen use efficiency. In 2023, PNM+VRI delivered both the highest yields and profit margins. In contrast, 2024's excessive rainfall reduced irrigation differences among treatments but still showed nitrate leaching benefits for PNM+VRI. Economic analyses confirmed profitability gains of up to \$107/ac for PNM+VRI compared to conventional practices. These findings underscore the resilience of integrated precision strategies under variable weather conditions.

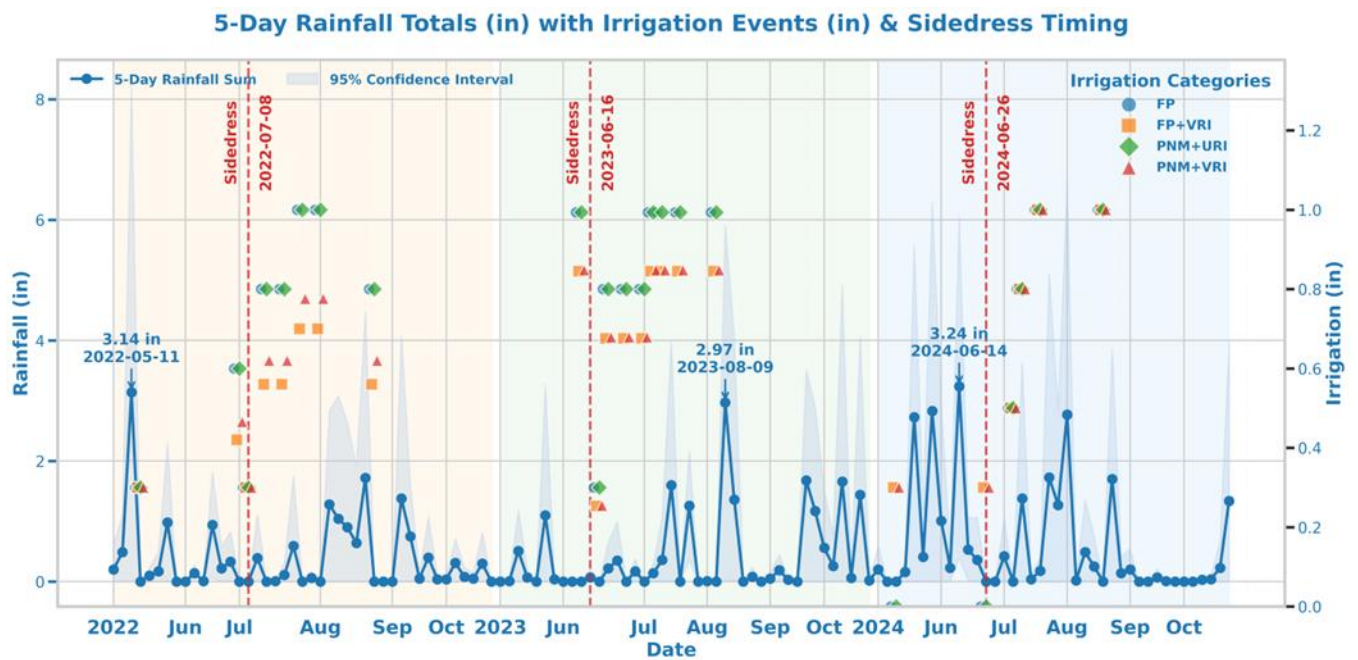


Figure 3. 5-Day Rainfall totals with irrigation events and Sidedress timing

Table 1 summarizes three years (2022–2024) of nitrogen (N) and irrigation treatments, associated costs, yields, and overall profitability under four strategies: FP, FP+VRI, PNM+URI, and PNM+VRI. **Nitrogen costs** were $\$0.86 \text{ lb}^{-1}$ in 2022 and $\$0.68 \text{ lb}^{-1}$ in 2023–2024. **Yield income** was $\$6 \text{ bu}^{-1}$ in 2022, and $\$5.50 \text{ bu}^{-1}$ in 2023–2024. **Irrigation expenses** were approximately **\$10 per acre-inch**. Economic return was computed for each transect by subtracting combined N and irrigation costs from the yield income. Profit was then compared against the FP grid within each block, ensuring a consistent assessment of economic performance. This approach demonstrates how precision techniques can enhance profitability under varying N and irrigation strategies.

