160. Evaluating the benefit of integrated precision nitrogen and irrigation management for maize in Minnesota

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Abstract

The objective of this study was to quantify and evaluate the agronomic, environmental and economic benefits of integrated variable rate irrigation (VRI) and variable rate nitrogen (VRN) management of corn in a sandy field in Minnesota, USA. Over three years (2022–2024), traditional farmer practice (FP) and precision nitrogen management (PNM)+VRI reduced 80% (19.61 kg/ha vs 10.87 kg/ha, $p<0.001$, $\eta^2=30.07$) of nitrate leaching and an extra US$1900/ha in profit with keeping consistent yield level (10 599 kg/ha vs 10465 kg/ha). VRI saved water during drought (269 mm rainfall, 2023), and PNM increased nitrogen use efficiency (NUE, $p<0.001$). Precipitation variability during the growing season affected irrigation savings (15% with VRI) and nitrate leaching trend, while PNM+VRI balanced productivity and sustainability.

Keywords: in-season nitrogen management, precision nitrogen management, variable rate irrigation, variable rate nitrogen, variable rate technology

Introduction

Proper management of water and nitrogen (N) is crucial for closing the yield gap (Epule *et al.*, 2023; Mueller *et al.*, 2012) in most grain crops. N is important for improving photosynthesis, biomass accumulation and yield while boosting crop health and vegetative growth (Andrews *et al.*, 2013; Evans and Clarke, 2019). Moreover, the availability of water is a critical factor in the regulation of plant transpiration. Water deficiency can negatively impact plant growth, reduce yield and increase N losses (Tanner and Sinclair, 1983; Zhang *et al.*, 2024). There is a strong demand to simultaneously optimize both N and water management using precision agriculture technologies to achieve high crop yield and high N and water use efficiencies while protecting the environment. Significant progress has been made in developing precision N management and irrigation strategies, but studies integrating precision management of both N and irrigation have been very limited. Therefore, the objective of this study was to quantify and evaluate the agronomic, environmental and economic benefits of integrated variable rate irrigation (VRI) and precision N management (PNM) of corn (*Zea mays* L.) in a sandy field in Minnesota, USA.

Materials and Methods

Study site and experimental design

The study was conducted from 2022 to 2024 at the Sand Plain Research Farm in Becker, MN, USA (45°21′–45°25′N, 93°51′–93°55′W). This study included a center-pivot irrigation system with two irrigation treatments—uniform rate irrigation (URI) and VRI—as well as PNM, which is an in-season site-specific N management technology. The farmer practice (FP) used URI and applied farmer N rate (FNR) of 246.6 kg/ha, with 50% applied before planting and 50% applied at V8 stage. The PNM strategy applied 20% of FNR, 30%FNR and 40% FNR before planting. The FP and PNM treatments were applied in strips running across the field and replicated 3 times. These strips were divided into grids with variable lengths (approx. 21 m×7–47 m), depending on their positions in the field. The four grids next to each covering the four different N rates formed a block. At V8 stage, normalized different vegetation index (NDVI) values calculated from a PlanetScope satellite remote sensing image were used to assess corn crop growth under different preplant N rates in each block and the sidedress N rate was adjusted accordingly for the PNM treatment grids, based on a calibration strip-based PNM strategy developed for corn (Cummings *et al.*, 2021) modified for irrigation fields. These combinations resulted in four treatment groups: FP with uniform rate N(URN) and URI, FP+URI, PNM+URI and PNM+VRI. Weekly soil moisture measurements and suction cup lysimeter data were collected to monitor crop water status and nitrate leaching losses. The irrigation management assistant (IMA) tool, described by (Singh *et al.*, 2023), was employed to optimize irrigation scheduling in this study. This web-based platform integrates real-time weather data (e.g., precipitation, temperature, solar radiation) from local weather stations, soil properties (e.g., texture, water holding capacity) sourced from the gridded soil survey geographic database (NRCS Soils, 2022), and crop-specific coefficients to calculate daily crop evapotranspiration (ET_c) via the Penman–Monteith equation (Allen, 2000). For VRI, Irrigation recommendations were triggered when soil water depletion exceeded predefined thresholds (minimum allowable soil moisture), and they were dynamically adjusted for crop growth stages and soil conditions. For URI, the irrigation recommendations were following the climate demand of the field.

The experimental protocol is illustrated in the Figure 1. Each number in the figure represents a block, and every block includes all N treatments.

The agronomic benefits of VRI and PNM were assessed in terms of yield, N use efficiency (NUE) and water use efficiency (WUE). NUE was calculated using Eq. (1):

$$\mathrm{NUE} = {}^{Y}\!/_{N}\ (\mathrm{kg/kg}) \tag{1}$$

where Y is yield and N is the total N rate applied (Quemada and Gabriel, 2016).

WUE was calculated using Eq. (2):

$$\mathrm{WUE} = {}^{Y}\!/_{\mathrm{ET}}\ (\mathrm{kg/mm}) \tag{2}$$

where Y is grain yield, and ET is evapotranspiration calculate from water balance method (Stanhill, 1986).

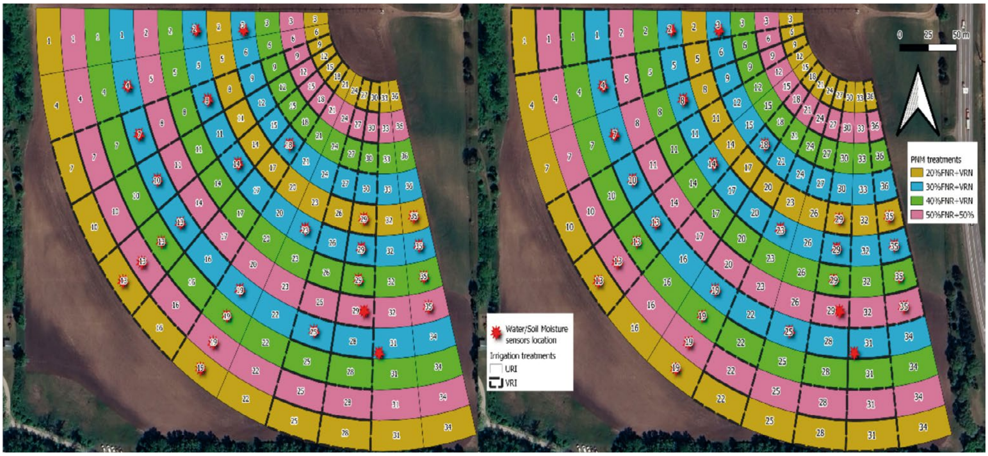

Figure 1. Experimental designs of the precision N management and variable rate irrigation study in 2022 (left) and 2023–2024 (right) at the Sand Plain Research Farm in Becker, MN, USA. Sensor locations were shown as red stars. Agronomic, economic and environmental assessment.

Economic benefits considered N costs (US$1.89/kg in 2022 and US$1.50/kg in 2023–2024), yield income (US$236.22/ton in 2022 and US$216.87/ton in 2023–2024), irrigation expenses (US$3.94/m^3) for each transect. Profit for each grid was calculated by comparing its economic return to that of the FP grid in the same block. This strategy enabled a consistent assessment of economic performance across all transects, emphasizing the advantages of precision technology under various N and irrigation management situations.

Nitrate leaching was assessed using suction cup lysimeters and a water balance model (Allan and Pereira, 1998) to calculate deep drainage (D) using Eq. (3):

$$D = P + I - \mathrm{ET} - R \pm \Delta S \tag{3}$$

where P (precipitation, measured via on-site weather stations) and I (irrigation) were field-measured, ET (evapotranspiration) was calculated following the FAO-56 method (Allan and Pereira, 1998), R (runoff) was modeled via the USDA-NRCS Curve Number approach (USDA-NRCS, 2004), and ΔS (soil water storage changes) was derived from weekly soil moisture monitoring at six depths (0.1, 0.2, 0.3, 0.4, 0.6, and 1 m).

Drainage water collected from suction cup lysimeters (Bergström and Johansson, 1991) installed at 0.9 m depth was analyzed for nitrate-N concentration (C) at 0.9 m, with leaching loads (Load = $C_{0.9} \times D$) calculated from cumulative drainage volume (D) at 0.9 m depth (Moreno *et al.*, 1996). To address outliers, the Tukey method (Tukey, 1977) was modified by extending bounds to $Q_1 - 2.5 \times \mathrm{IQR}$ and $Q_3 + 2.5 \times \mathrm{IQR}$, preserving ecologically plausible extremes while excluding laboratory artifacts.