Table 1. Summary table of information related to field, management, and results from precision nitrogen and irrigation management on-farm trial by different treatments (lb N/ac) at the Becker field trial.

Treatment	Avg. Preplant N Rate (B)	Avg Sidedress N Rate (C)	Total N (D = B+C)	Avg Irrigated Water (E)	Avg Yield (F)	Avg Applied N cost (G=D*price)	Irrigation cost (H = E *Price)	Yield income (J = F *Price)	Profit (K = J- H-G)	Profit gain/loss compared to FP	Nitrogen Use Efficiency	Water Use efficiency
	----- (lb N/ac) -----			(inches)	(bu/ac)	----- (\$/ac) -----				(Yield lb/ac / Applied N lb/ac) (%)	(Yield bu/ac / WB_ET in) (bu/ac-in)	
2022												
FP	103	120	223	13	173	191	131	863	541	0	43.33	14
FP+VRI	105	116	221	11	162	190	105	884	589	48	41.00	17
PNM+URI	68	122	189	13	168	163	131	920	626	85	49.97	13
PNM+VRI	68	124	192	11	163	165	110	1017	742	201	48.01	12
2023												
FP	98	98	196	6	163	138	59	975	778	0	46.36	12
FP+VRI	98	98	196	7	180	144	67	1082	872	93	51.45	10
PNM+URI	59	99	158	7	175	132	71	1051	849	71	62.75	10
PNM+VRI	59	98	157	6	174	127	65	1043	851	72	63.30	13
2024												
FP	83	114	198	10	158	135	96	866	635	0	44.55	9
FP+VRI	83	114	198	8	160	134	81	879	663	28	45.17	10
PNM+URI	77	114	190	10	164	129	96	900	674	39	48.24	8
PNM+VRI	77	115	192	8	163	131	81	896	684	49	47.66	9
Averaged (2022-2024)												
FP	95	111	206	10	164	154	96	902	652	0	44.75	12
FP+VRI	95	109	205	8	167	156	85	948	708	56	45.87	12
PNM+URI	68	112	179	10	169	141	99	957	716	65	53.65	10
PNM+VRI	68	112	180	9	167	141	86	986	759	107	52.99	11

WB_ET stands for evapotranspiration, calculated from the Water balance model.

Figure 4 summarizes the average yield, profit, N costs, irrigation expenses, and yield income for the various irrigation (URI and VRI) and N treatments for the three growing seasons (2022-2024). In 2024 (24.8 in, wettest year), ample rainfall lowered irrigation needs, yet VRI still cut irrigation costs from about \$39 ac⁻¹ to \$33 ac⁻¹, and PNM maintained a slightly better yield (163 bu ac⁻¹) than Farmer Practice, demonstrating that precision nutrient and irrigation management remains advantageous even under abundant rainfall. In 2023 (10.6 in, driest year), VRI-based treatments (FP+VRI, and PNM+VRI) leveraged targeted water use to reach yields up to ~186 bu ac⁻¹ in average, outpacing non-VRI methods; precise irrigation and lower nitrogen costs further boosted profitability. By comparison, 2022 (16.6 in, near average) required moderate irrigation, yet both PNM+URI and PNM+VRI again surpassed FP in yield and profit, underscoring that precision approaches consistently provide benefits across varying rainfall conditions. **Overall, The PNM + VRI treatment consistently outperformed other treatments, producing a relative economic profit of \$107 ac⁻¹ higher than FP (\$759 ac⁻¹ vs \$652 ac⁻¹) with similar grain yield (167 bu ac⁻¹ vs 163 ac⁻¹), demonstrating its ability to improve economic returns with similar yield.**

VRI consistently had lower irrigation costs than URI across all treatments, demonstrating their water resource management efficiency. Nitrogen cost was lowest for the PNM treatments, particularly under VRI, indicating the possibility of cost reductions with lower N application rates.