Statistical analysis

For each of the variables of interest (grain yield, NUE, WUE, ET, profit, and nitrate-N leaching Load), the data was aggregated by treatment (FP, FP+VRI, PNM+URI, and PNM+VRI) over the years. Normality was checked using the Shapiro–Wilk test (Shapiro and Wilk, 1965) and homoscedasticity using Levene's test (Levene, 1960). When the assumptions of normality and homoscedasticity were not met (e.g. yield for PNM with VRI and nitrate-N load for most groups), non-parametric Kruskal–Wallis test was used (Kruskal and Wallis, 1952) to compare treatment effects. For the variables that had significant overall differences ($p<0.05$), post-hoc pairwise comparisons was performed using Dunn's test (Dunn, 1964) with Holm adjustment to correct for multiple comparisons (Sahai and Ageel, 2012). The effect sizes as η^2 were calculated to quantify the treatment differences. The interaction effect between treatments was determined using two-way ANOVA with an OLS regression model. A $p<0.05$ was used throughout all analysis.

Results

Overall yield and profitability performance of different management strategies

As shown in Figure 2, 2022 was a normal year with 422 mm of rain, PNM with URI irrigated 142 mm of water, and VRI irrigated 114 mm of water. Meanwhile, The FP applied 142 mm and 104 mm for URI and VRI systems, respectively. In 2023, a dry year with 269 mm of rain, overall irrigation increased, with URI applying 171mm for PNM and FP, respectively. VRI applied 173 mm and 168 mm for PNM and FP, respectively. The year 2024 was wet with 629 mm of rain, which led to a supplemental reduction of irrigation: PNM with URI Irrigated 84 mm of water, and PNM+VRI and FP+VRI irrigated 99 mm of water.

Figure 3 summarizes the grain yield, profit, N costs, irrigation expenses, and yield income for the various irrigation (URI and VRI) and PNM treatments for the three growing seasons (2022–2024). The PNM with VRI treatment consistently outperformed other treatments, generating the highest grain yield (10 464 kg/ha) and a relative economic profit (US$105/ha) higher with FP (US$1994/ha vs US$1784/ha) with grain yield of (10,599 kg/ha) and economic profit of (US$1784/ha), demonstrating its ability to optimize both agronomic and economic outcomes.

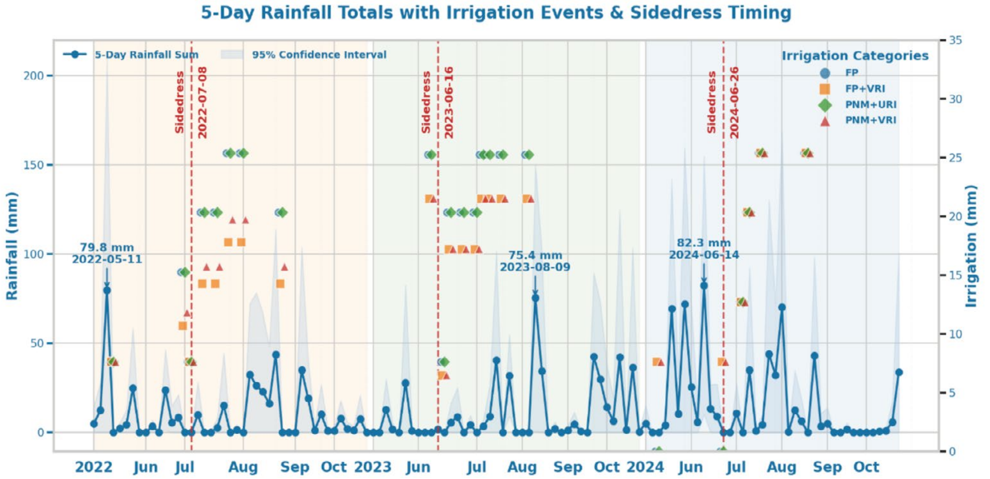

Figure 2. 5-day rainfall totals with irrigation events and sidedress timing.

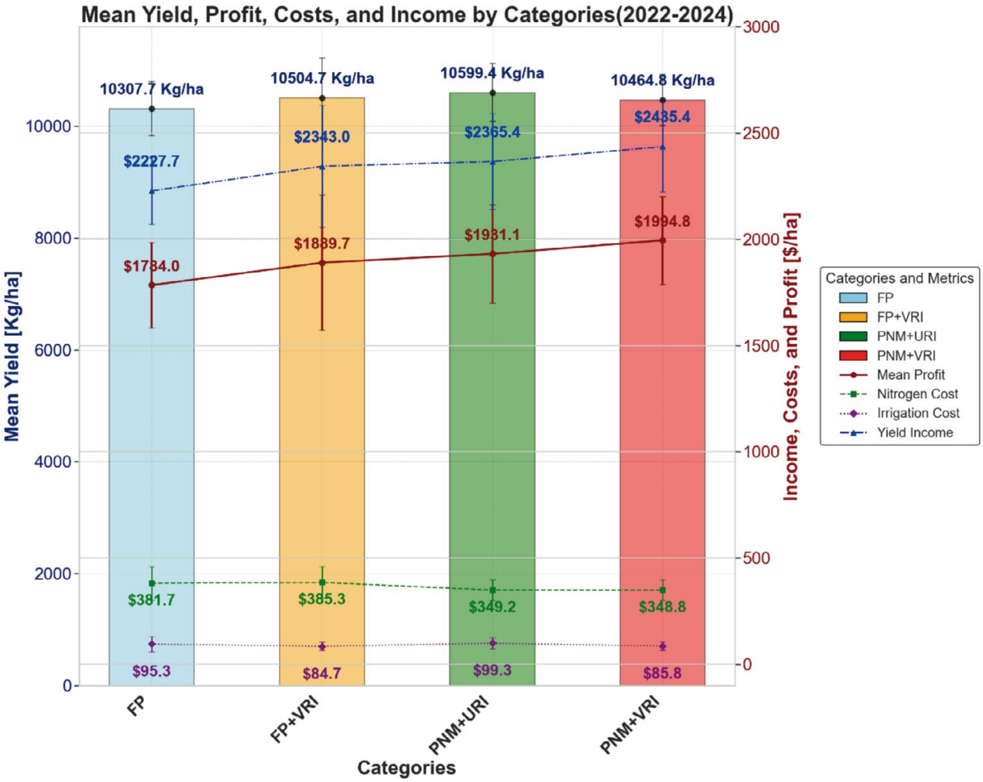

Figure 3. Mean yield, profit, costs, and income of different irrigation and N treatments across the study years (2022–2024).

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

Resource use efficiencies and nitrate leaching differences

Figure 4 shows the link between NUE and WUE with different irrigation and N treatments PNM improved NUE and VRI improved WUE, nevertheless, no single treatment optimized both. In 2023 with severe water stress (269 mm rainfall), PNM+VRI was the best for both NUE and WUE. In 2024 with excessive rainfall (629 mm), 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.

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 6.9 kg/ha, nevertheless, by 2024 this rose to 19.7 kg/ha. The PNM+URI treatment increased nitrate loading from 10 kg/ha in 2022 to 28.3 kg/ha in 2024. The big jump in nitrate load in 2024 could be attributed in part to the rainfall events after sidedress N application. In contrast, the benefit of VRI was shown by the reduction in nitrate loss from 19.6 kg/ha with FP to 11.8 kg/ha with FP+VRI. However, the integrated approach of PNM+VRI was the most effective strategy.