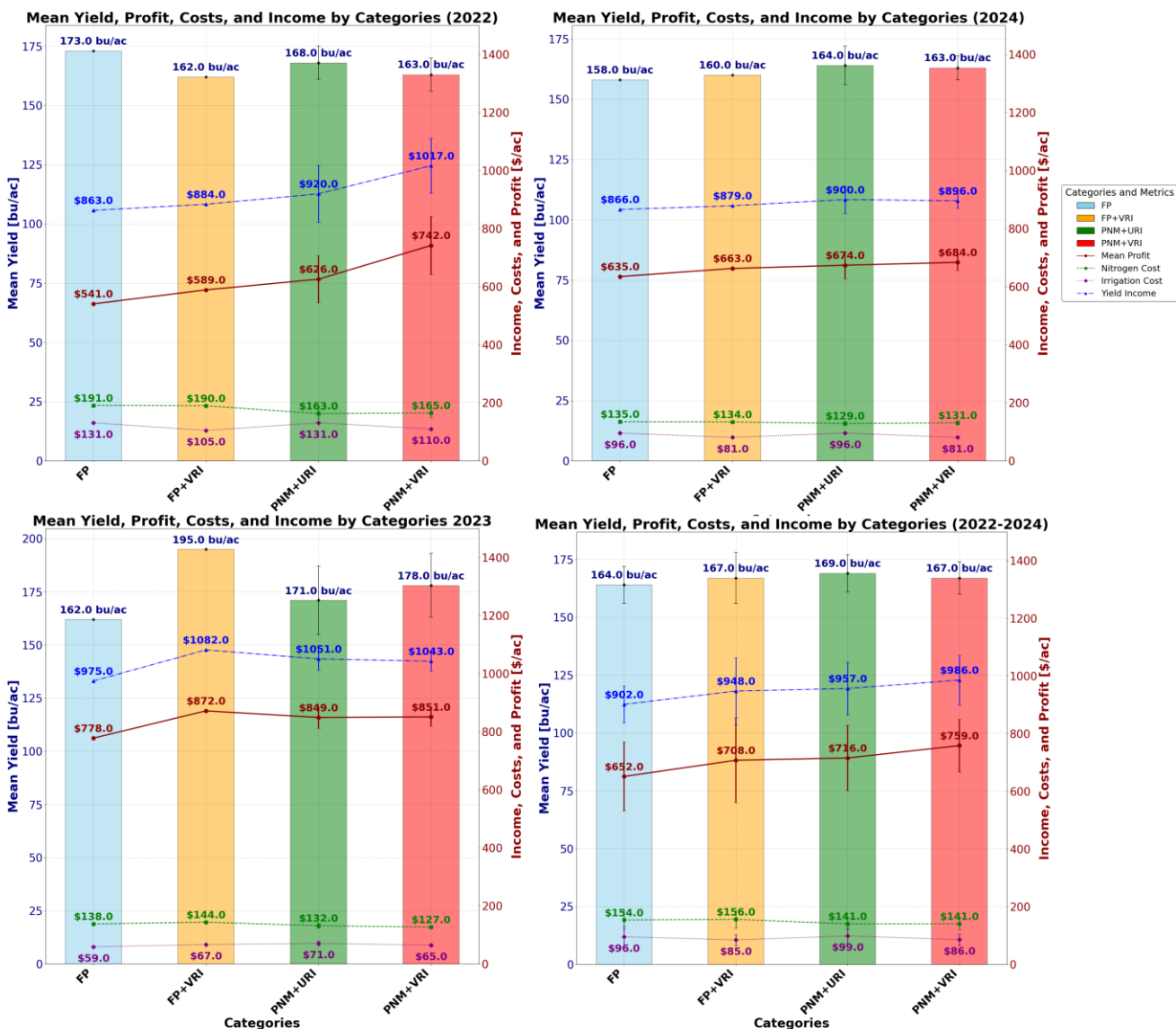


Figure 4: Mean Yield, Profit, Costs, and Income by Categories 2024.

Figure 5 shows the link between NUE and WUE with different irrigation and N treatments. In 2022 with moderate rainfall (16.6in rainfall), PNM improved NUE and VRI improved WUE, nevertheless, no single treatment optimized both. In 2023 with severe water stress (4.5in rainfall), PNM + VRI was the best for both NUE and WUE. In 2024 with excessive rainfall (10.6 in rainfall), VRI impact on WUE was reduced as large rainfall events reduced the opportunity for irrigation optimization. PNM still achieved NUE improvement. This shows the importance of adaptive irrigation and nutrient strategies to maximize efficiency under different climate conditions.

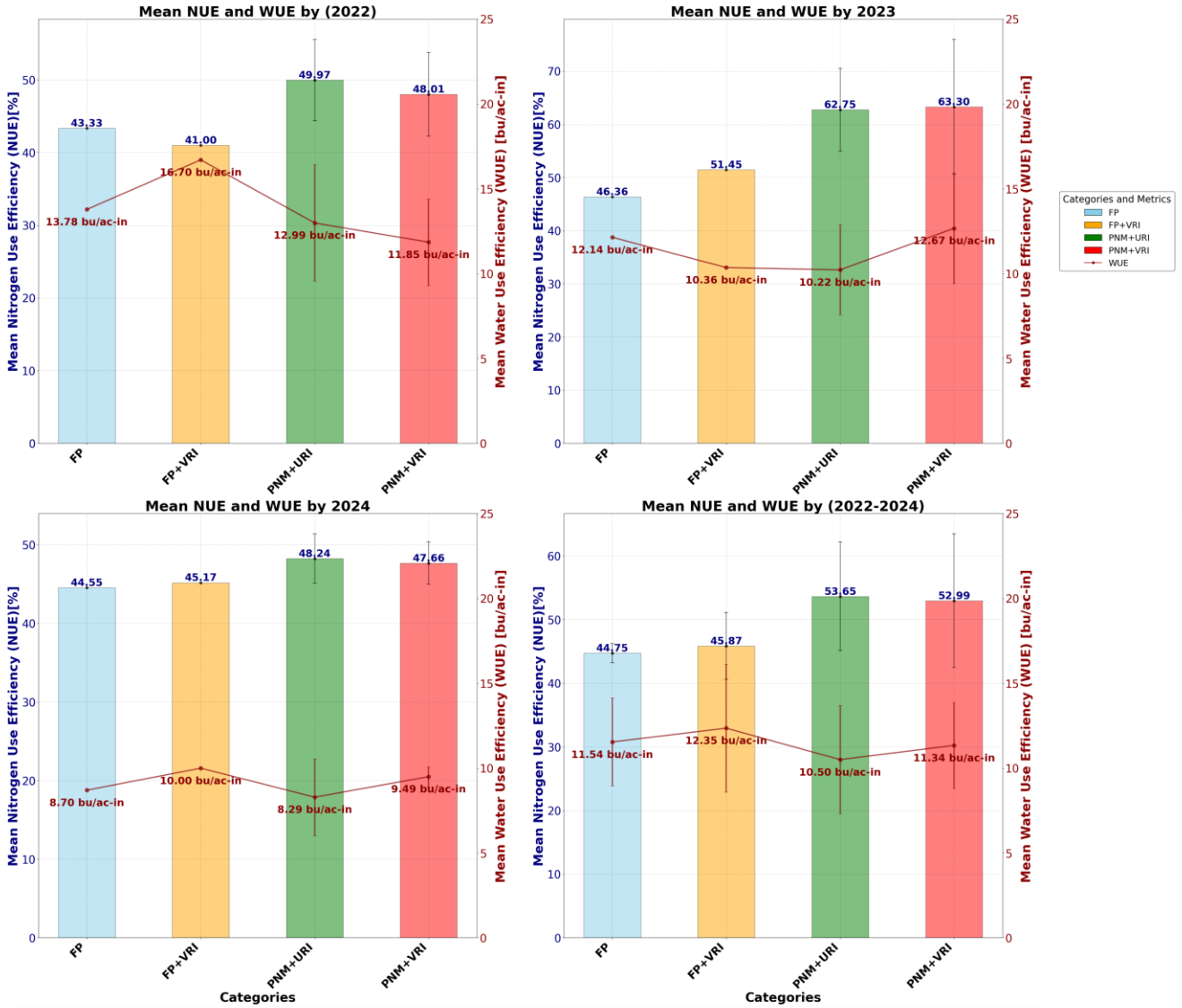


Figure 5: Mean N use efficiency (NUE) and Water Use Efficiency (WUE) by Categories 2024.

Figures 3 and 6 together provide a comprehensive overview of nitrate dynamics and the impacts of precipitation under different nitrogen and irrigation management strategies.

Figure 6 compares nitrate loads across four treatment categories: FP, FP+VRI, PNM+URI, and PNM+VRI. Over the 3-year study, the interplay between management strategies and nitrate load was influenced by both the timing of N applications and heavy rainfall. In 2022, the FP+VRI treatment had a low nitrate load of 6.2 lb ac⁻¹, yet by 2024 this rose to 17.6 lb ac⁻¹. The PNM+URI treatment increased nitrate loading from 8.9 lb ac⁻¹ in 2022 to 25.2 lb ac⁻¹ in 2024. The big jump in nitrate load in 2024 could be partly attributed to heavy rainfall events following sidedress N application. In contrast, VRI reduced nitrate loss from 17.5 lb ac⁻¹ (FP) to 10.5 lb ac⁻¹ (FP+VRI). However, the integrated approach of PNM+VRI remained the most effective strategy overall.

For 2024, with two critical rainfall events before and after the sidedress nitrogen application on June 26, 2024 likely increased soil saturation, promoting nitrate leaching, particularly in treatments with higher pre-plant nitrogen applications (e.g., FP and FP+VRI). The additional 0.3 in rainfall following the sidedress

further influenced nitrate dynamics, though precision nitrogen strategies such as PNM+VRI likely mitigated losses by aligning application timing with crop demand.

Together, these figures emphasize the importance of integrating precision nitrogen management and irrigation practices, especially in the context of unpredictable rainfall events. Treatments like PNM+VRI demonstrate their potential to reduce nitrate losses while maintaining efficiency, even under challenging weather conditions.