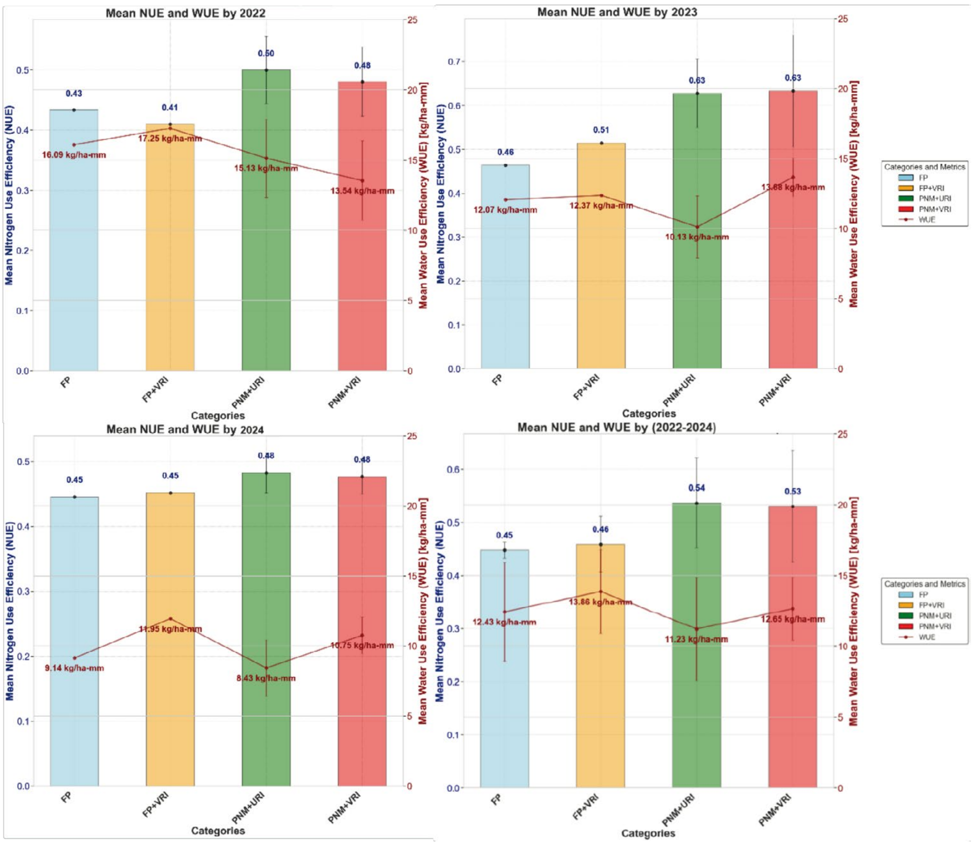

Figure 4. Mean NUE and WUE by different treatments across years.

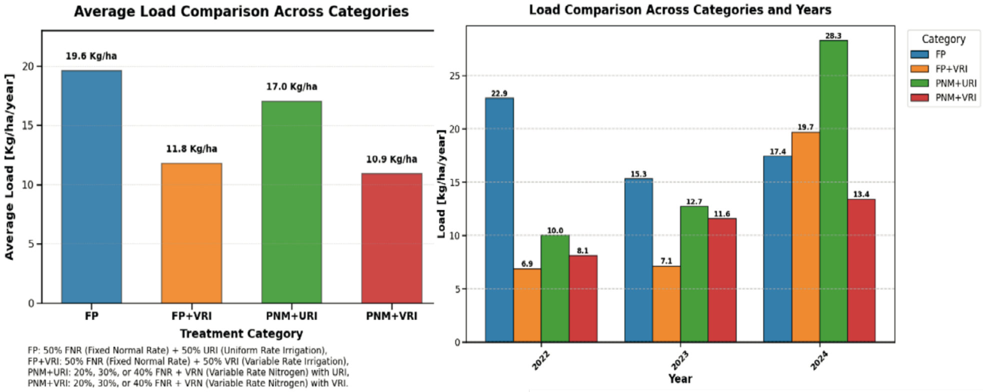

Figure 5. Load comparison of different management strategies across years (left) and in each year (right).

Discussion

The results indicated that integrating PNM with VRI could significantly improve agronomic performance and environmental sustainability in irrigated corn production. Over the three study years, PNM+VRI yielded 2% more and 18% better NUE than FP with statistically significant differences ($p<0.01$ for yield and $p<0.001$ for NUE). Although overall nitrate load was not statistically significant ($H=30.07$, $p=0.2445$), post-hoc analysis showed that PNM+VRI reduced nitrate leaching by 80% compared to FP (19.61 kg/ha vs 10.87 kg/ha, $p<0.001$, $\eta^2=30.07$).

It should be noted that PNM had higher nitrate leaching in some instances. One possible reason is that relying on NDVI to determine N status may result in wrong N application decisions. In some cases, low NDVI values – typically interpreted as N stress, may be due to water stress or other environmental factors. This misinterpretation may contribute to increased nitrate leaching due to over-application. It is important to correctly identify water, N or other stresses simultaneously during the growing season for making the right management decisions (Miao *et al.*, 2024).

From an economic perspective, PNM+VRI was the most profitable strategy among the treatments. This was likely due to the synergistic effect of optimized N application and adaptive irrigation practices that not only improved yield and NUE but also reduced input cost. However, only electricity cost of irrigation was accounted for in economic analysis and not the full value of water resource.

Future research should focus on sensor integration and machine learning-based strategies for simultaneous identification of N and water stresses to further improve the N and irrigation management for both food security, profitability and sustainable development.

Conclusions

This research emphasizes the significant potential of combining PNM with VRI as a strategy for optimizing resource utilization and promoting sustainability in irrigated corn management. The findings indicated that PNM+VRI could enhance yield, N and water use efficiencies and reduce nitrate leaching, thus achieving a balance among agronomic efficacy, profitability and environmental sustainability.

Acknowledgements

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