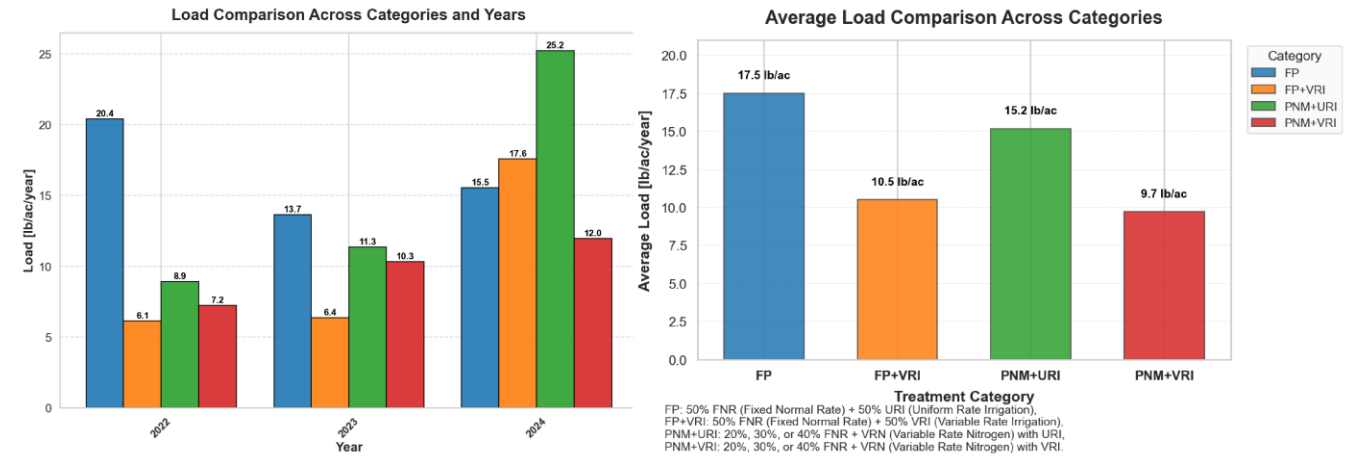


Figure 6. Nitrate leaching of different management strategies.

CONCLUSIONS The integrated approach of VRI and PNM improved water and nutrient efficiencies, sustained or enhanced yields, and reduced nitrate losses over three growing seasons. The research demonstrated the agronomic and economic value of transitioning to precision water and nutrient management in sandy, irrigated systems. Stakeholder interest and participation in field events confirmed the value of on-farm validation and outreach.

EDUCATION, OUTREACH, AND PUBLICATIONS Field Days:

At the Field Day event organized by UMN Extension on July 16, 2024, and August 10, 2023, in Becker, MN, Dr. Vasudha Sharma presented the latest developments of this project to an audience comprising farmers, industry professionals, government employees, fellow researchers, and graduate students. The presentation is entitled as:

- Sharma, V., Miao, Y., Kechchour, A., Taylor B., (2024). Precision Irrigation and Nitrogen Management Strategies in continuous corn for improved water and nitrogen use efficiencies. Field Day, UMN Extension, July 16, 2024. Becker, MN



Figure 5: Field Day event organized by UMN Extension on July 16, 2024 in Becker, MN.



Figure 7: Field Day event organized by UMN Extension on August 10, 2023 in Becker, MN.

Ph.D. student Ayoub Kechchour from University of Minnesota gave the results at the 2024 Stakeholder Meeting in Minnesota and also gave presentations (oral/poster) about the NRCS On-Farm Precision Nitrogen Project at the **academic/scientific events** listed below:

- Kechchour A, Miao Y, Sharma V, Flores A, Lacerda. (2024) Assessment of Corn Irrigation and Nitrogen Needs Through UAV -Based Multispectral and Thermal Remote Sensing of Nitrogen and Water Status. ASABE 2024 Annual International Meeting, Anaheim, California. (o)
- Miao Y, Kechchour A, Sharma V, Flores A, Lacerda L, Mizuta K, Lu J, Huang Y. (2024) in-season diagnosis of corn nitrogen and water status using UAV Multispectral and Thermal Remote Sensing. 16th International Conference on Precision Agriculture, Manhattan, KS. (o)
- Kechchour A, Vasudha Sharma, Yuxin Miao (2024) Precision irrigation and nitrogen management for enhancing water-nitrogen use efficiency. MN Ag Expo Mankato, MN (P)

- Kechchour, A., Miao, Y., & Sharma, V. (2024) Evaluating the Potential Benefit of Integrated Precision Nitrogen and Irrigation Management for Corn in Minnesota. ASA, CSSA, SSSA International Annual Meeting, San Antonio, TX. (o)
- Kechchour, A., Miao, Y., & Sharma, V. (2024) Innovative Solutions to the Water-Nitrogen-Alimentation Nexus in Minnesota. United Nations Framework Convention on Climate Change's 29th Conference of the Parties, held in Baku, Azerbaijan. (p)

Publications:

Kechchour, A Y. Miao , V. Sharma. 2025. Evaluating the Benefit of Integrated Precision Nitrogen and Irrigation Management for Maize in Minnesota. Submitted to ECPA.